Design of Human-Centred Augmented Reality Learning System for Laboratory Training based on Smart Object Interfacing

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

By

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Dedicated to

My late grandparents,

My parents

&

My loving family.

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DECLARATION

I hereby declare that the work contained in this thesis entitled "Design of Human-Centred Augmented Reality Learning System for Laboratory Training based on Smart Object Interfacing" is my own work done under the supervision of Professor Pradeep G. Yammiyavar, at the Department of Design, Indian Institute of Technology Guwahati (IITG), Assam. I hereby declare that to the best of my knowledge, it contains no materials previously published or written by another person, or a substantial proportion of material which have been accepted for the award of any other degree or diploma at IITG or any other educational institute, except where the due acknowledgment is made in this thesis. Any contribution made to the research made by others, with whom I have worked at IITG or elsewhere, is explicitly acknowledged in the thesis. I also hereby declare that the intellectual content of this thesis is the product of my own work, and as per general norms of reporting research findings, due acknowledgements have been made wherever the research findings of other researchers have been cited in this thesis.

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CERTIFICATE

This is to certify that the work contained in this thesis entitled "Design of Human-Centred Augmented Reality Learning System for Laboratory Training based on Smart Object Interfacing" submitted by Mr. Anmol Srivastava to the Indian Institute of Technology Guwahati, Assam (India) for the award of the degree of Doctor of Philosophy has been carried out under my supervision. This work has not been submitted elsewhere for the award of any other degree or diploma.

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Thesis Summary

Students studying in undergraduate electronics engineering programs often face difficulties like debugging circuits, operating test equipment and relating theory while conducting practical experiments during electronics laboratory sessions. These difficulties act as barriers to learning. This thesis presents the research that led to a Smart Learning System that has been prototyped as a solution to address problems of learning by students. The system is based on Augmented Reality and Smart Objects technology. It minimizes the cognitive load of students and helps in enriching their learning experience. The device has been further designed to augment human tutoring during laboratory sessions and assist laboratory instructors, who with faculty members carry out the main task of training and assisting students while conducting practical experiments.

The Smart Learning System is configured to (a) provide contextualized information to students immediately, (b) help them relate theory with practice and (c) assist in learning tasks like rigging up circuits and operating test equipment in laboratory sessions. Further, problems faced by students during circuit assembly on the breadboard are automatically sensed and highlighted via (i) active visualization through AR, and (ii) voice and text-based instructional modalities on smartphones. These instructions help them overcome difficulties in understanding and debugging of complicated circuits at the very moment they are engaged in conducting experiments – exactly how a human tutor would guide them.

The main aim of the thesis is to design Smart Learning System to assist students as if a human tutor conducts the teaching-learning instruction dialogue. Since human tutoring, especially in practical laboratory sessions, is based on imparting experiential knowledge, it is essential to provide Smart Learning System with the ability to predict problems or difficulties faced by students and guide or instruct them as human teachers do. To model and design this experiential or heuristic reasoning based instructional capabilities in Smart Learning System; this research focuses on human-centered design methods (Norman, 2013) and takes an interdisciplinary approach by combining the practices of Human-Computer Interaction (HCI) with those of Artificial Intelligence (AI). This method is mainly based on Herbert Simon's philosophy of considering AI as an empirical science (Simon, 1995). The main goal is to develop a solution for benefiting

student learners, especially in engineering institutes with a paucity of facilities, infrastructure, and teachers, such as those prevalent in India. A design based research methodology (Wang & Hannafin, 2005) has been adopted to conceptualize the proposed prototyped solution which has been built around Mark Weiser's vision of ubiquitous computing (Weiser, 1991).

User studies and design validating experiments conducted using SLS amongst undergraduate engineering students as a part of this research show that not only does it minimize the cognitive load experienced by students in labs, but it also helps them enrich their learning experience without inhibition. SLS also retains natural affordance of objects used in laboratory sessions and provides a multi-sensorial experience to its users. Overall, the total sample size of the participants who took part in these studies is 337. Future work for the design of such systems has also been presented. Design heuristics to conceptualize such AR and smart object based IOT learning aid in complex educational scenarios is the outcome.

The main contribution of this thesis is a novel Smart Learning System for assisting students of engineering institutes in practical electronics laboratory sessions that also reduces students' cognitive load while conducting practical experiments. The thesis shows that it is possible to interweave different emerging technologies – Augmented Reality, Smart Objects, Artificial Intelligence and Internet of Things together into a holistic system to enrich students' learning experiences. Lastly, the thesis presents a set of design heuristics and implications that will be helpful for HCI researchers and Interaction Designers to develop effective learning mediums using Augmented Reality or Mixed Reality to improve learning experiences of students in various contexts.

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Chapter 1: Introduction

Chapter Abstract: This chapter introduces the research context and the motivation for this research. Summary of all thesis chapters is presented.

1.1 Introduction to research context and thesis

Confucius, the Chinese educator, and philosopher, once said - “I hear and I forget. I see and I remember. I do and I understand.” This quote very aptly applies to engineering education that strongly relies on the practice of learning by doing to produce successful practicing engineers, capable of doing practical “engineering”.

Engineering is a practical profession devoted to the creation of technology through modification of fundamental resources (i.e. energy, materials, and information) available to humans (Lyle D. & Albert J, 2005). To attain this goal of modifying, manipulating or exploiting fundamental natural resources for the benefit of humans, practicing engineers utilize different types of laboratories to make observations, perform testing experiments and obtain experimental data that helps inform the design of new products, technologies or human knowledge. These laboratories are broadly categorized into two types (Al-bahi, 2008), namely Research and Development. Research laboratories are mainly exploratory and extend or seek knowledge that can be generalized or systematized – often without any specific use in mind. Investigations in a research laboratory (lab) may involve determining something that is not known by anyone or is not generally available. Development laboratories, on the other hand, try to answer specific questions by carrying out application experiments to obtain experimental data that can help guide the design and development of a product. Laboratories in engineering curriculum also aid in understanding abstract concepts and theories.

To produce proficient practicing engineers that are capable of working in these research and development laboratories, engineering education relies on “practical educational laboratories” to nurture hands-on skills in students. It enables the students to think both synergistically and analytically, gain necessary skills to solve real-world problems and develop an intuition to work with various physical setups. The motive for students in these labs is not to extract data necessary for a design, or evaluate new device or to discover a new addition to our knowledge of the world. Instead, students learn fundamental concepts using essential skills and abilities, which practicing engineers are assumed to know already. Table 1.1 describes the types of laboratories.

Table 1.1 Types of laboratories and their functions. Source: Author generated based on literature

Utilized by	Types of Laboratories	Function
Practicing Engineers	Research Laboratory	Knowledge extension, exploratory studies, uses are often not defined.
	Development Laboratory	Goal-specific, used for product design and development, requirement testing and analysis
Engineering Students of engineering institutes	Educational Laboratory	Skill development, nurture creativity and critical thinking

These practical educational laboratories of engineering institutes play an important role in providing a hands-on learning experience to students. However, students performing practical experiments in laboratories are often faced with difficulties in procedures and experimental setup which often prevents them from making deeper inquiry into the experiment being conducted. Estrada & Atwood (2012) reports that nearly 78% of the students feel frustrated in practical laboratory sessions as they are unable to operate various test equipment, troubleshoot experimental setup or understand underlying theory. All these factors add to the additional workload for students during learning. Further, students in these educational laboratories have to rely heavily on laboratory instructors who are already overburdened by addressing difficulties of a large number of student groups working on multiple sets of practical assignments.

In addition to these difficulties, current ineffective practices followed in educational laboratories prove insufficient in imparting required learning experience to students. These practices are oriented more towards surface learning based approaches (or rote learning) that almost encourage students to reproduce information for assessment without necessarily understanding its connection to knowledge. Thus, such practices fail to equip students with required skills and learnings for the long term that could be gained from working on a tangible experimental setup.

While conducting pre-laboratory orientation are considered as alternatives to negate rote learning, they do not prove to be useful as very few students prefer to attend such orientation classes or pay attention to what is said in them. Many educational practical laboratories supplement students' learning and teaching by employing a simulation-based approach using software-based simulators to help students visualize experiments and their working. Although it is an effective means to understand, it lacks hands-on practice necessary to nurture intuitive problem-solving skills in engineering students. It also inhibits ideation (Oviatt, Cohen, Miller, Hodge, & Mann, 2012).

Students often use internet-enabled smartphones and digital tablets in laboratories as an alternative to seeking out instructors for information regarding carrying out procedures in the practical experiment being performed by them. These devices have potential to act as an enabler for mobile augmented reality (AR) content – which can embed virtual information, such as 3-Dimensional (3D) or 2-Dimensional (2D) visualizations and videos onto real-world scenarios. AR can act as a great medium to provide contextualized information and visualization required for students in practical laboratories. However, in certain situations, where the experimental setup is complicated, students often need more hints and instructions regarding procedures or errors committed by them on a physical experimental setup. In such cases, mobile AR applications and physical laboratory objects embedded with specific computational capabilities or "intelligence" can help assist students. It is this scenario that has been addressed and reported in this thesis.

In physical experimental setups, sensors and microcontrollers can be used to embed intelligence, for example, the Toastboard by Drew et al., (2016), BoardLab by Goyal et al., (2013). By doing so, such artifacts can sense various experimental parameters to be measured or observed by students and provide a required set of instructions for students to follow. However, for achieving this, several important research questions are raised – how intelligence needs to be embedded into laboratory artifacts? If embedded with intelligence, how can they act as an instructional medium that can assist students – similar to a human tutor? How can interactions be designed with such artefacts? Up to what level of does this intelligence needs to be embedded so that it forces the students to learn.

One way to address such research questions is by adopting Mark Weiser's vision of ubiquitous computing where every day mundane objects are embedded with computational capabilities (Weiser, 1991). By coupling such objects with computational capabilities with the AR, it is possible to design effective, efficient and useful learning applications and systems for educational practical laboratories of engineering institutes. Such systems can provide innovative and novel ways to enrich the learning experiences of students in practical laboratory sessions. These systems can be further expanded to address a series of issues, outlined later in this thesis, that are faced by students and instructors in practical laboratories.

This thesis presents a first step towards the design of a novel learning aid in the context of educational practical electronics laboratory sessions of educational engineering institutes. Emerging technologies of AR and smart objects have been utilized to improve the learning experience of the students by reducing their workloads. The thesis is interdisciplinary in nature and derives knowledge from the fields of design, education, and technology, see Figure 1.1.

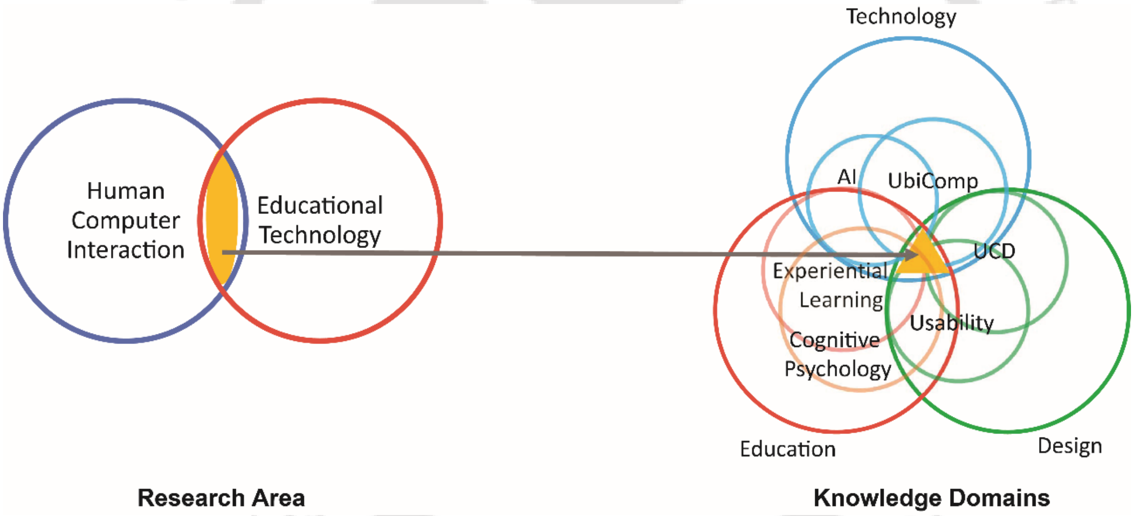


Figure 1.1 Interdisciplinary knowledge domains that informed the research area of this thesis. Figure Source: Author generated.

The thesis derives its philosophical understanding from the works of David A Kolb (for his experiential learning theory) (Kolb, 2014), Don Norman (for his human-centered design philosophy) (Norman, 2002), Mark Weiser (for his vision of ubiquitous computing) (Weiser, 1991) and Herbert Simon (for his insights into design science and artificial intelligence) (Simon, 1995). It also relies on a broad spectrum of research conducted at the UE & HCI Lab[1] at IIT Guwahati which has initiated India-specific context research in Human-Computer Interaction (HCI) and has set methodologies that are culture specific

[1] http://iitg.ac.in/uelab/index.html

to India. The primary research domain of this thesis is in Educational Technology that has been informed through the design research methodologies and human-centered design practices of HCI. The contribution of this thesis will be applicable in overcoming challenges faced in educational practical laboratories (with emphasis on electronics engineering).

1.2 Motivation and need for this research

When we look at the timeline of technology, specifically in the context of education, it has always played a vital role in shaping classroom-learning experiences. Figure 1.2 below depicts a simplified visualization of the evolution of educational technology over time (TED, 2012). During ~400 BC, wooden sticks were used to draw on the sand and acted as a technological medium. Near about 1440 A.D Gutenberg invented the printing press (Wikipedia, 2018), thereby eventually giving rise to books that radically changed the way learning and teaching takes place (Eisenstein, 1979). In fact, books and papers are such ubiquitously available today that they are hardly recognized as technology anymore.

Figure 1.2 A rough visualization showing evolution of instructional technology and its current state

Gradually with time, inventions like videos, radios, televisions were integrated into various educational settings. The invention of personal computers and the internet brought in the information age giving the power of knowledge to a vast scale of audience. Presently we have digital tablets and smartphones present in almost every classrooms. These have enabled new means of teaching such as blended learning; flipped classrooms and Massive open online courses (MOOCs). Intelligent adaptive systems, relying on Artificial Intelligence (AI), are being adopted in classrooms to understand individual learners and make learning more learner-centric. Such systems can deliver instructions to students at their own pace and time. Classroom spaces are not limited within the confines of walls anymore. The advent of large and easily accessible computing power is enabling people to learn anytime, anywhere.

There has also been an increasing number of research reporting in the field of HCI on Tangible Interaction for education as seen in venues such as Conference on Human Factors in Computing Systems, Interaction Design for Children, Tangible and Embedded Interaction (CHI, n.d.; IDC, n.d.; TEI, n.d.). A number of research work has been conducted amongst students of varying age groups ranging from pre-schools to higher education (Antle, 2007-a; Horn, 2013; Antle, 2007-b). These research studies emphasize on the physicality of user-interaction with tangible setups and show how it leads towards better learning experiences amongst students owing to embodiment effect. The results also highlight that students, especially from pre-school to the primary school level, engage in playful and entertaining ways of learning through tangible interactive learning setups. However, when we look at the scenario of practical educational laboratories of engineering institutes, this engaging and playful component of the learning experience is often missing by the time students enter higher education.

While students at early years of education are involved in playful learning through tangible interactive setup – which are objects with embedded computational capabilities, the same does not hold true for engineering students who also engage in tangible interaction with laboratory equipment and devices. A way to illustrate this perspective is through the example of hobbyist or amateurs who involve in 'do-it-yourself' (DIY) or maker activity. One can argue, that while for young children tangible interactive setups are a medium to engage in playful learning, similarly for adults (such as hobbyists and amateurs) engaging in hobby electronics, making or hacking things, and so forth are interactive tangible setups. A practical educational laboratory, which is a set of interactive tangibles in forms of test equipment and devices, is supposed to enable assimilation of knowledge among engineering students through tangible interaction. However, practical educational laboratories fail to capture the attention of engineering students to impart the desired learning experience (Johnstone, 2006; Watai, Brodersen, & Brophy, 2007). Even with the latest development in technologies and user-interaction modalities, practical educational laboratories rely on equipment and devices whose functioning remains arcane to students. Examples range from working on oscilloscopes to simple digital multi-meters. Instead of facilitating learning, such devices end up being a clutch or an obstruction in the learning process. Difficulties of operating these devices along with additional constraints steal the very purpose of the hands-on learning experience in practical laboratories. This became the moot point of concern in this thesis, which raises an important preliminary research question (PRQ):

PRQ: How can technology be intervened in complex learning environments like practical educational laboratories in higher engineering education to minimize difficulties faced by students during learning?

To explore this question (PRQ), we conducted early explorations (Srivastava & Yammiyavar, 2015; Yammiyavar, Srivastava, & Shashidhara, 2014) out of curiosity among school children to see how engaging learning experiences can be designed through objects with embedded computational capabilities. Working prototypes that enabled playful engagement of children while learning was developed and tested in pre-school and primary schools. Theory of Multiple Intelligence (Gardner, 2011), Bloom's taxonomy (Bloom, 1956) and Kolb's experiential learning cycle (Kolb, 2014) were used as a framework to access the effectiveness of the prototypes. Figure 1.3 depicts a snapshot of one such study conducted amongst pre-school children.

Figure 1.3 Initial exploratory studies conducted amongst school children to investigate the preliminary research question. Image Source: (Yammiyavar, Srivastava, & Shashidhara, 2014)

The results of these exploratory studies indicated a positive influence of such objects on classroom dynamics and learning experiences of schoolchildren. The complete details of these studies are presented in Annexure A. It was this type of learning experience that we wanted to embed for undergraduate engineering students of practical electronics laboratory sessions. The premise is that with the proliferation of technologies and confluence of easily accessible electronics and related platforms (like microcontrollers), it is possible to design interactive learning aids for complex learning environments of educational laboratories. This premise is based on Ubiquitous Computing, as envisioned by Mark Weiser's (Weiser, 1991). Mark Weiser was a pioneering computer scientist and is widely referred to as the father of Ubiquitous Computing, a term he coined in 1988 (Wikipedia, 2018). According to Weiser's vision, commonly used everyday objects will be embedded with tiny sensors, electronics, and computational capabilities to enhance living experiences of people and assist them in various everyday mundane tasks. What it implies in a broader sense is that technology will become ubiquitous and will eventually become unnoticeable by users when it is working for their benefit.

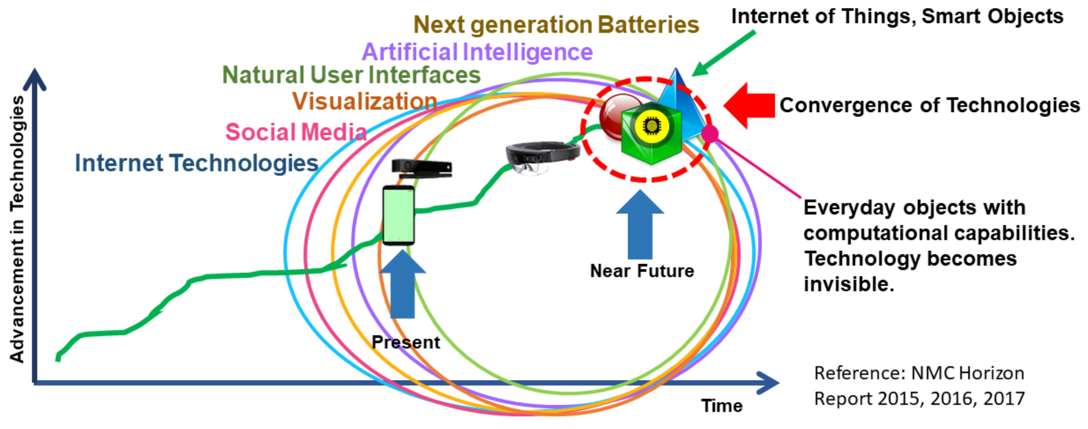


Figure 1.4 Learning Technologies in the Era of Ubiquitous Computing

According to the Horizon Reports (Adams Becker S, Cummins M, Davis A, Freeman A, Hall Giesinger C, 2017; Johnson, L., Adams Becker, S., Estrada, V., and Freeman, 2015; Johnson et al., 2016) that highlight the emerging trends in educational technology, ubiquitous computing technologies are going to play a crucial role in accelerating learning approaches in higher education. Figure 1.4 depicts a visualization of learning in the era of ubiquitous computing. It can be seen that at a certain point of time in future, various currently emerging technologies will converge together. In such a scenario it will be possible to create a spectrum of enriching learning experiences for students in complex learning environments such as educational practical laboratory sessions by embedding computational capabilities into artifacts used in these spaces (Dede, 2008).

However, if we are to design such interactive learning aids with computational capabilities in complex educational learning environments, how can this be realized? A number of technologies seem to be suitable for adoption in practical laboratories to enrich the learning experiences of students. These technologies are Virtual Reality (VR), Augmented Reality (AR), Interactive Table-tops, Projection-based displays, and Smart Objects (SO). Some of these technologies have been adopted in complex educational learning scenarios. Figure 1.5 depicts a few of these technologies used in educational learning environments of practical laboratories.

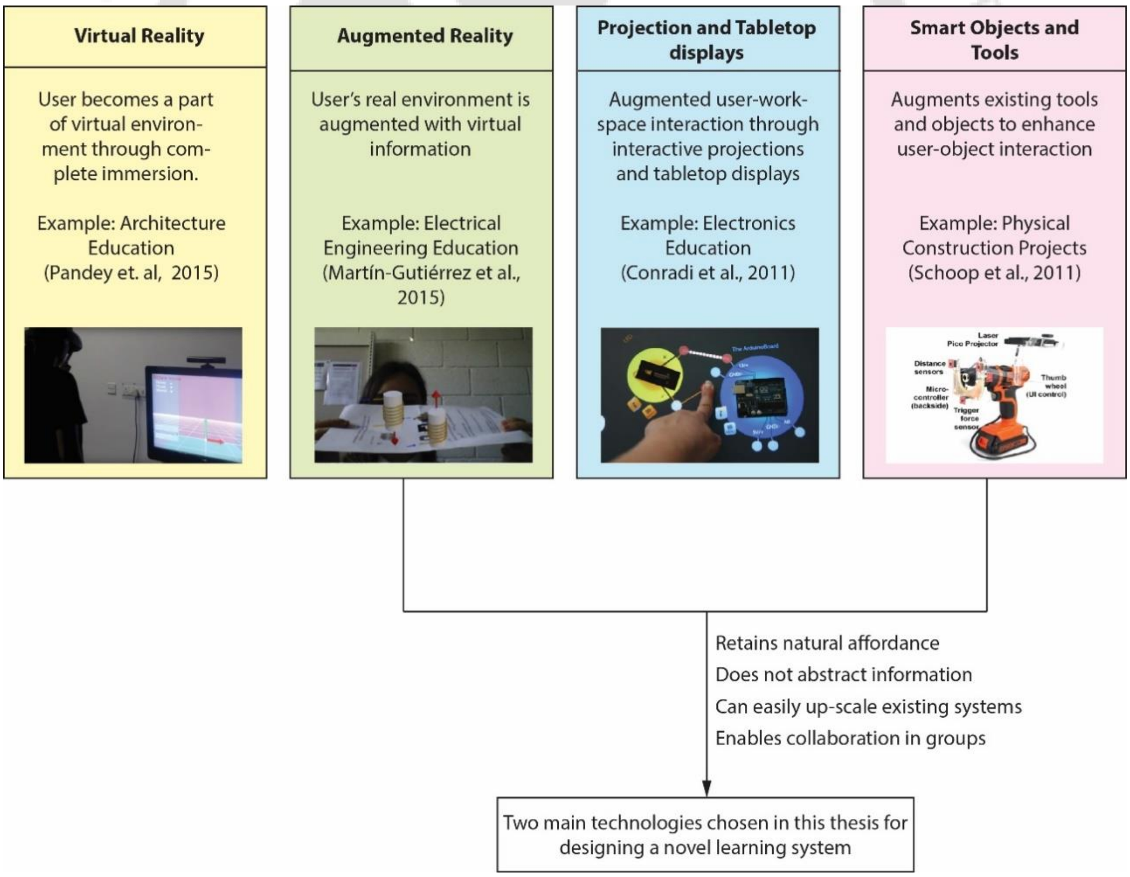


Figure 1.5 Different technologies that can be used in practical laboratories. Two main technologies of AR and smart objects were chosen in this thesis for designing a novel learning aid for practical electronics laboratory sessions.

Out of a number of ways in which innovation can be brought into teaching in educational laboratories using computers, defining laboratory objectives and emerging technologies, we choose new technologies of AR and smart objects. These were cautiously chosen owing to four main reasons:

(i) Unlike other technologies, such as VR or table-top displays, AR and smart objects can retain the "natural affordance" of the physical setup that students are required to work on in practical laboratories. Gibson (1977), as cited in (Greeno, 1994), proposed the theory of Affordance. "Affordance" refers to the possibility of an action on an object/ artefact. For example, a push button 'affords' being pressed, or a chair 'affords' being sat on. Affordance can be defined as an intuitive action that is invoked in an agent (i.e. the user) upon perceiving a system (i.e. artefact or object). This intuitive action enables agent-system interaction. In context of a practical laboratory session, AR and Smart Objects can augment already existing capabilities of laboratory artefacts, tools or equipment by retaining their natural methods of interaction that are familiar to students. Thus, this reduces the additional effort required by students to learn how to operate and interact with new technology tool, thereby, retaining natural affordance of the physical setup.

(ii) It is possible to represent information using these technologies without abstracting it,

(iii) AR and smart objects can be readily utilized to up-scale existing laboratory setup without requiring any additional requirements of hardware. This can be very useful for institutes with meager resources to implement these technologies, and

(iv) It is posited in this thesis that AR and smart objects can enable collaboration among student groups in practical laboratory sessions.

In this thesis, we also extend the use-case of these technologies (AR and SO) to merge with the Internet of Things (IoT) and AI. However, we find that there are dearth literature and design heuristics to come up with a holistic learning system interweaving these emerging technologies specifically in the context of electronics laboratories in the undergraduate curriculum. This thesis presents work on interweaving emerging technologies innovatively to improve the learning experiences of students.

1.3 Aims and Objectives

This thesis aims at investigating, exploring and developing mobile device based technology that will assist a student to learn as well as to be tutored while conducting laboratory experiments in the typical undergraduate curriculum.

The objectives of the thesis are:

a) To reduce the extraneous cognitive load of students while conducting a practical experiment in a laboratory.
b) To act as a human-like tutor to address specific barriers a student might face while conducting experiments.
c) Reduce the workload of human tutors
d) Make self-learning seamless, immersive experience in mixed-reality

1.4 Definitions used in this thesis

1.4.1 Augmented Reality

Augmented reality is a variation of virtual environment superimposed on a real environment screen on a device. While VR provides complete immersion of users in a 3D synthetic digital environment, AR, on the other hand, allows the user to see the real world in the background with virtual objects superimposed upon or composited with the real world. Hence, AR supplements reality rather than completely replacing it (Azuma, 1997). Figure 1.6 depicts an example of how AR looks.

Figure 1.6 A view of Augmented Reality on a mobile device. Virtual objects, in the form of 3D graphics, overlaid on a real-world environment. Source: (Amrit, Bansal, & Yammiyavar, 2015)

1.4.2 Ubiquitous Computing

As convincingly stated by David Ley (2005): "Ubiquitous computing is a vision of computing power 'invisibly' embedded in the world around us and accessed through intelligent interfaces: 'Its highest ideal is to make a computer so embedded, so fitting, so natural, that we use it without even thinking about it.' This is about a shift to human-centered computing, where technology is no longer a barrier, but works for us, adapting to our needs and preferences and remaining in the background until required. This implies a change in our relationship with ICT to a much more natural way of interacting and using the power of networked computing systems which will be connected not just to the internet or other computers, but to places, people, everyday objects and things in the world around us".

1.4.3 Internet of Things

The Internet of Things (IoT) assumes that the physical objects that have been embedded with electronics and computational capabilities are connected through the internet. Such objects, which are also referred to as Smart Objects, can be identified and tracked automatically via the Internet and enable the exchange of data (Kranz, Holleis, & Schmidt, 2010). The IoT falls under the paradigm of ubiquitous computing.

1.4.4 Smart Object

Smart objects refer to physical artifacts or tools that have been embedded with various electronics, sensors and connectivity modules such as RFID, Bluetooth or Wi-Fi. In other words, these are everyday objects that have been embedded with computational capabilities and can perform a specific task (Doggen, 2012; Weiser, 1991). These objects can be connected to form the Internet of Things (IoT). For example, Figure 1.7 depicts a MediaCup prototype (Gellersen, Beigl, & Krull, 1999) – a coffee cup augmented with various sensors, communication and computational capabilities that obtains context information such as where the cup is, how it is handled, and whether it is hot or cold for user awareness.

Figure 1.7 The MediaCup prototype that demonstrates how computational capabilities can be embedded in everyday mundane objects and utilized for context awareness. Image Source: Gellersen, Beigl, & Krull (1999)

In the context of education, such objects provide an edge over mobile devices that may seem similar to ubiquitous computing, but intrinsically cannot provide the affordances for education that interfaces of smart objects and intelligent contexts promise (Dede, 2008).

1.4.5 Embedded Intelligence

Embedded intelligence refers to the ability of a system (consisting of a software application or smart object), that has been embedded with computational capabilities, to assist learners (students) like that of a human tutor. To achieve this, the system can rely on multimodal interaction techniques, for example, interaction with physical objects using AR, or smart objects communication with a software module, and so forth. This definition has been proposed in the thesis based on insights from research studies (Baber & Baumann, 2002; Dede, 2008; Gellersen, Beigl, & Krull, 1999; Kranz et al., 2010).

1.5 Chapter Summaries

Chapter 1: Introduction – introduces the interdisciplinary context of the research and outlines the research issues being dealt with in this thesis. The motivation, of this research, have been discussed and reported. Summaries of all the Chapters are presented.

Chapter 2: State of the Art-Literature Review – examines various research studies conducted using Augmented Reality and other emerging technologies in education under the umbrella of ubiquitous computing. Discusses research gaps. The review ends by posing relevant research question for the thesis and presents a research framework.

Chapter 3: Design Research Framework and Methodologies – presents complete design research framework and outlines the plan of the thesis.

Chapter 4: User Need Analysis through User Research Studies – presents a user-centered design investigation for identifying user needs. Discusses different studies conducted in this thesis.

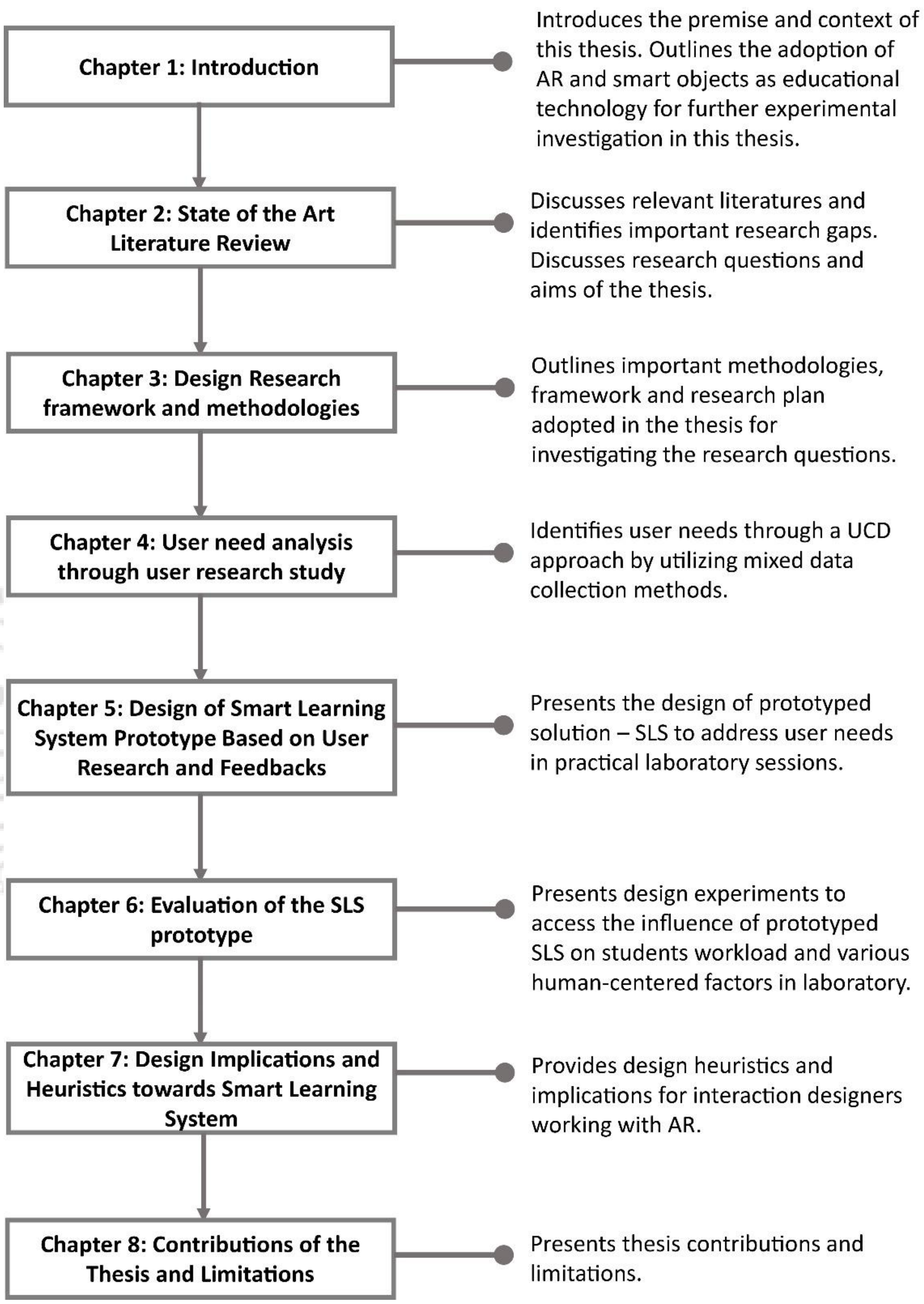
Chapter 5: Design of Smart Learning System Prototype Based on User Research and Feedbacks – presents the design and rationale of the proposed prototypical solution. The chapter presents an in-depth insight into the development of prototype and conceptual model extending the use of the prototype for IoT and AI.

Chapter 6: Evaluation of SLS Prototype – presents an evaluation of SLS prototype based on design experiments conducted across India. The chapter also explains broad themes that emerge from data analysis. Reports of hypotheses testing.

Chapter 7: Design Implications and Heuristics towards Smart Learning System – presents design implication and heuristics for designing SLS.

Chapter 8: Contributions of the Thesis and Limitations – presents the contributions of the thesis and its limitations.

A chapter flow diagram is presented as follows:



Chapter 2: State of the Art-Literature Review

Chapter Abstract: This chapter identifies research gaps and opportunities after conducting a state of the art literature review. Based on the literature review, research questions have been formulated for further investigation in this thesis. Aims of the thesis have been outlined.

2.1 Introduction

A systematic literature review was carried out to determine relevant literatures that were prompted by preliminary research questions stated in Chapter 1. A comprehensive literature search was conducted to identify research gaps and gain relevant insights into developing innovative techniques for aiding students in electronics laboratories. Figure 2.1 highlights the literature review process adopted. Published literatures (papers, journals, articles, books, reports) belonging to various knowledge domains were identified relevant for this thesis. The searched literatures were categorized into four broad domains as depicted in Figure 2.1.

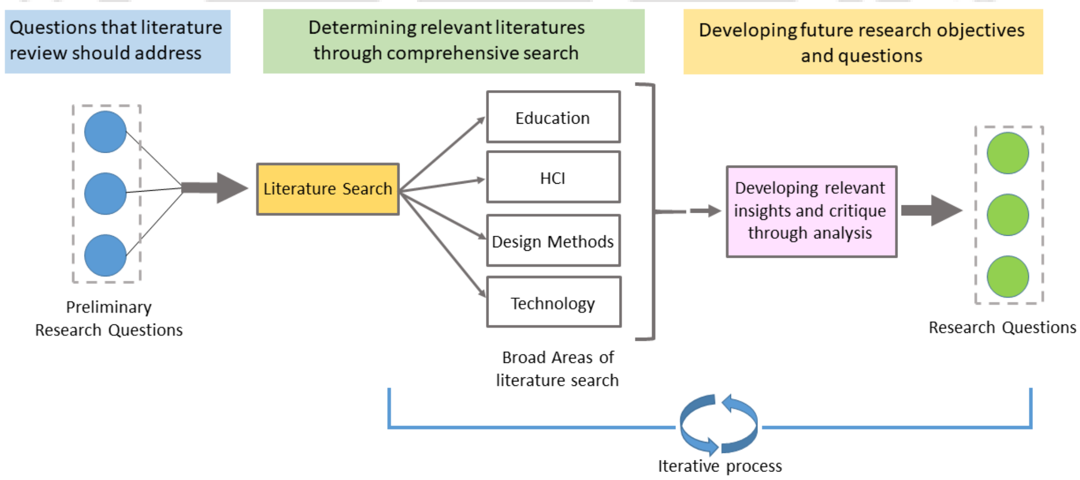


Figure 2.1 Literature review process utilized in this thesis. Figure Source: Author generated.

The purpose of the literature review is to understand the current state of the art as well as to identify gaps and opportunities. Literatures from the field of HCI in emerging technologies like AR and Ubiquitous Computing have been explored to understand how technology can be adopted and used innovatively in engineering practical electronics laboratories to improve students' learning experiences. Literatures from AI, both philosophical and application areas, have also been reviewed to understand how these technologies can be synthesized to form a new synergistic system capable of augmenting learning experiences and supplementing teaching activities.

2.2 Understanding challenges in engineering educational practical laboratory environments

Educational laboratories try to simulate the experiences of practicing professional engineers for undergraduate students so that they can attain an ability to design and conduct experiments, as well as analyze and interpret data (Al-bahi, 2008; Lyle D. & Albert J, 2005). To help students to gain these skills, it becomes essential for engineering curriculums to define clear "objectives" that these educational laboratories should meet. Defining these educational laboratory objectives is also an area of major concern amongst engineering education research community and there have been a number of published research articles (Al-bahi, 2008; Felder & Brent, 2004; C. Hart, Mulhall, Berry, Loughran, & Gunstone, 2000; Lyle D. & Albert J, 2005; Sutton & Charles, 1996) that have tried to address them.

Two main authoritative bodies in India and abroad responsible for defining educational laboratory "objectives" for engineering education were referred to in this thesis. These are (i) Accreditation Board for Engineering and Technology Inc., (ABET, n.d.), and (ii) All India Council for Technical Education (AICTE, n.d.-b). ABET Inc. is an international body responsible for defining goals for engineering education as well as accrediting engineering institutions across the United States as well as a few other countries. AICTE is the statutory body and a national-level council for technical and higher education in India and was of prime consideration because the research carried in this thesis has been conducted across various engineering institutes in India.

ABET Inc. along with engineering educational professionals came up with a list of 13 objectives for successful engineering laboratories (Lyle D. & Albert J, 2005), as shown in Table 2.1 and described in detail in Annexure B1.

Table 2.1 Objectives of Engineering Laboratories by ABET Inc. Source: Carnevale, D. (2002) (as cited in Lammi (2009)) and (Al-bahi, 2008).

Objective	Description
1	Instrumentation: Apply appropriate tools to make measurements
2	Models: Identify the strengths and limitations of models
3	Experiment: Devise an experimental approach
4	Data analysis: Demonstrate the ability to collect, analyze, and interpret data
5	Design: Build and test prototypes for given requirements using specific methodologies
6	Learn from failure: identify unsuccessful outcomes and re-engineer them
7	Creativity: Demonstrate capability in real-world problem solving
8	Psychomotor: Demonstrate competence engineering tools and resources
9	Safety: Identify health, safety, and environmental issues
10	Communication: Demonstrate effective oral and written communication skill
11	Teamwork: Work effectively in teams, show responsibility and meet deadlines
12	Ethics in the laboratory: Reporting information objectively, interacting with integrity.
13	Sensory awareness: Use the human senses to gather information

These objectives can be generalized for all types of educational laboratories across various engineering disciplines. When comparing the documentation for laboratory-based learning experiences for students provided by AICTE (AICTE, 2018), it was observed that there are no standard set of objectives defined as is the case with ABET. Instead, AICTE has defined outcomes based on various individual engineering sub-disciplines. Two of these objectives have been extracted from the model curriculum of Computer Science and Electrical and Electronics engineering disciplines and consolidated in Table 2.2.

It was observed that AICTE mostly deals with technical nuances of the course and has focused more on laboratory outcomes based on a conventional approach. AICTE has also defined a set of "educational outcomes" – which have been described in Annexure B2, that provide overall objectives for "technical courses" that try to cover broad aspects of laboratory objectives – which can be considered similar to ABET Inc. However, the AICTE report lacks a structured insight into laboratory objectives for students in comparison to ABET Inc. The AICTE report has no mention of laboratory resources, cognitive load, availability, and quality of tutors. It is a one-way monologue and fails to be helpful at the micro level of learning and instruction design for the student and physical laboratory environment.

Table 2.2 A consolidated list of laboratory outcomes extracted from AICTE model curriculum of first-year UG engineering for Computer Science, Electrical, and Electronics discipline. Source: (AICTE, 2018)

Engineering Discipline	**Laboratory Outcomes**
Computer Science (Programming for problem-solving)	• To formulate the algorithms for simple problems • To translate given algorithms to a working and correct program • To be able to correct syntax errors as reported by the compilers • To be able to identify and correct logical errors encountered at runtime • To be able to write iterative as well as recursive programs • To be able to represent data in arrays, strings, and structures and manipulate them through a program • To be able to declare pointers of different types and use them in defining self-referential structures • To be able to create, read and write to and from simple text files
Electrical and Electronics Engineering	• Get exposure to common electrical components and their ratings • Make electrical connections by wires of appropriate ratings • Understand the usage of common electrical measuring instruments • Understand the basic characteristics of transformers and electrical machines • Get exposure to the working of power electronic converters

On the other hand, although both of these laboratory objectives (given by AICTE and ABET) are not formally validated, they provide a sound list of laboratory activities that will be suitable for students' in educational laboratories.

When considering students' learning experiences in these laboratories from educational theories viewpoint, it is observed that these objectives are based on experiential learning and are spread across the various domain, i.e. cognitive, psychomotor and affective, of Bloom's Taxonomy (Bloom, 1956). In terms of experiential learning, Kolb's Theory of Experiential Learning (Kolb, 2014) provides a good framework for hands-on learning. This theory emphasizes the role of learning by doing and explains how it leads to the assimilation of knowledge via the process of active experimentation, concrete experience, reflective observation and abstract conceptualization. It forms a foundation of hands-on learning approach encouraged and practiced in engineering education and practical educational laboratories (Abdulwahed & Nagy, 2009; EIT, n.d.). Both Kolb's Experiential Learning Theory and Bloom's Taxonomy can be used as a model for laboratory activities in higher cognitive as well as sensorial domain and can help understand assimilation of knowledge in students.

It is observed that despite numerous attempts being made in literatures on defining proper laboratory objectives, there have always been challenges to engage students fully to help them get a look and feel of the experiment thereby breaking the cycle of active experimentation or concrete experience. Studies (Aghababyan, Martin, & Harris-Brasiel, 2014; Estrada & Atwood, 2012) suggest that almost 78% of the students feel frustrated in educational laboratory sessions due to issues like troubleshooting of equipment and lack of understanding regarding experiment. This frustration causes boredom in students, which prevents them from learning further. These difficulties disrupt students' experiential learning cycle, thus leading towards reduced learner's satisfaction.

Due to these challenges, student's attention in practical laboratories is mostly hinged upon finishing the ritual of the experiment rather than understanding the crux of the experiment process that requires them to get insight into the real-world problems. Research studies in cognitive science (Sweller, van Merrienboer, & Paas, 1998; Van Gog & Paas, 2008; Watai, Brodersen, & Brophy, 2007) have also reported that because of these difficulties, practical laboratories are a place of the extreme cognitive load for students which hinders with their learning process. Similar observations have been reported in studies (Lyle D. & Albert J, 2005; Paas, Tuovinen, Tabbers, & Van Gerven, 2010), which also suggest that students' cognitive load is increased in these labs which hinders with their learning.

According to Cognitive Load Theory (CLT) (Chandler & Sweller, 1991; Sweller, 1994), our working memory is limited with respect to the amount of information it can hold and the number of operations it can perform on that information. Working memory is a part of short-term memory that is concerned with immediate conscious information processing (Baddeley, 1983). At any given instant our working memory can a maximum of plus minus seven chunks of information (Miller, 1963). An elaborate discussion on the types of memory and human brain's information processing can be referred through work of famous psychologists Alan Baddeley (Baddeley, 1983) and George Miller (Miller, 1963). The learner has to use this limited working memory efficiently, especially when learning a complex task. These cognitive loads have been categorized into three types.

- Intrinsic Cognitive Load is the inherent level of difficulty associated with the complexity of the learning content. It is determined primarily by knowledge and skills associated with the complexity of the learning content and instructional objectives.
- Germane (Relevant) Cognitive Load is the load devoted to the processing, construction, and automation of schemas or instructional activities that benefit the learning goal. This germane load leads to a better learning outcome.
- Extraneous Cognitive Load imposes mental work that is not immediately relevant to the learning goal and consequently wastes limited mental resources. The extraneous cognitive load is generated by the manner in which information is presented to learners and is under the control of interface designers. Germane load, therefore, helps a novice learner to become an expert (Sweller, 1994).

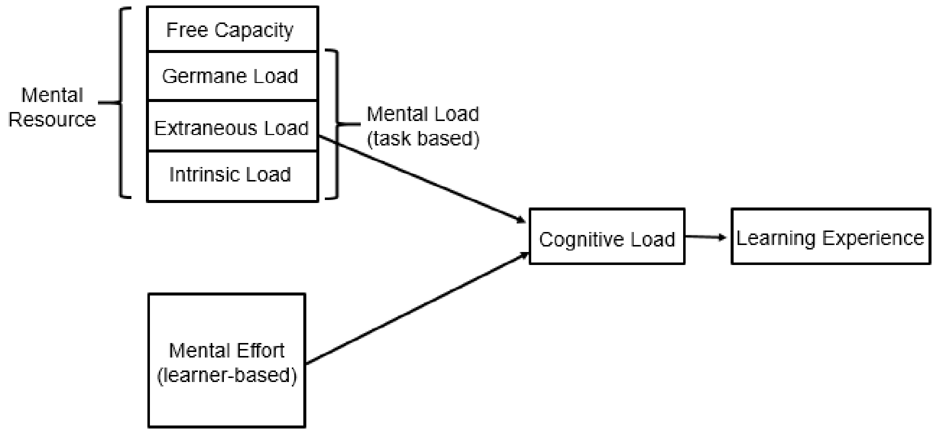


Figure 2.2 Cognitive Load of the learning experience. Image adapted from: (Deshpande, 2013)

Figure 2.2 explains the relationship between mental effort, mental resource, and learning experience. If the sum of the intrinsic and extraneous load exceeds mental resource, then learning experience suffers. Variations in cognitive load results due to interaction among instructional environments (educational laboratories and related equipment interfaces), learner's prior knowledge and complexity of learning task. Therefore, it is posited that if the cognitive load of students in practical electronics laboratory sessions is reduced, their learning experience can be improved.

When considering the lab sessions curriculum wise in terms of circuit-based courses such as Electronics and Electrical engineering – which is the focus of this thesis, students from all disciplines have to undergo practical electronics laboratory sessions during their first year of undergraduate studies. However, engaging students in these lab sessions remains challenging. Many institutes struggle to retain the interest of students due to two main factors; (i) students of different disciplines are seldom interested in studying a non-core subject, and, (ii) teaching a large number of students of varied background is often quite difficult for instructors (Sutton & Charles, 1996). Challenges also arise for laboratory instructors regarding teaching, giving time to students and often handling a large number of students – who face difficulties in a time-limited laboratory session. Students in these practical electronics laboratories are required to assemble physical circuits on a Breadboard (Portugal, 1971), which is a passive device used for prototyping physical electronic circuits. However, despite its widespread use, it remains prone to a number of issues such as loose wire connections, misplacements of electronic components and faulty connections. In addition to assembling circuits, students are required to operate test equipment like cathode ray oscilloscope, variable power supplies, function generators and at the same time make connections between theoretical and application aspects of the experiments. All these steps combined together pose various constraints and challenges for students – thus leading towards increased cognitive load (or workload), poor learning experience and poor learner's satisfaction. Similar concerns have been raised by Watai et. al., (2007) in their study of electronics engineering lab sessions reports that:

> "Students often get bogged down with procedural and practical difficulties that distract them from the concepts and objectives of the labs and prevent deeper inquiry".

Another most commonly reported drawback in educational laboratories is on the lack of contextualized or situated instruction that can help student relate theory and the current hands-on practical. Although lab objectives are listed in manual, it lacks connection with a real-world setting that would demonstrate the concept and application of the experiment (Watai et al., 2007). Therefore, students become over-dependent on lab instructors to explain to them the procedures as well as the concepts behind the experiment.

Pitterson & Streveler (2016) investigated and presented a detailed analysis of teaching and learning complex electronic circuit concepts by investigating students' prior knowledge, learning activities and learning environments. Pitterson et al., (2016) reported that student knowledge and understanding of basic electrical concepts are often disjointed and in pieces. Students also face difficulties in understanding about electrical and electronics circuits due to the abstract nature of concepts. Key findings included – lack of real-life applications, time-constraints due to a rigorous schedule, lack of multiple representations of content to name a few. More importantly, it was observed that the methods to overcome these shortcomings are often old and not in pace with current educational scenarios. These methods mostly rely on old techniques such as rote learning, passive methods of lecturing and more importantly lack of adoption and acceptance of new technologies. These factors act as bottlenecks in educational laboratories that affect learners' experience, satisfaction levels, and their workload. At the same time, it also presents an opportunity for research in educational laboratories regarding design and technological intervention using promising advances in the field of Information and communications technology (ICT).

Lyle D. & Albert J (2005) states that engineering schools still struggle to come up with innovative means to improve the learning experience of students in complex learning environments like practical laboratory sessions. The authors also suggest a need to direct research on engineering laboratories as a discipline by implementing new technologies. Most of the current research work in the educational laboratory focuses on the design of laboratory learning environments, activities and objectives. Another important observation made during the literature review process was that there is a lack of research in this area in India. There is a paucity of literatures about improving learning experiences in Indian engineering educational laboratories. This issue needs to be considered attentively given the large educational scales of setups of a country like India.

The constraints and lack of innovative technology in practical educational laboratories, as identified from the literatures, urge a need for research in this direction to push the envelope of learning technologies for creating better learning experiences for an engineering student to reduce external variables. To enable meaningful engagement – all within resource constraints that a country like India faces – in terms of infrastructure and education professionals.

2.3 Use of Ubiquitous Computing technologies in education

With the recent disruption of emerging technologies like AR, AI, and embedded systems, it is now possible to create a spectrum of enriching learning experiences for students in complex learning environments like educational laboratories. Researchers can now experiment with a gamut of technologies available to them to come up with novel learning technologies. Dede (2000) predicts that artifacts with semi-intelligence (also called smart objects) having capabilities to communicate wirelessly will find increasing usage in educational sectors in the near future. These smart objects are based on the vision of ubiquitous computing, as proposed by Weiser (1991). According to Weiser's vision, commonly used everyday objects will be embedded with tiny sensors, electronics, and computational capabilities to enhance living experiences of people and assist them in various everyday mundane tasks. What it implies in a broader sense is that technology will become ubiquitous and will eventually become unnoticeable by users when it is working for their benefit.

According to the NMC Horizon Report (2017) (Adams Becker S, Cummins M, Davis A, Freeman A, Hall Giesinger C, 2017), such emerging ubiquitous computing technologies are going to play a crucial role in accelerating learning approaches in higher education. In such a scenario it will be possible to enrich learning experiences of students in complex learning environments such as practical laboratory sessions by embedding computational capabilities into artifacts used in these labs (Dede, 2008). Such objects enable tangible interaction with the real-world objects as opposed to the 2D windows, icons, menus, pointer (WIMP) based graphical user interface (GUI) thereby increasing the effect of physicality and ideation (Dede, 2008; Oviatt et al., 2012). Research on tangible interaction in education highlights the importance of physicality in terms of improving learning and learning experience owing to embodiment effect and multi-sensorial experience. It has proven to be very beneficial in case of children (O'Malley, Fraser, & Others, 2004; Yammiyavar et al., 2014) and as suggested by Dede (2000, 2008), it will play an important role in higher education too. Müller & Erbe (2007) further suggest the use of AR to be ideal for multi-user collaborative and work applications which will be suitable for environments like educational laboratories.

Figure 2.3 depicts some of the important literatures surveyed in this thesis that highlight and predict the growing trend of various emerging technologies in education and their applications.

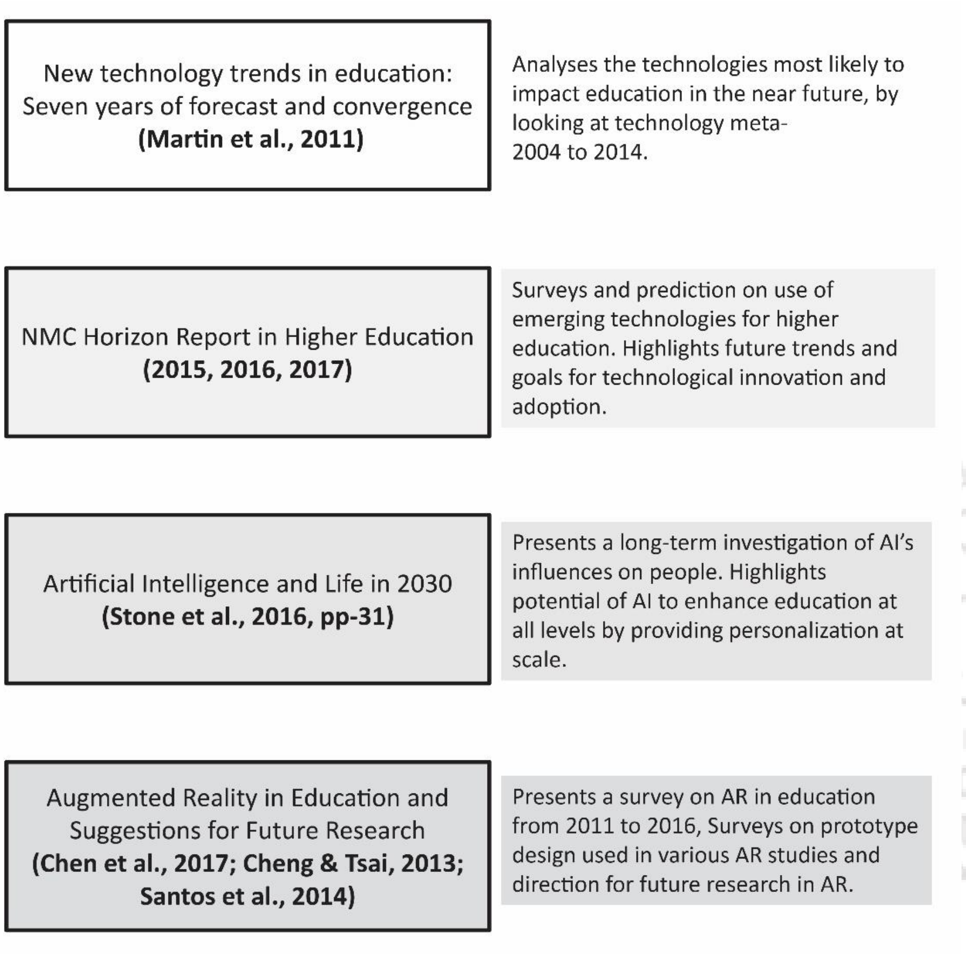


Figure 2.3 Important literatures that highlight and predict the growing trend of technologies in education

There have also been several interesting research work on user task, and workspace augmentation in the field of HCI and computer supported collaborative work, as depicted in

Table 2.3. Reviews and finding of relevant research works that can be extended and applied in the context of educational practical electronics laboratories is presented in Section 0.

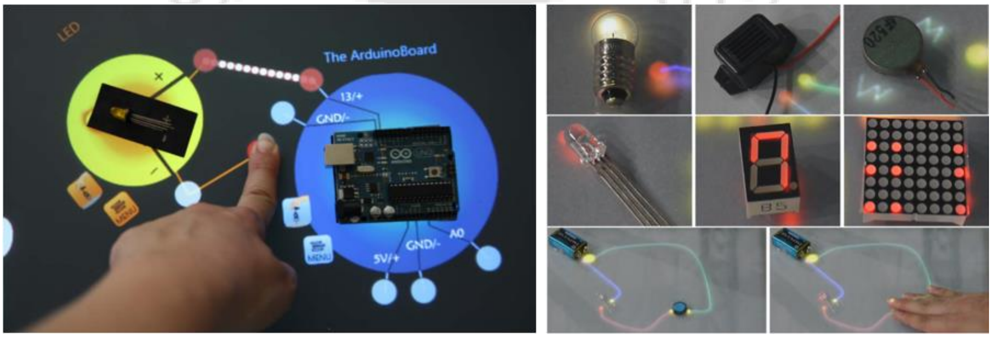
Table 2.3 Summary of selected literatures of AR and smart objects in education and end-user tasks assistance

No.	Primary Authors, year of publication	Technological Space	Domain	Description
1.	(Cheng & Tsai, 2013)	Augmented Reality	Science Education	Provides and in-depth review of significant literatures of AR in science education. Highlights that there are limited investigations with respect to the state-of-the-art application of AR-related learning. Identifies and suggests research gaps such as the need to explore learning experience, which has been scarcely discussed in literatures.
2.	(Henderson & Feiner, 2011)	Augmented Reality (HWD)	Mechanical Assembly	The authors present a study with their AR prototype for a psychomotor task like assembly for turboprop combustion engine amongst 22 participants and show that AR can help in task performance.
3.	(Martín-Gutiérrez, Fabiani, Benesova, Meneses, & Mora, 2015)	Augmented Reality	Electrical Engineering	The authors present a study with AR amongst 50 participants from electrical engineering in higher education. The study concludes that AR improves learner's satisfaction.
4.	(Knibbe, Grossman, & Fitzmaurice, 2015)	Smart Objects and Digital table-top, Augmented Reality	Makerspace/ Prototyping	Presents a novel system for immersive instructional workspace for novice and intermediate makers. The authors also give insights into tool augmentation by embedding/ attaching various electronics and sensors to them for task assistance.
5.	(Drew et al., 2016)	Smart Objects	Electronics Prototyping	The authors present a novel debugging tool for electronic design projects that reduces debugging time by providing immediate visualization on a computer screen via 2D-GUI. Informal usability amongst 7 participants with the tool is presented. All participants reported to like the tool and found it useful.
6.	(Tabard, Hincapié Ramos, & Bardram, 2012)	Digital Table-top, Augmented Reality	Biology	The paper reports a novel augmented workbench that can support more exploratory or design-oriented way of doing science by providing information management and computational resources in the laboratory. 7 participants consisting of 3 post-docs, 2 PhDs, and two bachelors students were recruited for this exploratory study and highlighted a need for such solutions.

2.3.1 Research work in HCI field for teaching electronics based on Ubiquitous Computing

There have been research publications (Chan, Pondicherry, & Blikstein, 2013; Greenberg & Fitchett, 2001; Resnick, Martin, Sargent, & Silverman, 1996) in the directions for making electronics learning easy by utilizing specially designed tangible setup for children and entry-level users. These tools have mainly aimed towards simplifying the circuit prototyping tasks to help users understand electronics. Several other examples include studies (Akiyama & Miyashita, 2014; Conradi et al., 2011) that present research to improve electronics education by integrating hardware components with context-aware digital information presented visually through table-top displays. While these tools are a remarkable step for novice users, they find less use in a complex learning environment of educational practical electronics engineering laboratory where students often have to handle complex tasks that not only include prototyping physical electronic circuits on breadboards, but also troubleshoot them, operate test equipment, make analytical inferences from them and relate it with theory.

Another downside of these toolkits is that they present information in an abstracted form by representing electronic components as a higher level building block. For example, the authors (Akiyama & Miyashita, 2014; Conradi et al., 2011) represent simulated behaviours of electronic circuits alongside actual electronic components which are not electrically active, for example, a light emitting diode (LED) not glowing electrically but through projections. Figure 2.4 represents this abstracted format utilized by these authors to teach electronics.



(a) **(b)**

Figure 2.4 Abstraction of electronic components into a higher-level building block. (a) The flow of electrons prototype by Conradi et al., (2011) on Microsoft Surface. (b) Augmented workspace for learning electronic modeling by Akiyama & Miyashita, (2014). Images Source: (Akiyama & Miyashita, 2014; Conradi et al., 2011)

In Figure 2.4 (a), Conradi et al., (2011) utilized Microsoft Surface and Byte tags to implement the system. Observe that Simulations of electrical connections are done digitally on the tabletop. The yellow circle depicts a glowing LED. Notice a physical LED placed on top of the yellow circle. Akiyama et al., (2011), see Figure 2.4 (b), utilized projection mapping and webcam to identify electronic components and their orientation on the position on user's workspace. It can be observed that LED and bulb glow using projection mapping without requiring any physical electrical connection.

A study conducted by Booth, Stumpf, Bird, & Jones (2016) on end-user physical circuit prototyping have focused on problems faced by users during prototyping of electronic circuits. Booth et al., (2016) conducted a study amongst 20 amateur users by asking them to build an electronic circuit involving wiring components on a breadboard and writing an Arduino microcontroller program. Participants in the study reported facing the most number of difficulties with hardware implementation and circuit related failures. The study concluded that there is a lack of "hardware debugger" to assist users with circuit implementations and highlighted this as a future direction that requires research inquiry.

Another similar research work conducted by Mellis et al., (2016) on engaging amateurs in the assembly of electronic devices points-out the challenges faced by the participants with circuit debugging. Mellis et al., (2016) report a study conducted amongst eight workshop participants who were involved in a personal fabrication activity and required assembling circuits for constructing Wi-Fi connected devices. Future research directions such as automated circuit assembly to reduce the manual labour involved in creating custom circuits and move much of the onus for testing and debugging to vendor have been proposed.

These studies (Booth et al., 2016; Mellis et al., 2016) in HCI highlight difficulties faced by end-users such as makers and hobbyist who are interested in physical circuit prototyping. Further, it is observed that most common effect of these difficulties, as reported by authors, is the amount of time consumed in debugging the physical circuit. This is mainly due to a large number of wires, misalignment of electronic components and power management issues. Figure 2.5 depicts a cause and effect diagram derived from these studies.

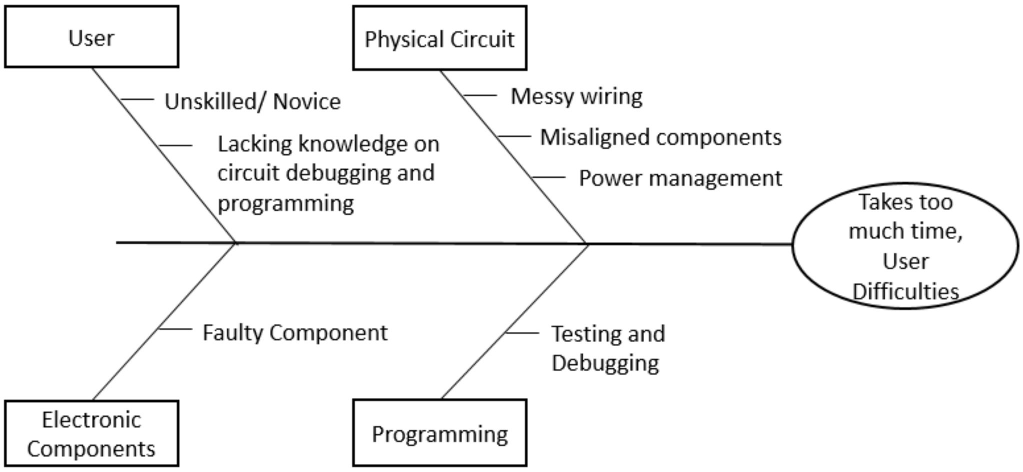


Figure 2.5 Cause and effect diagram derived from the literature studies in HCI (Booth et al., 2016; Mellis et al., 2016) that highlight constraints faced by the user regarding time consumption and effort for prototyping physical circuits. Source: Author generated based on literature review.

Research studies reported by Abd El_Gawwad, Mohammed, Abo El-Ezz, Fathy, & Mohammed (2012); Drew et al., (2016); C. Wang, Bryan, Wu, Hung, & Chen (2016) have tried to address some of these constraints by presenting a novel tools for easing physical circuit prototyping. Abd El_Gawwad et al., (2012) devised a “smart breadboard” utilizing a software and a programmable hardware such as a field programmable gate array that can make electrical connections between various electronic components without the need of physical wires. This setup overcomes the messy electrical connections through wires on breadboard – a difficulty that also leads to wrong connections or loose wiring and is often faced by the breadboard users.

Wang et al., (2016) utilized a method of printing a conductive circuit layout that can be attached to a specially designed setup of the breadboard and used for building an electronic circuit. This minimizes the need to use electrical wires for making electrical connections.

However, these solutions again lead towards abstraction of electronic circuits by replacing physical electrical connections with either digital connections or through a hidden PCB layout. Another issue is that these setups require to be operated by a dedicated software with 2D GUI to enable circuit connection. Such interfaces, due to their affordance, reduce the ideation, problem-solving and inferential reasoning (Oviatt et al., 2012) thus leading towards an incomplete experiential learning cycle and reduced multi-sensorial experience. When considering a practical electronics laboratory scenario, such solutions often do not find much use as they do not align with the main objectives of educational laboratories (Al-bahi, 2008) that require students to identify unsuccessful outcomes and re-engineer them as well as gain sensory awareness.

Drew et al., (2016) presented a debugging tool called "Toastboard" that consists of a hardware and software system to assist users with physical circuit prototyping. This system can detect various mistakes made by users while prototyping electronic circuit on a breadboard, indicate these mistakes in real-time via onboard LED bar and on a web-based visualization software. Figure 2.6 depicts the complete setup of Toastboard. This research work is perhaps one of the closest towards understanding how mundane laboratory objects can be embedded with computational capabilities to address the problems faced during debugging circuits and providing contextualized information without abstracting the circuit setup or changing the affordance. However, when considering the application of this research in educational laboratories, questions and concerns arise regarding the type of intelligence that needs to be embedded in such objects to enrich the learning of students. This aspect is discussed in Section 2.4.

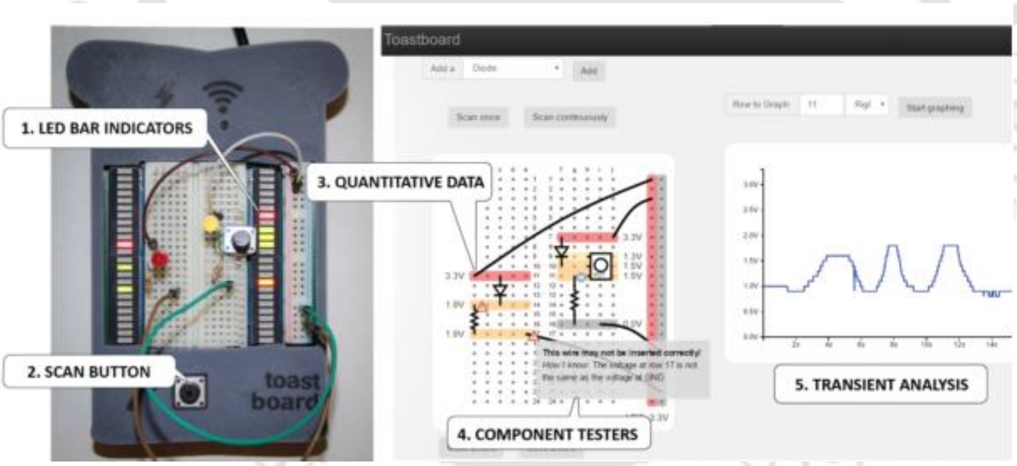


Figure 2.6 The Toast board device and accompanying software. (1) LED bars indicate power, ground, or other voltage. (2) A push button triggers a scan. (3) Quantitative voltage data is displayed in the accompanying software. (4) Components are associated with testers that run on every scan. (5) The voltage at a selected row can be viewed over time as a graph. Image Source: (Drew et al., 2016)

While the investigations reported by authors (Drew et al., 2016) point towards the direction of automating the debugging process, difficulties experienced by students in educational practical electronics laboratories at engineering institutes are far too complex which involve multiple levels of tasks, each with its own nuance and constraints as well as background theoretical knowledge. As reported in research studies (Lyle D. & Albert

J, 2005; Sutton & Charles, 1996; Watai et al., 2007), students not only have to involve in physical circuit prototyping but also in operating test equipment and making connections with the theoretical concepts.

Although studies reported above represent a significant step towards easing the prototyping task of users on a breadboard, easing tasks like operating test equipment and relating theory to practice in a practical laboratory yet needs to be addressed. This thesis proposes that these shortcomings can be met by combining them with the use of AR which can enable new modes of interaction with the surrounding environments by augmenting it with digital information. Section 2.3.2 discusses the relevant literatures in AR for learning purpose.

2.3.2 Use of Augmented Reality as learning technology in higher education

While working on experiments in practical labs, students require on-spot instructions that can help them correlate theory and practice. Since AR can augment physical environments with contextualized digital information, its uses in laboratories can help students get contextualized information along with visualization capabilities without disrupting the natural affordance of the experimental setup. Santos et al. (2014) emphasized upon the affordance of AR technology. These include (i) Real world annotation, (ii) Contextual Visualization and (iii) Vision-haptic visualization. The study suggests enhanced AR learning experiences regarding encouraging exploration ability of students, promoting collaborative learning and increased concentration owing to its immersive nature. Azuma (1997) and Siltanen (2012) provided insights into the use of AR and highlighted both marker and marker-less techniques to overlay digital content on real environment. Further potential applications of AR in medical, manufacturing, repair, entertainment, military, etc., were also surveyed by Azuma (1997).

Chen, Liu, Cheng, & Huang (2017) presented a review of studies from 2011 to 2016 based on AR for education. Out of fifty-five articles considered by authors, 23.64% applied AR for higher education (i.e., undergraduate level) with 14.55% focusing on delivering AR instructional content for engineering, manufacturing, and constructions. The authors also reported that 40% of AR studies, out of fifty-five reviewed articles, were focused on science.

Müller & Erbe (2007) experimented with AR-based learning spaces for understanding working with various sub-systems about energy exchange processes and further explored multi-modal and multi-user applications. Andreas, Hannes, Karin, & Judith Glück (2006) have explored the use of AR for enabling spatial abilities of students. Montoya, Díaz, & Moreno (2017) presented a study on the use of static and dynamic content using AR. When considering the literature on AR for learning, most of the studies above indicate that AR encourages and motivates students, reinforces learning by involving students in creative inquiry and eases teaching process for teachers. However, barriers still exist with the use of AR in the classroom. These are due to factors like (i) time and technical expertise required to develop content, and, (ii) many teachers are untrained to deal AR based problems (Bower, Howe, McCredie, Robinson, & Grover, 2014) – regarding both content and technical requirements. Further, although teachers believe in the usefulness of AR, there is a lack of a framework to use AR in classes. Even though many studies, as reported, above indicate a positive attitude towards AR and how it motivates students, this gap (i.e., missing framework) persists which can be readily adopted by teachers. Further, although various mixed methodologies have been employed in AR research for learning, a proper design framework is yet to emerge, as they are not evident in the published literature.

In the context of practical laboratory sessions, AR applications are required to be capable enough to enable higher order thinking in students and encourage collaboration. Studies in AR for the real-time assistance of users with repair and maintenance tasks by Henderson & Feiner (2011) have presented several cognitive design guidelines in terms of information representation and psychomotor aspects of tasks. Cuendet, Bonnard, Do-Lenh, & Dillenbourg (2013) have also presented several design implications for developing AR based application specifically focusing on the usability aspects. Müller & Erbe (2007) suggested the need for creating better AR interfaces by an understanding of presence and interaction with the work environment. Liarokapis & Anderson (2010) presented an exploration of the use of AR for improving teaching in a classroom setting. The authors present the use of AR to teach information technology by augmenting various 3D models of necessary computer hardware such as a motherboard, RAM, etc. Mejías Borrero & Andújar Márquez (2012) conducted studies to explore AR as a method to enhance the use of remote lab in electrical engineering. The authors use AR to augment real spaces with virtual 3D objects as an obstruction for a remotely controlled robot.

Cheng & Tsai (2013), have reported various studies of AR in different educational contexts and have reported the need to study learner's experience using AR. The authors report that although many studies focused on various cognitive aspects of learning, there is a dearth of literatures that emphasize on capturing learner's experience using AR.

One of the closest work towards developing AR application for electrical engineering educational laboratories has been presented by Martín-Gutiérrez, Fabiani, Benesova, Meneses, & Mora (2015), see Figure 2.7. The authors describe the use of AR to present content regarding the operation of electrical machines and operating various test equipment in labs. The authors emphasized that by appropriately placing markers on tools, AR can be used to provide machine training to students and guide them in maintenance tasks, setup, and learning procedures. Several applications of AR to augment textbooks, study mechanical element like gears, etc., electric motors have also been presented. Various tracking techniques and head-mounted devices have been used.

(a) **(b)** **(c)**

Figure 2.7 Augmented Reality for electrical engineering. (a) A head-worn device utilizing marker based image tracking to display 3D content to students regarding equipment operation. (b) and (c) Content such as 3D images are shown when the mobile device is pointed towards lab manuals. Image Source: (Martín-Gutiérrez, Fabiani, Benesova, Meneses, & Mora, 2015)

However, in case of practical electronics laboratory, instead of dealing with large electrical equipment and setups, as presented by Gutiérrez, M. et al., (2015), students are required to work on discrete electronics components that require to be prototyped on breadboards and often deal with messy electrical connections which cause frustration to students. Even though studies in AR have shown how various theoretical and practical concepts can be connected by utilizing AR's ability to provide contextualized information, there is a dearth of research studies highlighting how AR can be utilized in practical electronics laboratories for circuit building, teaching how to operate test equipment and relate theory with practice.

Further, there is a need to consider usability aspects of AR not only in terms of merely projecting digital data onto real space, as has been a trend in most AR based research, but also in terms of adding usable functionalities and features that can help conceptualize a finished AR product for use in complex learning environments like educational laboratories. Another aspect that has not been highlighted in these studies on AR is the basis on which the authors have chosen the content to be displayed for students.

2.4 Understanding the role of Artificial Intelligence in augmenting learning experiences of students in educational laboratories

The literatures reviewed above highlight a potential and scope of expanding the application of smart objects, i.e., objects with embedded computational capabilities, and AR for practical electronics laboratory sessions. The Toastboard presented by Drew et al., (2016) also provides a rich body of work towards understanding how a mundane object such as a breadboard, be augmented to assist the user in debugging. However, if this solution is expanded for use in educational practical electronics laboratories, questions arise regarding the learning of students through the explicit or direct instruction approach utilized in such systems for highlighting student's mistakes.

Even human instructors and peers often make the mistake of just pointing out the errors in laboratories. This does not necessarily lead to learning or satisfactory learning experience for the student. For use in educational laboratories, students require more than just simple prompts regarding mistakes made. The prompt needs to be instructional in nature through which students can derive learning, self-reflect upon their actions and gain the ability to understand where they are going wrong and why they are going wrong. Interconnecting facts and interconnections between bits of information so that an 'insight' happens for the student. In such cases, any system that is designed requires a certain level of intelligence that can assist the student like a human tutor. Replacement or substitution of the human tutor is not the idea – assisting and augmenting is the focus of this thesis.

This requirement probes inquiry into the intelligence aspects that is required to be embedded into learning aid for practical laboratories. Here intelligence means the ability of a system to instruct students in a manner similar to that of a human tutor. Further, while it is possible to embed intelligence into objects, increasing its intelligence level leads to complex interaction between humans and objects which needs to be exchanged in some form of dialogue. This further leads to concerns regarding just how much intelligence needs to be embedded into the device to allow simple user interactions? Further, how do we embed intelligence into objects? Since students in practical electronics laboratory session interact with many other types of equipment (for example cathode ray oscilloscope, function generator, multimeter to name a few), physically embedding computational capabilities to leverage intelligence in each of these objects can be daunting – thus requiring exploring interactions with AR which is a much simpler way to embed "intelligence" in form of digital information over real environments.

The use of AI in Education (AIED) can be considered to help characterize the type of intelligence that can augment students' activity and learning experiences in educational laboratories. It can be found that in AIED, intelligent tutoring systems (ITS) are widely studied and used to facilitate students' learning experiences in universities for various subjects. ITS also find many applications in areas such as training of students and medical staff (Beck, Stern, & Haugsjaa, 1996; Moursund, 2006). They are designed to be adaptive systems that can understand learners and deliver individualized student-centered learning content. For doing so, AI researchers try to model human teaching tactics and strategies and embed them into ITS as "expert systems". This modelling can be broadly achieved in three ways (Du Boulay & Luckin, 2016) via (i) observing the human expert teacher, (ii) theoretical understanding and derivations from theories of learning, and (iii) observing students. The goal of observing human experts is to understand how expert systems can be modelled by computerizing the expertise of human experts and their knowledge. There has been an increasing body of work in developing expert systems to observe and codify expert teaching at the fine level of granularity (Du Boulay & Luckin, 2016). Expert systems generally consist of four major components as depicted in Figure 2.8.

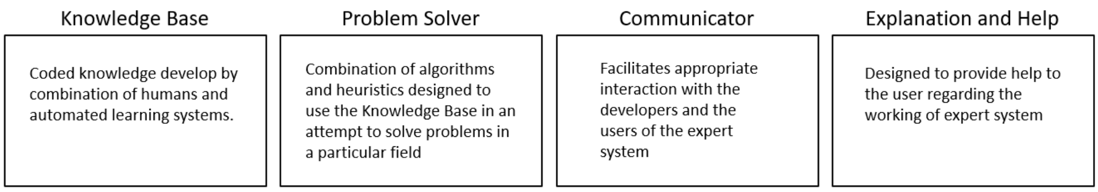


Figure 2.8 Major components of an expert system. Figure Source: Author generated based on literature (Du Boulay & Luckin, 2016; Negnevitsky, 2005).

Such system can provide a basis and direction to “characterize” intelligence that can be embedded into objects or systems to assist students in practical laboratory sessions. Another aspect of ITS is regarding the student model which is generally defined by large-scale datasets of logs of student work with e-learning (Mavrikis et al. 2010 as cited in Du Boulay & Luckin, 2016). When considering the scenario of a practical laboratory session, modelling of students will require more than just large datasets that consist of their academic performance, gender, or e-learning assessments information. It will require an understanding of the difficulties that are experienced by students while working on tangible laboratory setups and require intuition and past hands-on experiences to troubleshoot and debug problems. Furthermore, in certain situations, these laboratories often deal with the paucity of human instructors and proper infrastructure – as is the case in many educational institutes across India (MHRD, 2017). Such constraints are often ill-defined and raise concerns that are central to understanding how intelligence can be applied in such environments and how can expert systems be designed for solving such problems. One way in which such investigations can be carried out is through a human-centered design approach (Norman, 2002) that helps identify real user needs, preferences, expectations, feedbacks and integrates them in complex systems designed for utility and usability. When adopting this approach, Herbert Simons’s philosophy (Simon, 1995) of considering AI as an empirical science plays a key role. Simon (1995) states that to design expert systems for such ill-defined problems requires vigorous exploration of human heuristic search techniques as a source of the idea for intelligent systems. Doing so will require “knowing how much knowledge, and what kind of knowledge, is required by a program to extend it to real-life tasks” (Simon, 1995).

It is clarified at this point that while this thesis does not intend to attempt to design complex AI systems or present an AI algorithm. This thesis does, however, derive its philosophical understanding of AI from works of Simon (1995) merged with the philosophy of human-centered design to address a larger issue that is faced in educational practical electronics laboratories of engineering institutes that of conducting sessions consisting of a large number of students (about 50) per session. As prevalent in India, such issues can be addressed at large scale by using AI from the aforementioned perspective and will be evident from the conceptual scenario presented in Chapter 5:.

Currently, expert systems are mostly computer based and heavily rely on keyboard-mouse GUI models. If this concept is extended further and embedded into objects and systems used in educational practical electronics laboratories, it is posited in this thesis that difficulties faced by students during learning will be minimized thereby improving their learning experience.

Having reviewed significant literatures from various fields ranging from HCI, ubiquitous computing, educational technology, AR and AI, we now proceed towards summarizing the findings, limitations and inferences in the following section.

2.5 Insights from the state of the art-literature review – gaps, and opportunities

The state of the art review conducted in this chapter provides some interesting directions for this thesis in terms of understanding how emerging technologies (smart objects, AR and AI) can be applied in various educational contexts. A number of constraints and limitation have been observed in practical laboratory sessions through literature survey that act as a bottleneck and require human-centered approach for investigation. Figure 2.9 is conceived to depict these bottlenecks identified in the literature review and which is intended to be addressed in this thesis.

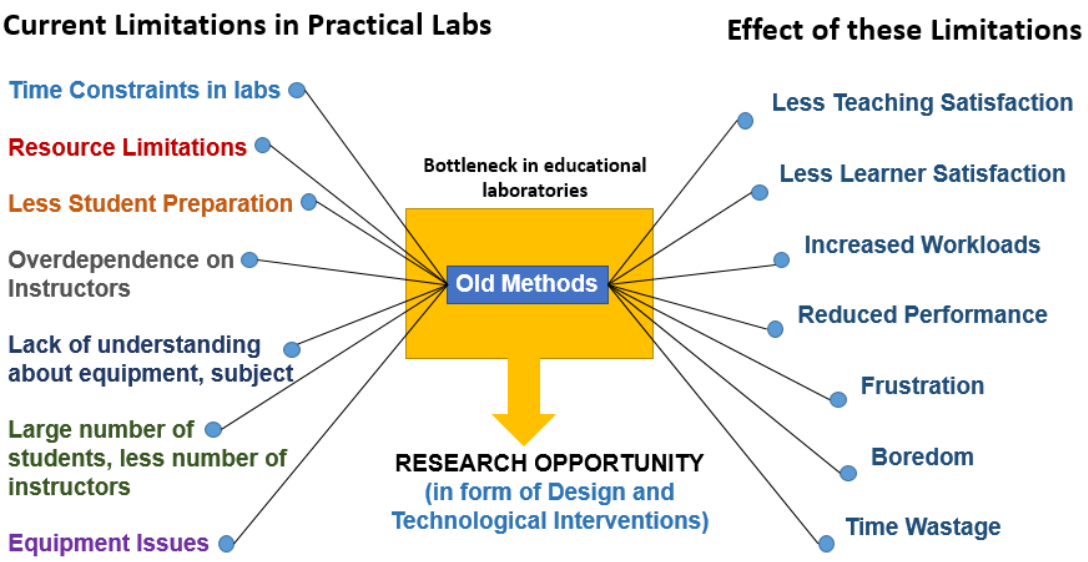


Figure 2.9 Limitations and constraints in educational laboratories as observed from literature survey.

It is also observed that there is a dearth of practices reported in literatures that deal with improving practical electronics laboratory learning experience of students in engineering institutes, especially those from developing countries, as well as a lack of novel system addressing student difficulties in practical educational sessions in electronics laboratories. There are significant research gaps as seen from the literature review which are depicted in Figure 2.9. These need to be addressed. They invoke significant research questions – described in Section 2.5 that follow next.

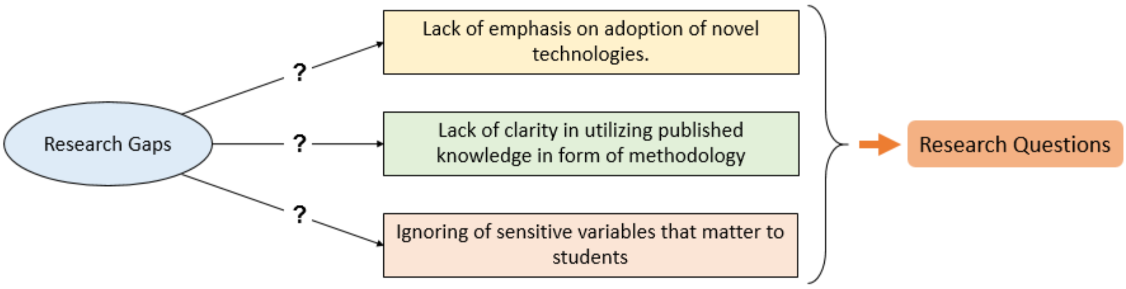


Figure 2.10 Research gaps that have been identified from the literature review

Research gaps regarding design heuristics require understanding how can emerging technologies – smart objects and AR, be utilized and designed specifically for educational practical electronics laboratories sessions. In Section 2.2.1 it can be seen that there have been a few significant works done by authors Abd El_Gawwad et al., (2012), Wang et al., (2016), Drew et al., (2016) that attempts to address the need of overcoming difficulties experienced by users during circuit prototyping. However, if such works are extended towards the use in practical electronics laboratory session, questions arise regarding the type of learning intelligence that needs to be designed and embedded into such objects. This discussion has been placed in the previous Section 2.3 (first paragraph) that tries to understand the nature and characterization of intelligence.

Secondly, from literatures of AR, as discussed in Section 2.2.2, we find that although many authors have presented studies that show how overlaying digital data (in the form of 3D graphics, images, and videos) over real world can assist users in various tasks, these studies lack insight into how and on what basis were these content decided? Further, it is also seen that these studies mostly utilize marker-based tracking techniques to overlay digital information on large objects – such as motors, etc. However, in cases of electronics laboratories, students are often required to work on discrete electronic components and setups as opposed to large setups – thus raising concerns like, how AR can be utilized in such environment? Further, how can already existing laboratory artifacts be augmented in electronics laboratories? Combining together all the concerns regarding design considerations for utilizing these technologies, issues regarding the type of intelligence to be embedded into smart objects, content for AR and establishing user interactions with objects with embedded intelligence arise. This thesis therefore also attempts to conceptualize and present a novel system that interweaves various technologies AR, smart objects, AI together that can help in improving the learning experiences of students in educational practical electronics laboratory.

From the literature review, it was also identified that sensitive variables like workload faced by students in practical laboratories had not been considered. In case of studies (Drew et al., 2016; C. Wang et al., 2016) it is observed that the central focus is on the technical requirements of the tool and less emphasis has been given on the effect of such tools on users. Drew et al., (2016) have discussed user feedbacks received through informal inquiries. Cheng et al., (2012) have reported various studies of AR in different educational contexts and have reported the need to study learner's experience using AR. The authors report that although studies focus on various cognitive aspects of learning, there is a dearth of literatures that emphasize on capturing learner's experience using AR. Further, we find that studies have not considered accessing cognitive load of users (or students) while learning – which is a crucial factor that affects learning experiences in complex educational laboratory environments (Van Gog & Paas, 2008). This thesis, therefore, proposes to measure these sensitive variables.

To measure cognitive load, NASA Task Load Index (NASA-TLX) (S. G. Hart & Staveland, 1988) is the most commonly used multi-dimensional subjective rating tool that is used to access workload rating based upon a weighted average of six workload subscale ratings. This NASA-TLX tool is proposed to be used in this thesis to measure the cognitive load of learning of our proposed novel intervention. The six sub-scale are Mental Demand, Physical Demand, Temporal Demand, Effort, Performance and Frustration levels. In addition to NASA-TLX, Perceived Learner's Satisfaction (PLS) scale (Y. S. Wang, 2003) that uses Learner Interface, Content, Personalization, and, Peer Collaboration to measure learner's satisfaction is used. To capture learning experiences of students, this thesis utilizes a qualitative aspect of HCI rooted in Grounded Theory (Berg, 2001). Apart from capturing perceived cognitive load, perceived learner's satisfaction and learner's experience, Perceived System Usability has been adopted from (Sun, Tsai, Finger, Chen, & Yeh, 2008), willingness to continue usage and relative advantage – taken on a respective scale, were proposed to be measured.

2.6 Research Questions and Objectives

Based on research gaps identified from literature review, following fundamental research questions were formulated to be investigated in this thesis.

- **RQ1:** Can ordinary objects/ equipment collaborate and participate intelligently with the user?
- **RQ2:** If yes, how to establish interaction between such equipment and the user? Which usability engineering principles apply?
- **RQ3:** What type and how much intelligence needs to be embedded into these objects? In what form should it be embedded?
- **RQ4:** What effect do these objects have on learning experience?
- **RQ5:** What cognitive load perspectives should be considered?
- **RQ6:** Are there guidelines /heuristics for Embedding Intelligence in objects? If not, can they be developed based on experiments?
- **RQ7:** How do people behave around such technologies and environments? What effect do these technologies have on human learning?

Here, embedded intelligence refers to the ability of a prototyped solution to assist students like a human tutor during practical laboratory session. The assistance can be delivered to students through various interaction modalities such as AR, Voice and Graphical User Interface.

The research stages set for this thesis are:

1. Conduct user research involving teachers and students (undergraduates) across various engineering institutes to address research concerns and questions.
2. Generate models/ frameworks linking potential areas in instructional practices.
3. Develop prototypes to demonstrate & validate the viability of our models.
4. Gather data on learners' experience through various design methods to understand the influence of our proposed prototype on learning.

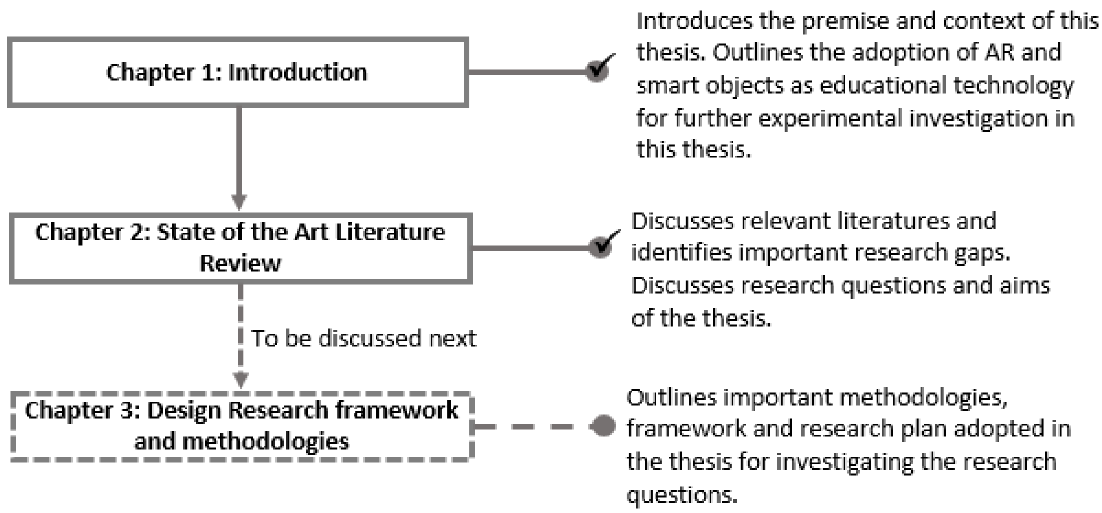
5. Assess usability, learning experiences and cognitive load using proposed intervention.
6. Analyse data for inferences, test hypothesis built around research questions to validate positions taken in this thesis.

2.7 Chapter Summary and Conclusion

This chapter reviews literatures on engineering educational laboratories with a focus on difficulties experienced by students in practical electronics laboratories sessions. This review identified lack of innovative technologies in laboratories. To investigate the answer to this issue important literatures on the use of ubiquitous computing for education and learning, augmented reality and artificial intelligence were reviewed. It was found that there is a death of innovative solutions from practical electronics laboratories. Several research questions were initiated from this review that has been investigated in this thesis. Further, based on the literature reviews, a design based research methodology rooted in the user-centered design approach has been found suitable for further investigation. A design research framework and a plan of this thesis have been presented in the next Chapter 3.

A quick recap of previous chapters:

A visual summary of the chapters covered so far is provided as follows:



Chapter 3: Design Research Framework and Methodologies

Chapter Abstract: This chapter presents the design research framework and outlines the plan followed during the research. The flow of reporting thesis and plan of experiments conducted is presented.

3.1 Restating the Research Questions

Based on the literature review in chapter 2, following research questions were raised that are restated as follows.

- **RQ1:** Can ordinary objects/ equipment collaborate and participate intelligently with the user?
- **RQ2:** If yes, how to establish interaction between such equipment and the user? Which usability principles apply?
- **RQ3:** What type and how much intelligence needs to be embedded into these objects? In what form should it be embedded?
- **RQ4:** What effect do these objects have on learning experience?
- **RQ5:** What cognitive load perspectives should be considered?
- **RQ6:** Are there guidelines /heuristics for Embedding Intelligence in objects? If not, can they be developed based on experiments?
- **RQ7:** How do people behave around such technologies and environments? What effect do these technologies have on human learning?

3.2 Design Research Methodology and Framework to investigate Research Questions

To address the research gaps and questions identified in Chapter 2, a design – based research methodology (F. Wang & Hannafin, 2005) with emphasis on human-centered design (HCD) approach (ISO 9241-210:2010, 2010; Norman, 2002) is adopted in this thesis. This design-based research enables the researcher to improve their understanding about the context – which in this thesis is educational practical electronics laboratory, develop contextually dependent interventions by creation of innovative and novel learning tools, and, lead to development of knowledge that can be used to inform practice and other designers (Design-Based Research Collective, 2003 (DBRC)). This approach has shown considerable potential in areas of technology-enhanced learning (F. Wang & Hannafin, 2005) and is helpful for investigations in complex learning environments of educational laboratories where various findings about user needs and requirements are often overlooked. According to DBRC (2003), as cited in Wang et al., (2005):

> "…design-based research enables the creation and study of learning conditions that are presumed effective but are not well understood in practice, and the generation of findings often overlooked or obscured when focusing exclusively on the summative effects of an intervention."

A Human-Centred Design (HCD) approach focuses on meeting user need satisfaction by integrating user preferences, expectations, and feedbacks in the design process. This HCD approach involves an iterative cycle of design, implementation, analysis, and redesign, see Figure 3.1, that enables improvement of pre-existing situations by integration of user needs or prototype experiences and creating a design solution that did not exist before (Duong, Farel, Stal-Le-Cardinal, & Boquet, 2015; Norman, 2002).

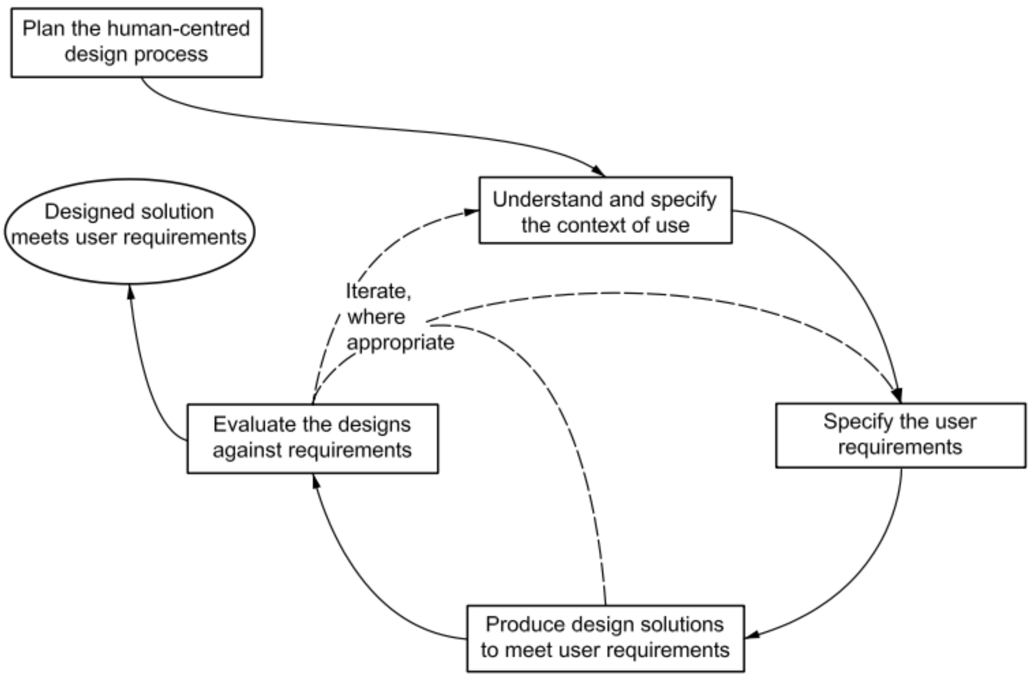
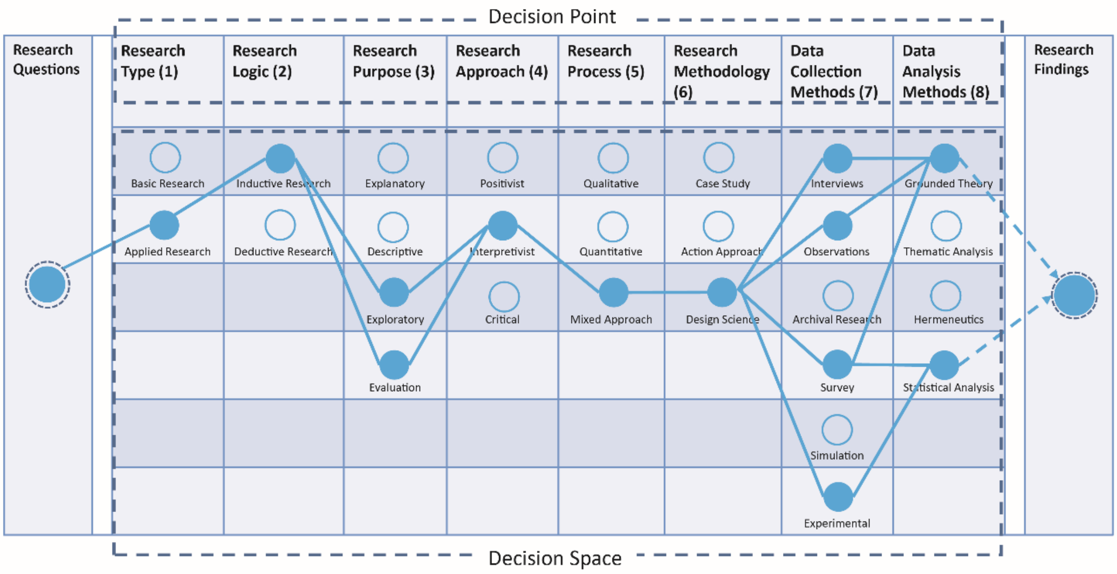


Figure 3.1 A human-centered design research process and approach adopted in this thesis. Source: (ISO 9241-210:2010)

Figure 3.2 (a) represents a generalized diagram that tries to encompass most common decision paths (Wohlin & Aurum, 2015) followed to investigate research questions outlined and has been followed in this thesis. The figure illustrates how multiple design and research methodologies are intrinsically linked and nourish design-based research reported in this thesis. It attempts to present a total perspective on the nature of research and methodologies adopted for experimental investigations carried out in the thesis.



(a)

RQ1, RQ6 → 3 (Descriptive Research) → 4 (Interpretivist) → 5 (Qualitative) → 6 (Design Science) → 7 (Interviews) → 8 (Thematic Analysis) → 1 (Basic Research) → **Research Findings (discussed in Chapter 5 and Chapter 7).**

RQ2→ 4 (Interpretivist) → 3 (Exploratory) → 2 (Inductive Research) → 5 (Qualitative) → 6 (Design Science) → 7 (Observations) → 1 (Applied) → 8 (Grounded Theory) → **Research Findings (discussed in Chapter 5).**

RQ3 → 6 (Design Science) → 4 (Interpretivist) → 7 (Experimental) → 5 (Qualitative) → 8 (Grounded Theory) → 3 (Exploratory) → 2 (Deductive Research) → 1 (Applied Research) → **Research Findings (discussed in Chapter 5).**

RQ4, RQ7 → 1 (Applied Research) → 3 (Evaluation) → 4 (Interpretivist) → 5 (Mixed Approach) → 6 (Design Science) → 7 (Experimental) → 8 (Grounded Theory) → 2 (Deductive Research) → **Research Findings (discussed in Chapter 6 and Chapter 6).**

RQ5 → 1 (Applied Research) → 3 (Evaluation) → 4 (Positivist) → 5 (Quantitative) → 6 (Design Science) → 7 (Experimental) → 8 (Statistical Analysis) → 2 (Deductive Research) → **Research Findings (discussed in Chapter 6).**

(b)

Figure 3.2 (a) A generalized view of common decision points used for investigation of research questions presented in this thesis. (b) Decision points in research design presented in this thesis.

The decision paths followed for investigation of each research question in decision space is represented in Figure 3.2 (b). The numbers represent corresponding decision points as shown in Figure 3.2 (a) represented in the decision space.

Figure 3.3 conveys a simplified format of the complete research plan in seven stages followed in this thesis. Stage 1 – understanding the research via literatures has been discussed in previous Chapter 2.

The next Chapter 4 discusses user research studies conducted in Stages 2, 3 and 4 and how they led towards the identification of user needs in practical electronics laboratory, gathering requirements for a prototyped solution and towards the development of heuristics for embedded intelligence.

Stages 5, has been discussed in Chapter 5, pertains to conceptualization, design, and development of Smart Learning System (SLS) prototype based on insights received from user research studies.

Chapter 6 discusses Stages 6 and 7 on Design Experiments conducted to evaluate the SLS prototype.

Chapter 7 presents design implications and heuristics identified from the user studies and experimental investigations carried out in this thesis. These heuristics will be useful for interaction designers working on novel educational technologies utilizing augmented reality, internet of things and artificial intelligence. Major contributions and limitations of the thesis have been discussed in Chapter 8.

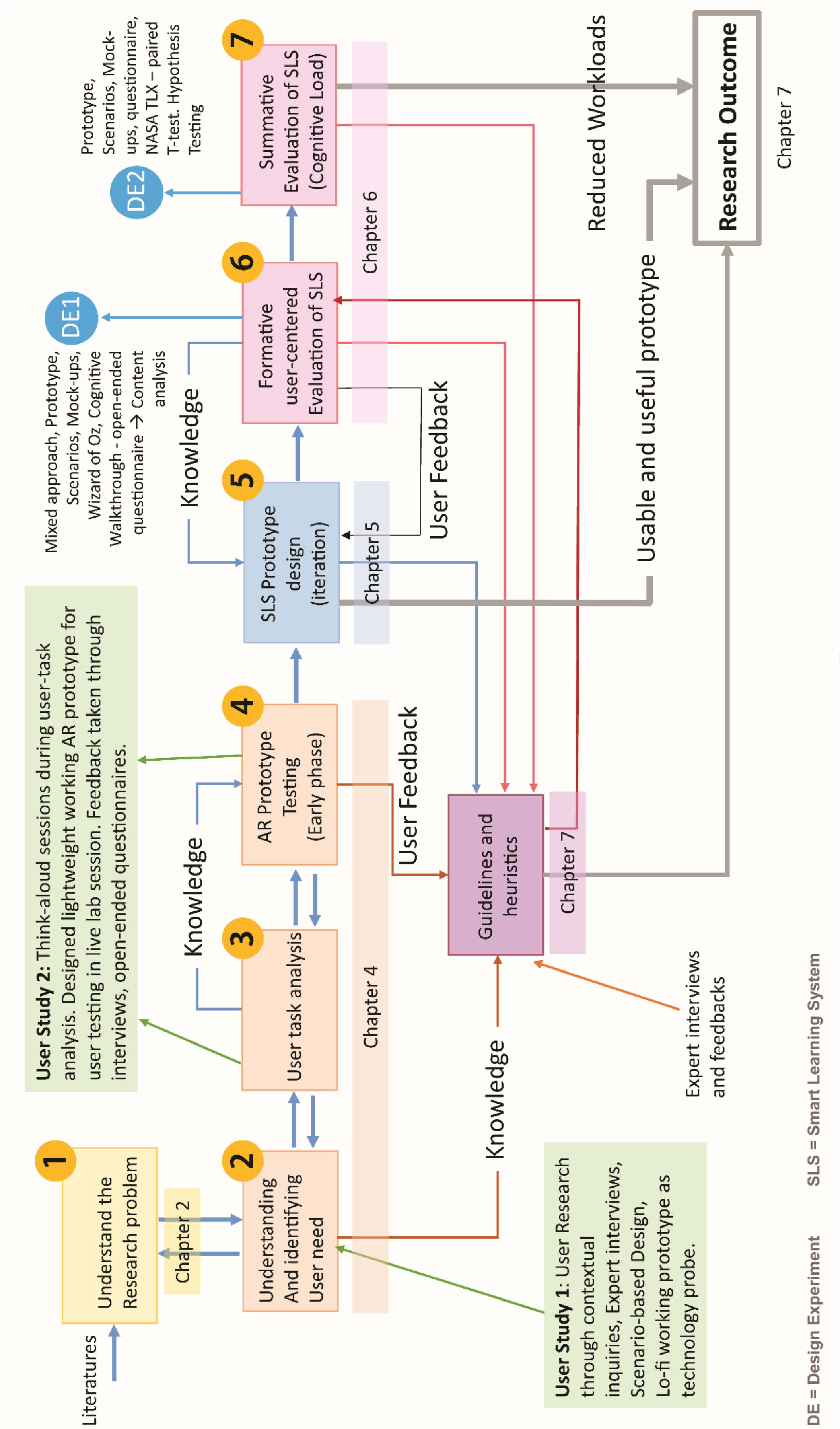
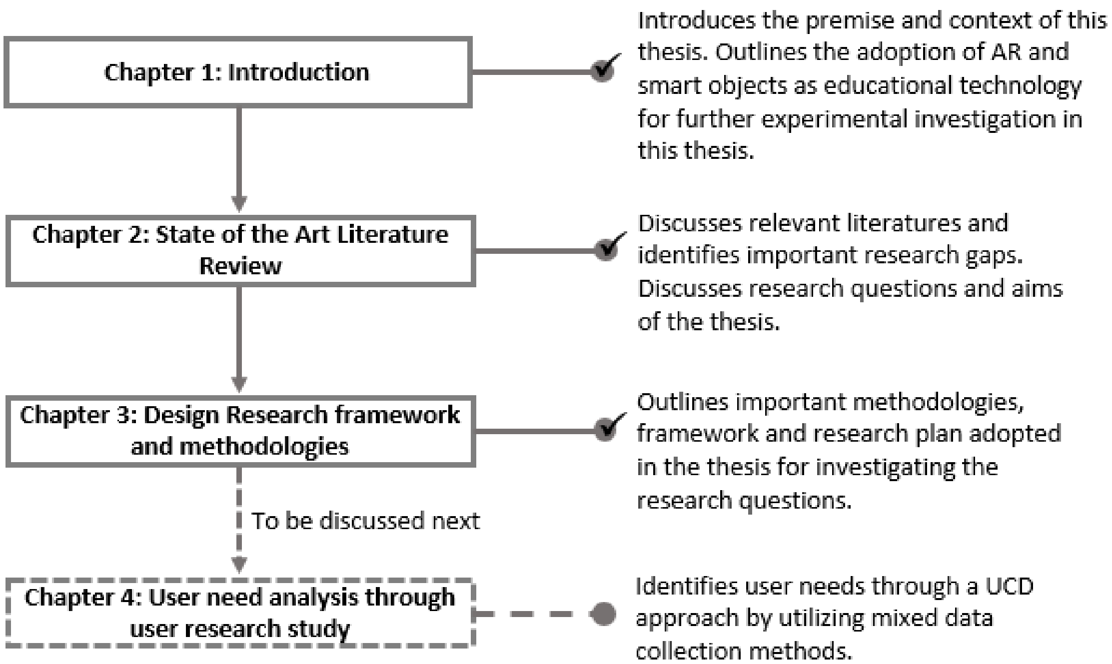


Figure 3.3 User Centered Design process and research plan of this thesis

A quick recap of previous chapters:

A visual summary of the chapters covered so far is provided as follows:



Chapter 4: User Need Analysis through User Research Studies

Chapter Abstract: This chapter presents user research studies conducted in practical laboratory sessions to identify user needs and requirements. Based on the user research and need analysis guidelines to design prototype for practical electronics were formed. An early prototype was made using this guideline and tested in live practical electronics laboratory. Results of these user research studies have been presented.

4.1 Need Analysis through User Research Studies

User research studies were conducted involving N=168 participants (10-course instructors + 158 engineering undergraduate students).

The aim was to:

- Identify user (both students and instructors) needs and difficulties,
- Identify possible areas of intervention in practical electronics laboratory,
- Conceptualize and inform the design of embedded prototype as a part of the proposed solution in a ubiquitous computing scenario, and,
- Come up with guidelines for embedding intelligence into objects and applications that could assist users.

The population of interest was mainly undergraduate students who were undergoing or had undergone electronics laboratory practical sessions. Subject Matter Experts (SME) were course instructors consisting of univeristy professors and teaching assistants (TA), who were involved in taking practical electronics laboratory. They also participated in user research studies. All SME who were approached during this research agreed to participate in the study. TAs are generally post-graduate (Master of Technology) or PhD students who assist university professors in practical laboratories. SMEs gave insights into problems faced during practical laboratory sessions, how to overcome such hindrances and feedbacks for and on prototype development. Various data collection methods like contextual inquiries, interviews, open-ended questionnaires, structured questionnaires and field observations were utilized during this phase. Audio and video recordings of interviews and observational sessions were made and analysed using content and interaction analysis techniques.

A breakdown of sample size is mentioned as follows:

- Number of students observed and interviewed in live laboratory sessions during contextual inquiries = 15
- Number of students interviewed to elicit problems faced in practical electronics laboratories in a one-to-one session = 20
- University Professors interviewed = 3
- Teaching Assistants Interviewed = 7
- Number of first-year engineering undergraduate student participants who filled out a questionnaire regarding their confidence level in various laboratory activities and the use of the Internet during laboratory sessions = 65
  The questionnaire was sent via e-mail (refer Annexure C1 for questionnaire). The students were also interviewed face-to-face. Only the questionnaire was online.
- Online Open-ended questionnaire filled by TAs who participated in interviews = 3. (Refer Annexure C2 for questionnaire).
- Open-ended questionnaire filled by Faculty who participated in interviews = 2. (Refer Annexure C3 for questionnaire)
- Workload assessment and an open-ended questionnaire filled by student participants during research Stage 4 = 23, (Refer Annexure C4)
- Number of students interviewed and observed during early prototype phase = 35
- Total sample size of participants in user research = 168

The user research studies consisted of two studies as shown in Figure 4.1. Study -1 that was conducted to identify user needs, requirements and to understand how different emerging technologies can be integrated into practical electronics laboratory sessions.

Study – 2 was user testing of the early AR prototype based on which further iterations and developments were made to the design of the prototype. Study -2 helped in gathering functional requirements and features of the prototype based on which a complete Smart Learning System (SLS) prototype was developed and conceptualized for user testing and hypothesis validation. The SLS will be discussed later in Chapter 5 that follows.

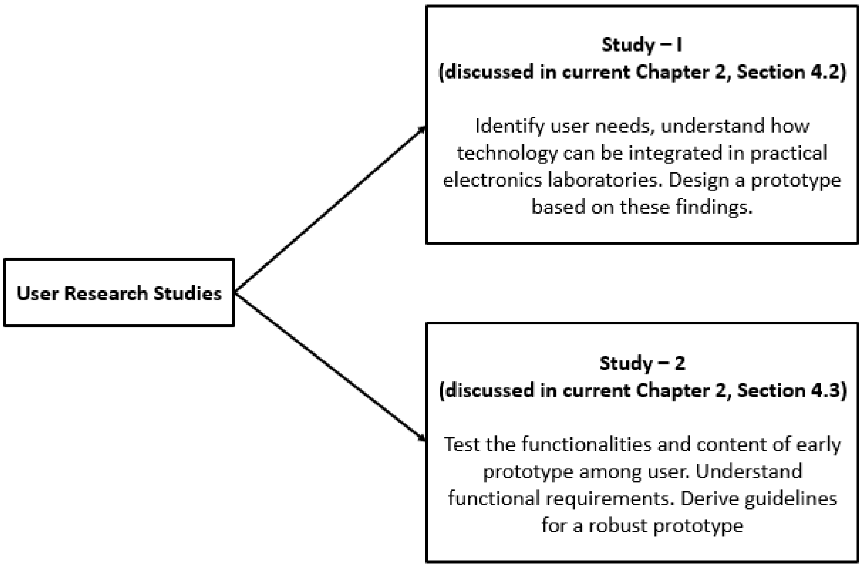


Figure 4.1 User studies conducted as a part of user research.

4.2 Study – 1: Identifying user needs and requirements

The Study – 1 utilized mixed design methods for investigating user needs in practical electronics laboratory sessions. Contextual inquiries comprising of field observations and semi-structured interviews were conducted for identification of user (students and instructors) difficulties, needs, and requirements in a practical electronics laboratory session. Contextual Inquiry is a qualitative data gathering and data analysis methodology which involves talking with users in their workplaces as they do real work. It provides a concrete observational data based on in-the-moment experience that is different from the data given in questionnaires (Raven & Flanders, 1996). Structured and open-ended questionnaires were utilized for gathering user responses and feedbacks regarding practical electronics laboratory sessions. Study-1 also informed how different technologies of AR and smart objects integrate into complex learning environment of practical electronics laboratory sessions to improve student's learning experiences. Storyboarding techniques of scenario-based design methods (Davidoff, Lee, Dey, & Zimmerman, 2007; Rosson & Carroll, 2002) and low fidelity working AR prototype were utilized to understand technology integration in practical electronics laboratory sessions. Figure 4.2 depicts a block diagram of Study-1. Following sub-sections, 4.2.1 to 4.2.6 discuss details, results, and findings of Study - 1.

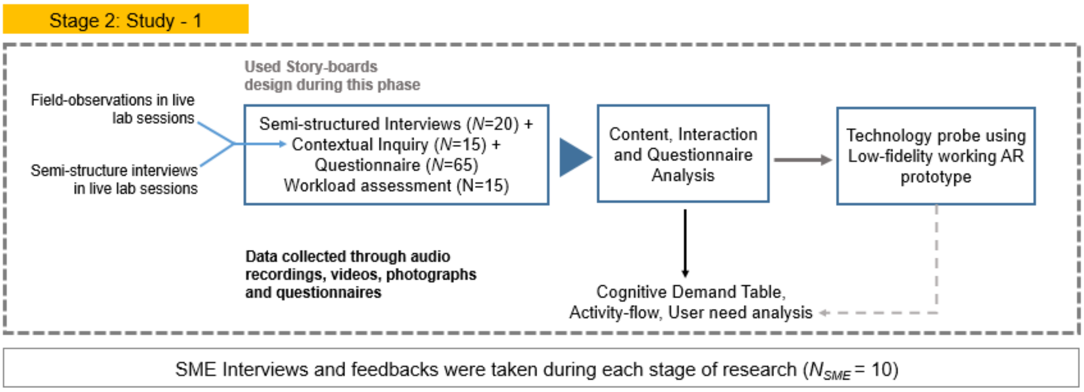


Figure 4.2 Stages involved in Study-1

4.2.1 Contextual Inquiries: Understanding practical electronics laboratory environment

Two field observations were carried out in live practical electronics laboratories of first and second-year undergraduate students at University -1 in Guwahati (Assam, India) to understand the activity-workflow and dynamics of practical electronics laboratory sessions (see Figure 4.3). Video recordings of these sessions were done which were later analyzed using the interaction analysis process as per guidelines provided by (Jordan & Henderson, 1995).

It was observed that usually, a group of three to four students involve in experimentation process. Overall class strength in these labs varies from 30 to 35 students at University - 1. The students are also provided with various lab manuals and visual aids for as-assistance, such as charts containing infographics about various electronics components or equipment (see Figure 4.3 (d)).

(a) (b) (c) (d)

Figure 4.3 Field observations carried out in practical laboratory sessions showing a typical laboratory setup. (a) Students assembling electronic circuit on a breadboard. (b) Measuring the output from the circuit on test equipment. (c) and (d) Students taking help of instructors and charts. Pictures were taken during field observations.

A typical setup of electronics practical laboratory consists of various test equipment like variable power supply unit, frequency generator, cathode ray oscilloscope (CRO) and digital multi-meter (DMM) as shown in Figure 4.4. An ideal workflow of students performing the experiment is represented in Figure 4.5.

(a) **(b)** **(c)**

Figure 4.4 Laboratory equipment setup. (a) Clockwise from top left, frequency generator, digital multi-meter, analog cathode ray oscilloscope and variable power supply. (b) Students assembling circuit on a bread-board. (c) Students often carry boxes to keep prototyped circuits and work on them later if they are not able to complete it in one laboratory session. Photo captured during a field study.

Start → Get Components → Refer Circuit Diagram from Manual → Assemble Circuit → Check experimental procedures from manual → Make connections with input and output devices → Follow procedure to get the desired results → Report results and inferences of the experiment in a lab report → Take a viva test from lab instructor → **End**

Figure 4.5 A simplistic representation of basic workflow of students in practical electronics laboratory

Table 4.1 gives a brief description of laboratory equipment along with the aim of students while working on them. To rig-up electronic circuits, students use a breadboard, a device consisting of an array of holes arranged horizontally and vertically for inserting electronic components and electrical wires to prototype electronic circuits. Students also operate various test equipment to provide input to this prototyped electronic circuit and measure its output parameters.

Table 4.1 Devices and components used by students in labs

Device/ Equipment/ Component Used	Device/ Equipment Type	Functionality	Aim for students
Breadboard	Prototyping Device	Rigging, Assembling electronic circuits	Be able to use the device properly for circuit assembly.
Variable Power Supply	Input Device	To supply input voltage or current to the electronic circuit	To be able to operate these test equipment
Function Generator	Input Device	To provide various input electrical waveforms to the circuit	To be able to operate these test equipment
Cathode Ray Oscilloscope	Output Device	To measure and view various output waveforms from the circuit	To be able to operate and understand the use of CRO for circuit testing.
Digital Multi-meter	Output Device	To measure resistance, electrical connectivity, voltage or current in an electronic circuit. Also used to check the proper functioning of electronic components like transistor or diodes.	To be able to operate multi-meter for measuring parameters, troubleshooting circuits and identifying electronic component configurations.
Electronic Components	Passive, Active, Sensors, Transducers	Building blocks of an electronic circuit.	Students are required to be familiar with various electrical characteristics of these components and know when to use them

In the first year undergraduate laboratory sessions, students are not allowed to carry laptops or smartphones. Senior undergraduate students, i.e., second year and onwards, are allowed to use laptops in their labs. They prefer to use circuit simulators before rigging up the circuit. This helps them compare ideal values with the measured output values of the prototyped electronic circuit. It was observed that whenever students face difficulty while performing the experiment, they mainly prefer interacting with laboratory instructor for assistance. Main difficulties are encountered while operating CRO which is often frustrating for the students. Sometimes the breadboards are also faulty which makes it difficult for students and instructors to troubleshoot the rigged circuit.

Instructors help students in identifying various electronic components, troubleshooting circuits, operating test equipment and explaining underlying theory about the experiment. However, due to the crowded nature of practical lab sessions, instructors are often unable to address all the student groups facing difficulties. Sometimes instructors also find it difficult to explain the working of lab equipment to students or re-tell basic concepts to students repetitively. Table 4.2 describes our observations on individual expected roles of students and instructors in the ideal scenario and compares them with the one in reality.

It was also observed that students rely on the internet for minor troubleshooting issues or understanding a particular experimental procedure or concept even though the use of smartphones is prohibited in practical laboratory sessions – especially for first-year students, (this is a particularly interesting observation as it presents an opportunity to utilize an already existing technology for assisting students). However, the information available on the internet is mostly unstructured and scattered and students often end up wasting a lot of time searching for correct explanations, articles or videos. Sometimes, it also becomes a distraction for students.

We also interacted with Subject-Matter Experts (SMEs) to understand how they prepare for laboratory sessions. In IITG, a group of TAs practices the required experiment, which has to be taught in class, a day or two before the laboratory sessions. During this time, they rig up complete experiments, take readings as well as note down probable difficulties that can be faced during the experiments. Observations indicate that even TAs sometimes encounter errors or difficulties that are untraceable – which bogs them too! Sometimes even when the circuit is assembled correctly, and even though the test equipment is working fine – they are not able to get the desired output.

Table 4.2 Expected individual roles of students and instructors in laboratory and difficulties experienced by them in reality.

	Student	Instructors
Expectation	• Attend pre-lab sessions to gain an understanding of experiments. • Expected to know about nuances of experiments from before. • Perform and finish experiments systematically within the stipulated time. • Should be able to operate various test equipment. • Able to troubleshoot and report the difficulties.	• Expected to assist students in the lab. • Know about all experiments accurately. • Should be proficient in handling test equipment. • Enable students to develop practical skills. • Be able to help students relate theory and practical experiments. • Guide students accordingly to enable their creative and hands-on skills through an inquiry-based constructivist approach. • Manage a large group of students (sometimes assisted with teaching assistants) and conduct practical session successfully.
Reality	• Do not attend pre-lab sessions regularly. • Are often unaware of theory and concepts behind the experiment. • Struggle hard to work with test equipment. • Unsystematic in assembling circuits. • Afraid to experiment with circuits due to the fear of blowing-up electronic components or short-circuiting the equipment. • Sometimes, forced to complete the experiment in limited time. • Sometimes they need to complete complex circuits in next lab session, which decreases their readiness for next experiment as they lag behind by one session.	• Difficult to predict the connections if it goes wrong. Becomes tedious to find out. • Are sometimes unaware of specific practical concepts. • Do not understand internal workings of test equipment. • Overburdened by the class strength. • Are not able to address the need of each student group in lab sessions.

This issue also experienced by students while performing the experiments. Such mysterious behaviours of electronics, even for simple circuits – for example, a half wave rectifier, causes a lot of frustration amongst the users.

To collate the observations together, several broad issues faced in laboratories have been observed, such as difficulties in operating test equipment by students and instructors, time constraints for students to complete the experiment. Students lack readiness for practical experiments in terms of understanding theory and working on experimental setup. The use of internet in practical electronics laboratory session although helpful – sometimes causes distraction among student groups leading to lack of concentration.

4.2.2 Interaction Analysis

Video recordings made in live laboratory sessions were analyzed using interaction analysis process as described in the literature (Jordan & Henderson, 1995). Laboratory activities performed by students were broadly broken down into four stages (see Figure 4.6).

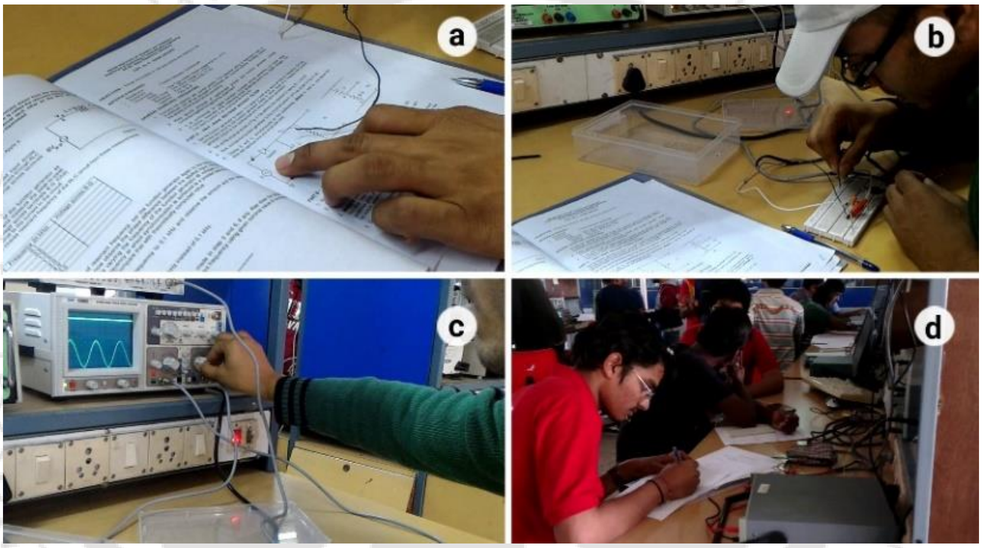


Figure 4.6 An atypical interaction analysis of think-aloud sessions and live laboratory sessions. (a) Referencing from lab manual. (b) Assembling the circuit by continuously referring to lab manual. (c) Operating test instrument to provide input to the circuit and measure output. (d) Reporting the findings and observations.

Students generally make mistakes or face difficulty in any of these four stages while conducting an experiment. These stages are:

(a) Referencing,

(b) Assembling,

(c) Operating test equipment (OTE), and

(d) Reporting.

Table 4.3 depicts a hierarchical task analysis of these stages along with the difficulties associated with them.

Table 4.3 Hierarchical Task Analysis and difficulties associated with these steps

Broad Category	Interactions With	Difficulties
Referencing	Lab manual	Insufficient, Poorly designed.
	Peers	No difficulties observed or reported by participant.
	Instructors	Availability to instruct individual student group is an issue if there is a large batch of students.
	Internet	Distraction
Assembling	Breadboard	Faulty, Requires effort.
	Electronic Components	Unable to identify values, configuration.
	Wires	Too many wires lead to messy setup.
Operating Test Equipment	Digital Multi-meter	Sometimes it is difficult to use transistor tester.
	Cathode Ray Oscilloscope	Most difficult - due to flickering, unpredictable behavior. Not aware of CRO's working. Reported MWWL=50.71
	Function Generator	No difficulties observed or reported by participant.
	Power Supply	Sometimes students forget to check for high input voltage or current values.
Reporting	Laboratory Report	Incomplete and lacks structured information.
	Viva	Difficult if unable to connect practical and theoretical concepts.

It was posited in the thesis that by collating all the mistakes made during these steps as the desired instructions to correct these mistakes, a system can be devised with embedded intelligence to help assist students and instructors in laboratory activities. This aspect has been discussed later on in the thesis.

To further understand user needs and get a better understanding on designing a solution in the context of practical electronics laboratory, interviews were conducted amongst students and SMEs and are described in Section 4.2.3.

4.2.3 Interviews

4.2.3.1 Interviews with student participants

Open-ended interviews were conducted amongst 35 undergraduate students enrolled in electronics engineering course (15 participants interviewed during contextual inquiries in live laboratory sessions + 20 second-year student participants interviewed during one-on-one session outside of laboratory sessions). The participants belonged from the first and second year of their electronics-engineering course with ages between 18 to 20 years and were selected because they were undergoing or had already undergone Basic Electronics Laboratory (EE102) course and could narrate their experiences and difficulties faced in laboratories. The open-ended interviews allowed us to explore the attitudes, perception, and expectations of students regarding practical laboratory sessions. Table 4.4 presents a few excerpts from students' interviews and highlight some of the problems described by them.

Table 4.4 Excerpts from a few students' open-ended interviews

Participant	Excerpt
P1	"…lab manual is not very informative in itself…we are not precisely able to do what we want…. We get to know what is to be done only in labs…. Mainly analog circuits have issues, as we are not able to get output at once. It requires step-wise verification of current and voltage…"
P2	"… There are many faulty equipment…breadboard were faulty, we need to ask for new breadboards… In digital electronics, we didn't know many things. We were able to perform only after coming to lab and asking friends… Big circuits take time and show problems… leads to frustration but after it works, we feel excited… "
P3	"…sometimes the fault is only realized after implementing the whole circuit and when it leads to wrong output or other problems…can't be pointed out initially…"
P4	"…lab manual only tell procedures, not the implications of errors or combination of component arrangement…"
P5	"…big circuit connections take a lot of time and show the problem if they are transported…they sometimes give more problems when we try to minimize the problems…it takes a lot of time and requires a lot of patience….sometimes we forget to check input voltage while performing experiment…it leads to blowing up of resistance…"
P6	"We are not aware of CROs capabilities. It is not problematic, it's our ignorance."

During these interview sessions, we also utilized scenario-based design technique to present various storyboards of concepts to students regarding innovative technologies that can be used to improve learning experiences in laboratories and has been discussed in Section 4.2.3.2 that follows.

Audio recordings of the interviews was taken and transcribed using the technique of content analysis (Berg, 2001, pp 238). The analysis aimed at understanding how laboratory practices are conducted and to identify various cognitive aspects that come into play while students performed the experiments. Various factors of the cognitive load while performing practical experiments in labs were identified. Based on the analysis, a cognitive demand table, refer to Table 4.5, was constructed using Applied Cognitive Task Analysis (ACTA). This methodology helps in extracting information about cognitive demands and skills required for a task (Militello & Hutton, 1998).

Table 4.5 Cognitive Demand Table

Difficult cognitive element	Why difficult?	Shortcomings identified
Instructions and procedures	Improper instructions create difficulty in understanding on how to perform an experiment in the lab.	Insufficient theory and precautionary measures
Faulty equipment	Causes frustration and consumes time as debugging becomes difficult.	Fault in breadboards, digital multi-meters.
Complicated circuit	Cumbersome to rig and time-consuming. Difficult to carry.	Difficult to trace errors, large wire connections, wrong placement of electronic components.
Lack of equipment knowledge	Leads to cluelessness. Unable to validate results.	Not able to troubleshoot misaligned settings.
Time Constraints	Allotted time falls short for large experiments. Attention shifts on completion rather than understanding how it works.	Focus on experiment completion.
Debugging of circuit	Trial and error based debugging. Causes frustration. Consumes time.	Try all possible ways to debug the error.

We also observed that students reported Cathode Ray Oscilloscope (CRO) to be the most difficult test instrument to operate in the lab. We therefore also administered a

NASA TLX questionnaire to get an understanding of the workload experienced by students to operate CRO alone. Figure 4.7 illustrates the workload experienced by students as rated on the TLX scale. Overall, the mean weighted workload (MWWL) experienced by students for operating CRO alone is 50.71 which can be considered to be fairly high when compared with a number of sub-tasks associated with an experiment.

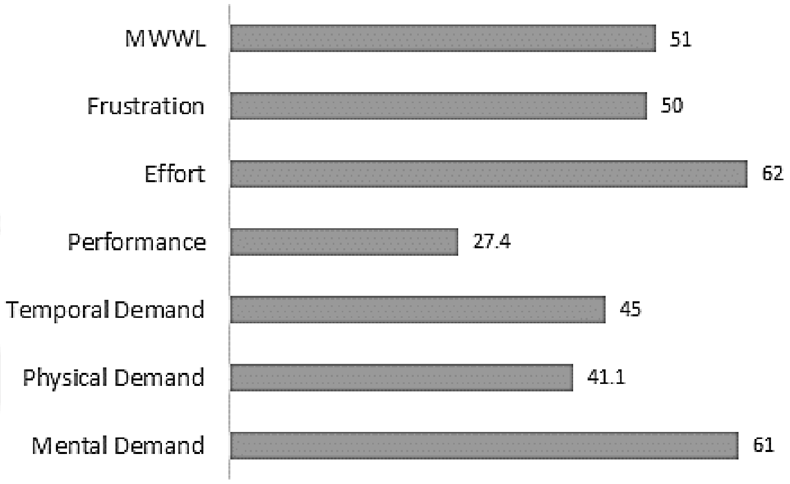


Figure 4.7 Graph depicting mean sources of workload experienced by students, (N=23), for operating CRO alone. (0 = Low, 100 = High).

4.2.3.2 Interview responses on conceptual storyboards of technology use in laboratory

Scenario-based design technique, which allows for envisioning future use systems at an early point in the development, was also utilized. As a part of this technique, a number of conceptual scenario on the use of different emerging technologies in practical electronics laboratory were generated through brainstorming. The scenarios were generated after careful observations from contextual inquiries. Three conceptual scenarios were selected to be presented to participants in the form of storyboards (see Annexure C5). The idea of storyboarding was adopted from authors Davidoff, Lee, Dey, & Zimmerman (2007) to explore divergent design concepts. This methodology allowed us to exploit the concreteness of our solution proposal and evoke further requirements for analysis and technology probe (Rosson & Carroll, 2002). It also enabled us to understand user's perception, acceptability, and need for new technologies.

During the interviews, student participants were presented with three storyboards of conceptual scenarios regarding technological interventions that can be possible in practical electronics laboratory sessions and improve students' learning experience. The storyboards depicted possible interactive learning systems that were envisioned to assist students intelligently in practical electronics laboratory sessions as well as assist instructors in teaching. The participants were asked to rank these illustrated storyboards according to their needs and its potential use in future. Out of three conceptual scenarios presented, Scenario 2 was ranked highest, see Figure 4.8.

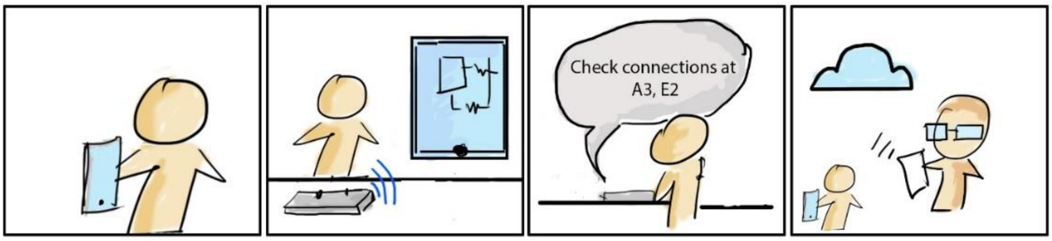


Figure 4.8 One of the conceptual storyboard presented to students, which depicts the use of AR and smart object in practical lab sessions.

The scenario illustrates a laboratory session where students perform their experiments on an intelligent breadboard, also referred to as Smart Object (SO). The breadboard is connected to a computer or digital tablet that shows visualizations for circuit assembly. The system is also able to detect wrong connections and pin-point it to students. This system is also able to guide students by instructing them about various theoretical concepts of the experiment. The students can simultaneously update their experimental readings to their records and upon completion of the experiment; this record is sent to their instructors for evaluation.

The students were strongly able to relate to this depiction but pointed out that such a learning system alone will not be sufficient in laboratories. They suggested a strong need for laboratory instructors to help them out with their experiments. We further found that although students rated this scenario to be most useful, they were also skeptical of how such systems can nurture their learning. The following response from one to the participants elicits this:

"Don't agree with scenarios completely. Step-by-step debugging is necessary. In conceptual scenarios, we get a lot of help from virtual systems. It will not nurture my intuitiveness. It is giving much more data than simply telling syntax."

This response correctly highlights the concern raised in Chapter 2 regarding the use of technology in educational laboratories and characterization of intelligence that needs to be embedded into objects and systems that aid and assist learning. The user-centered investigation is being carried out to address this same issue – which is also one of the major concerns addressed in this thesis.

4.2.4 Questionnaires

4.2.4.1 Structured Questionnaire

After interviews, an online questionnaire form was sent to the first year undergraduate students of IITG enrolled in Basic Electronics Laboratory course (EE102) via e-mail. Three follow-up emails were sent to students as a reminder to complete the form within a span of one month. The main aim of this questionnaire was (i) to assess students' self-confidence level to work with various equipment in a lab session, and, (ii) to get a general idea on their perception of using the internet to search for information. Out of 76 responses, 65 usable questionnaires were received. Ages of the participants ranged from 17 to 20 years, with an average age of 18 years with 4.62% female participants and 95.38% male participants. Table 4.6 presents a section of the questionnaire (for complete descriptive statistics see Annexure C6).

The online questionnaire form was sent to students after they had attended first two practical electronics laboratory sessions and were familiar enough with laboratory practices and equipment to answer the questionnaire. Participants were asked to rate their confidence level on the ability to understand various electronic components, operating test equipment, assembling circuit and troubleshooting on a 10-point Likert scale (1 = Low, 10 = High) in a 15-item questionnaire. This questionnaire was adapted from (Watai et al., 2007) and modified for our study. In addition to these 15 items questionnaire, a 5-items questionnaire was also sent along asking participants to rate, on a 5-point Likert scale (1= Strongly Disagree, 5 = Strongly Agree), how they used the internet for collecting information regarding given experiment and distraction it caused.

Table 4.6 A section of questionnaire showing descriptive statistics of students' ability. N=65

Items	Mean	Std. Dev
Ability to understand and operate features of CRO at first attempt	7.88	1.97
Ability to operate the features on CRO when it behaves unpredictably	6.80	2.23
Ability to measure and interpret waveform of CRO	8.37	1.63
Ability to set correct amplitude and frequency on function generator	8.74	1.80

Firstly, we observed that students rated their confidence level to work around various laboratory equipment high - as opposed to the statements received from participants during contextual inquiries. This perhaps indicates that although students perceived a fair confidence level to work around with various equipment and experiments in a laboratory, they are often underprepared for practical laboratory sessions. Secondly, we see that students rate fair confidence towards operating CRO (see Table 4.6), which was completely contradictory as compared to their responses during interviews.

Table 4.7 shows the results of a survey on the use of the internet for gathering information in labs amongst N = 65 undergraduate students. 33.8% students reported that they find information-gathering process on internet time-consuming in a lab session.

Table 4.7 Response of students (N=65) regarding the use of the internet for information finding on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree)

Item	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I always use the internet to search for information regarding experiments in the lab.	9.2%	15.4%	23.1%	27.7%	24.6%
I sometimes get distracted while searching for information regarding experiments experiment on the net.	23.1%	13.8%	24.6%	21.5%	16.9%
I am quickly able to find the required information regarding experiment through the net.	15.4%	9.2%	13.8%	47.7%	13.8%
Gathering information on the internet is time-consuming in a lab class.	6.2%	20%	20%	20%	33.8%

4.2.4.2 Open-ended questionnaires

In addition to the above questionnaire, open-ended questionnaires were given to first-year students in laboratory sessions asking them to describe anything they mainly found good or frustrating while performing experiments. N = 23 participants opted to fill out the questionnaire. We also sent open-ended questionnaires to TAs (N=3) and faculty members (N=2) asking about problems faced by them in labs and to highlight areas they felt were difficult for students. The questionnaire also inquired about how they overcome difficulties they face and what measures need to be adopted to solve them. The responses obtained helped us to conceptualize our design solution in terms of defining the embedded intelligence component as well as the type of instructions that are required to assist students in laboratories. All questionnaire used in user research studies have been presented in Annexure C.

The findings and analysis, as well as the responses of these questionnaires, have been highlighted in the following Section 4.2.5.

4.2.5 Findings from students' responses received via questionnaires

Figure 4.9 below depicts the difficulties experienced by students based on the total responses obtained from the open-ended questionnaire. The analysis of the questionnaire revealed that although students rated high confidence regarding their ability to troubleshoot and operate various test equipment, the interviews yielded opposite results (refer to Table 4.6). This indicates that students often come unprepared in laboratories or have a little understanding regarding the working of such instruments.

It was also found that searching for information on the internet in labs was time-consuming and distracting for students. Further, the amount of effort and frustration experienced by students to debug large circuits and operate test instruments often inhibits deeper inquiry into the crux of experiment and underlying theory. Referring to Figure 4.7, it is evident that merely operating a CRO – which is only a part of whole activity while experimenting, requires high effort and causes frustration.

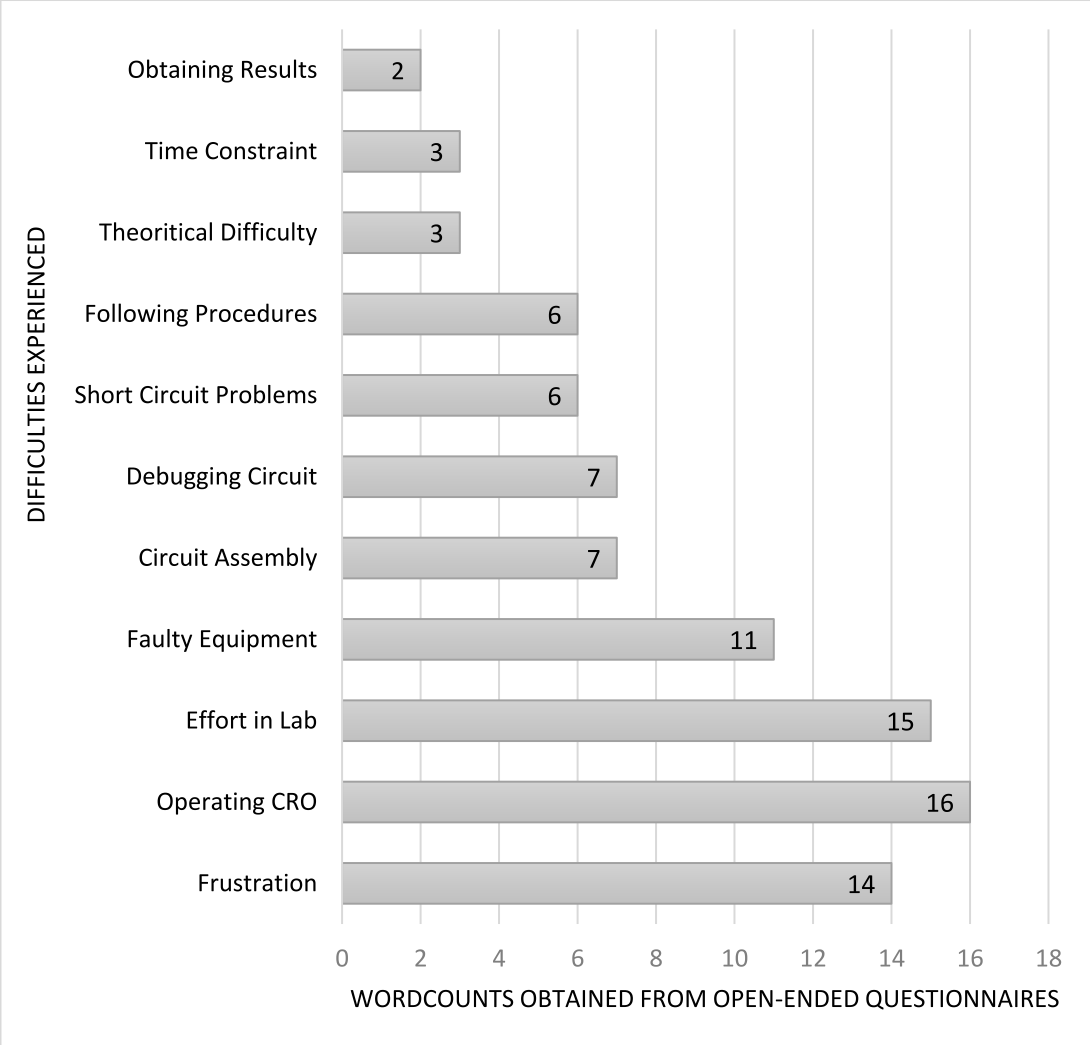


Figure 4.9 Word-count of difficulties experienced and reported by students in electronics laboratory after content analysis open-ended questionnaire (N=23).

4.2.6 Open-ended Questionnaire Responses of Subject Matter Experts on difficulties faced in laboratory

The instructors were asked to elicit responses regarding the types of difficulties experienced by them as well as students in practical labs, how they overcome them? What type of teaching materials do they use to teach students? Best practices that students should keep in mind while performing practical experiments. Responses from interviews and open-ended questionnaires from SMEs were transcribed and analyzed.

Figure 4.10 depicts an example of how different patterns for user need and its likely solution, as suggested by SMEs, were identified. Table 4.8 represents the responses of instructors obtained from one of the open-ended questionnaires.

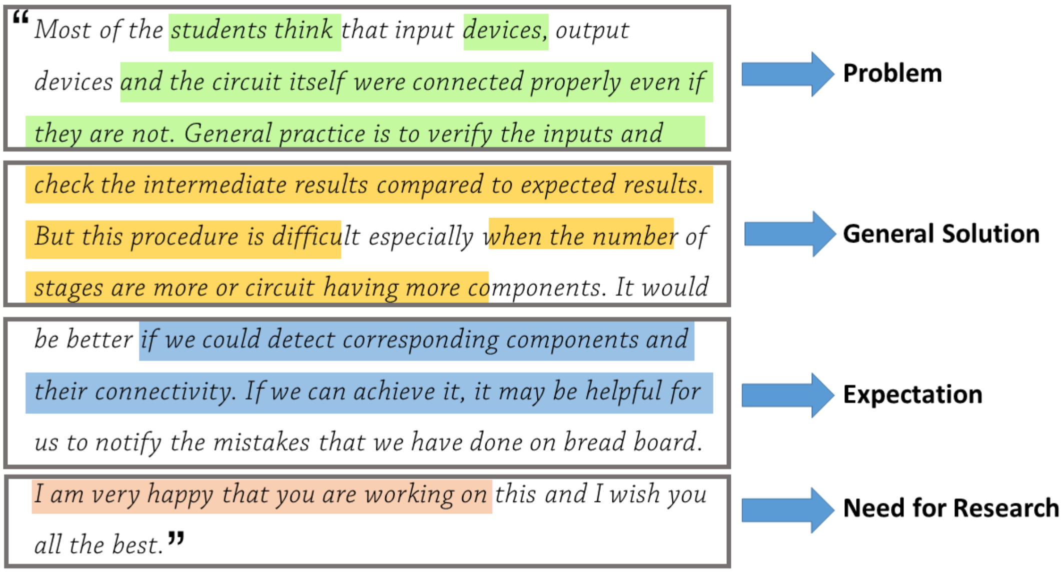


Figure 4.10 Finding patterns from transcribed SME responses

Table 4.8 Qualitative responses of lab instructors (N=3) regarding difficulties they experience in labs

	Do you face any problems in while conducting lab classes for students?
I1	"I think more practical knowledge on the use of equipment such as CRO, function generator should be given. We or even the lab staff are aware of only limited operations, which are generally encountered."
I2	"Most of the students think that input devices, output devices and the circuit itself were connected properly even if they are not. General practice is to verify the inputs and check the intermediate results compared to expected results. However, this procedure is difficult especially when the number of stages is more or circuit having more components…"
I3	"Due to the lack of previous knowledge about the experiments, it becomes difficult to explain the essence of the experiment to the students."

Instructors reported that many students get confused while using breadboards and often do not follow the practice of using a series column as a ground (GND) or voltage supply. It was also reported that loose connections and unsystematic wiring of circuits by students are the primary cause of errors. The instructors also highlighted that students do not systematically debug circuits and give up in between while debugging. They also emphasized that students' often come unprepared for lab classes, which is one of the main reason for their lack of understanding regarding experiments. Operating CRO was also reported as a problem faced by the student. Figure 4.11 depicts the difficulties highlighted by SMEs as identified from interviews and questionnaires.

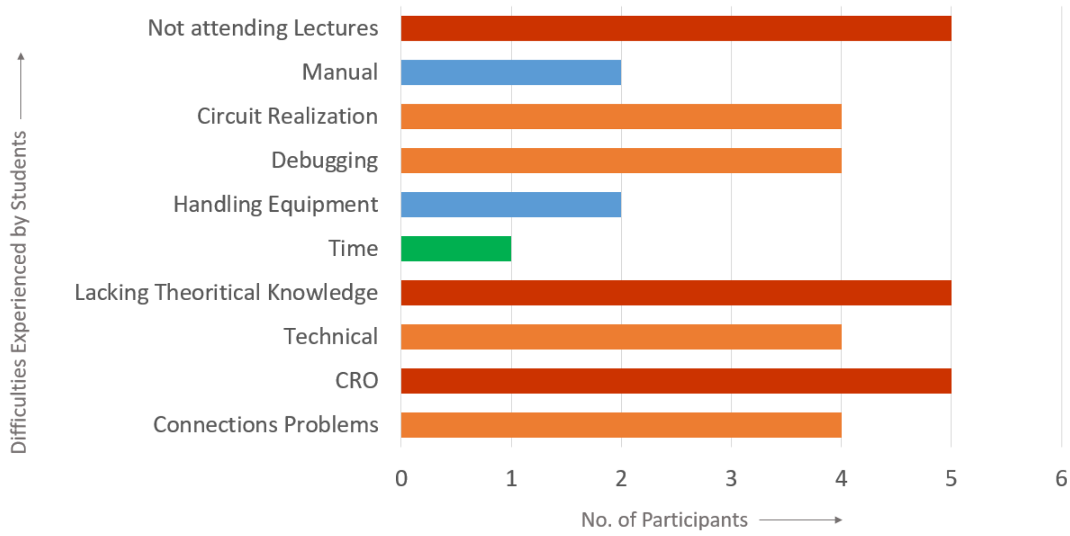


Figure 4.11 Difficulties faced in practical laboratories as highlighted by SMEs.

4.2.7 Technology Probe

To understand how AR can be utilized for the benefit of students and instructors in practical electronics laboratory, a technology probe study was conducted with a low-fidelity working prototype of AR. This technology probe study was conducted amongst N=10 randomly selected students from electronics engineering background, see Figure 4.12 (a) and (b). The AR prototype could only superimpose 3D circuit model on a breadboard with the help of a marker, as shown in Figure 4.12 (c).

(a) **(b)** **(c)**

Figure 4.12 Technology probe study conducted with low-fidelity working AR prototype. (a), (b) Users interacting with AR prototype in a laboratory. (c) The early content of prototype demonstrated to users.

Three (N = 3) out of 10 participants reported being aware of AR. All study participants reported that AR would prove highly beneficial for them in practical electronics laboratories. The participants also suggested that merely projecting 3D visualization was not sufficient (unlike the literatures on AR for education, discussed in Chapter 2) and further interactivity and content should be added to be able to provide better information on circuit assembly on a breadboard. Table 4.9 depicts some of the statements of students from the interview regarding AR for practical electronics laboratory.

Table 4.9 Positive and supportive view of student participants on AR

Participant	Response
P1	"It is very cool! It would make our task (assembling circuit) easy... It is a very good initiative! Where can we get this application? It is really good; I like it."
P2	"It may help! It will make our task very easy."
P3	"It should show the labels of components with values apart from colour codes…also, show the values of resistors."

Based on the positive response received from the participants, further developments were made in our AR prototype, discussed in Chapter 5. This prototype was evaluated amongst 35 students for further development and refinement in Study – 2 will be discussed in Section 4.4. A summary of findings from Study-1 is provided in the following Section 4.3.

4.3 Summary of Findings from Study – 1

Study – 1 provides essential insights into difficulties experienced by both students and instructors in practical electronics laboratory sessions. The study also helped in giving initial directions for understanding how technologies like AR and smart objects can be integrated into the complex learning environment. Findings of study -1 have been summarized as follows:-

(1) Need for user task assistance: There are two primary users in practical electronics laboratory, students, and instructors. Both these users often face difficulties while interacting with the experimental setup in the practical laboratory. The primary motive for student users is to learn, while instructors help facilitate learning of students through feedbacks and assistance. However, there are two significant constraints observed in this situation. (i) Students facing difficulties with experimental laboratory setup while performing a task, and (ii) Instructors are facing difficulties in handling experimental setup as well as assisting students. While instructors can assist students in practical laboratories, it is observed that instructors themselves do not get any assistance or feedback in real-time.

Secondly, it was observed that trivial difficulties of students often burden instructors. Difficulties experienced by students are mostly related to the handling of equipment, debugging circuits and searching for information regarding the practical experiments. Such difficulties can be minimized by providing contextualized instructions via AR. We propose that these difficulties can be identified by automating students' experimental activity by utilizing AR and smart objects.

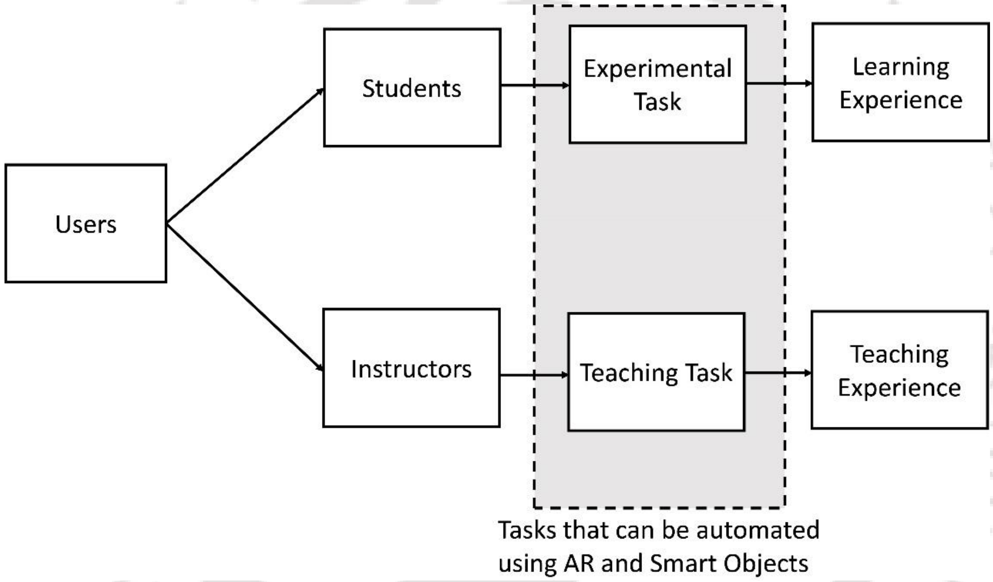


Figure 4.13 Users and their tasks that can be automated by utilizing AR and smart objects.

(2) Providing a layered set of instructions to students: Instructors, based on their experiential knowledge often give this assistance to students through a layered set of instructions. These instructions are not generally given directly, but rather in a manner, that invokes inquiry amongst students. The information provided by an instructor is structured and specific to the context of use, unlike the information available on the internet, which is unstructured – and consumes a lot of student's time for searching. Through technology probe study, we identified that creating content for the AR application and the way it is delivered to students is essential. We therefore utilized think-aloud technique to capture the experiential knowledge of instructor and presented it to students through AR during Study – 2 that has been discussed in the following Section 4.4.

4.4 Study – 2: User testing with early AR prototype and gathering insights into functional requirements for designing novel learning tool

From Study – 1 it was identified that for a successful learning experience, it is important to design better learning content and functionalities that need to be embedded into novel learning systems that utilize AR and smart objects. We posited that if instructors' experiential knowledge along with course content is embedded into such learning systems and application, effective instructional content could be formulated. To capture the tacit knowledge of instructors, think-aloud sessions were conducted amongst two (N = 2) laboratory instructors and task flows were generated for two experiments namely Resistor-Inductor-Capacitor (RLC) circuits and Full-wave rectifiers. This think-aloud session falls under Stage 3 of the research plan (see Figure 3.3 for reference). The main idea behind these think-aloud sessions was to capture nuances and techniques that are utilized by experts to navigate through problems faced during electronics experiment. The laboratory instructors who participated in these sessions had years of experience on conducting the same laboratory sessions and were able to provide good insights on performing the experiment and troubleshooting it. Thorough qualitative analysis (content and interaction analysis) were done for these think-aloud sessions based on which inferences were made and incorporated in our design solution. The task flows acted as an instructional database and was coded and embedded into the early AR application, see Figure 4.14.

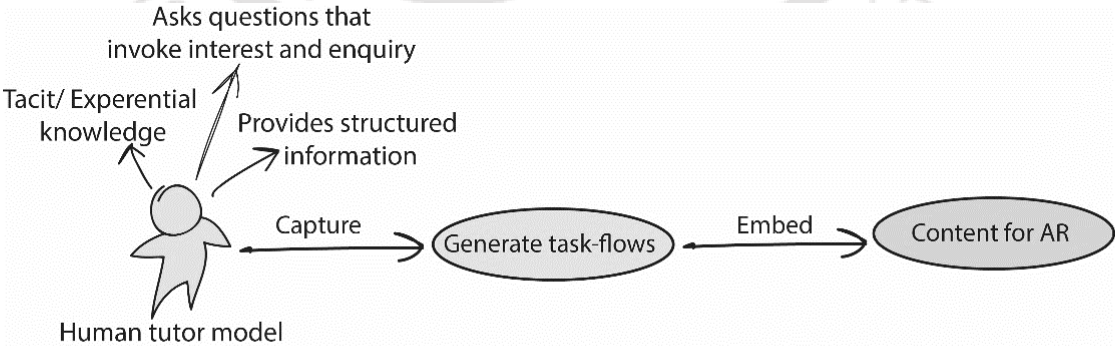


Figure 4.14 The design process for AR content generation for Study - 2. Human tutor's experiential knowledge and ability to guide students for a specific experiment were captured in task-flows through think-aloud sessions and embedded as instructions in AR application that were conveyed to the student via voice-based instructions on AR app.

Further functionalities were designed based on the findings from Study – 1. These functionalities allowed early AR application prototype to provide voice-based instructions regarding experiments, show circuit assembly in 3D on a breadboard with the help of a marker, overlay video on laboratory manuals and provide voice based instructions to operate CRO.

The intention of Study- 2 was to gain insights and feedback regarding the design and use of AR in practical lab sessions and come up with a novel learning system that could assist users with their tasks in laboratory sessions. The question was when students and instructors would accept AR as a means of learning.

An early AR application prototype was developed that could project 3D circuit diagrams on breadboard and information regarding electronic component regarding full-wave rectifier (FWR) experiment (see Annexure D1), give step-wise instruction for circuit assembly and provide voice-based instructions regarding FWR experiment. The prototype could also project video on laboratory manual for RLC Circuit experiment (see Annexure D2) and provide necessary information using CRO operation. This early AR prototype was subjected to user-testing (i.e., stage 4 of the research plan, see Figure 3.3) amongst thirty-five (N=35) undergraduate students ($Mean_{age}$ = 18.30, SD_{age} = 0.80) in two live practical lab sessions of EE102 at IIT Guwahati. All the students belonged from the same lab group and were undergoing basic electronics course as a part of their curriculum. The students were asked to provide an assessment of AR prototype features and usability aspects through interviews.

Before the user testing, the students were briefed about the functionalities of AR application – which were installed on their smartphones with due consent. The assessments were collated using open-ended questionnaires and semi-structured interviews. Observational studies were also conducted to observe classroom dynamics and how students used the AR application. 26% of students (12 out of 35) reported to be aware of AR technology or had heard of it.

Students reported animated video simulation feature to be of most use as it helped them relate theory with the experiments easily. The students also suggested that it would be better if an extended tracking feature is added so that they can compare output waveforms and theoretical waveforms side-by-side. The second most liked feature was regarding instructions to operate test equipment like CRO. Students often find it challenging to adjust flickering waveforms and stabilize the output as many of them are unaware of the functions to operate a CRO. The AR application, when pointed toward CRO, helped students by providing voice-based instructions to operate the equipment. Students who found it difficult to translate 2D circuit diagrams on a breadboard mostly liked the 3D circuit-building feature. Students who did not find such difficulty presented a neutral view on this functionality.

Overall, the students found 3D circuits representations (see Figure 4.15) to be a useful feature, especially while referring to component information during experimentation. The feedback suggested that if the 3D circuits' graphics and circuit building instructions are made more interactive and visually appealing, it will be more helpful to promote learning entertainingly. It was also observed that students had to switch between the AR prototype application and mobile camera – which is used by them for data collection. This indicates that the AR application should also have data capturing capabilities using the smartphone's camera to improve the utility and usability of the application.

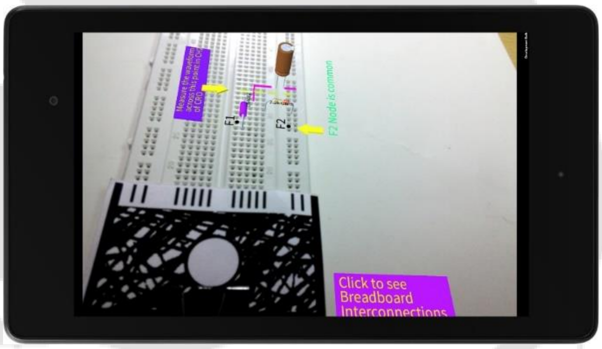


Figure 4.15 3D Circuit representation in early AR prototype

Voice-based instructions were reported to a useful feature for independent learning outside of the lab sessions. During lab sessions, students preferred visual and text-based instructions. Students also suggested including more language options for voice-based instructions in the application as they feel more comfortable getting inputs in their native language. Figure 4.16 depicts a graph of most liked AR application functionalities obtained from responses of 20 students who filled out the open-ended questionnaires during the observational study.

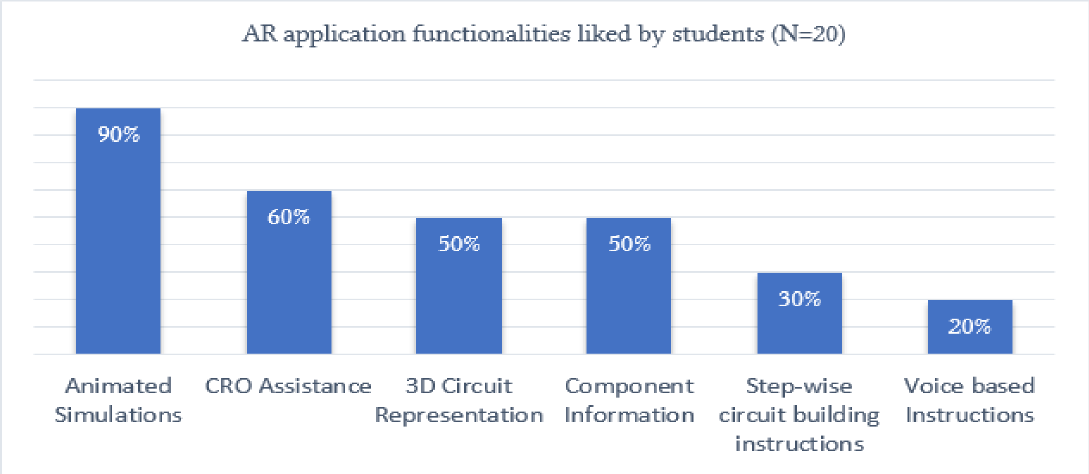


Figure 4.16 AR functionalities liked by students, in percentage, obtained by extracting effective responses of twenty users from content analysis of interviews and open-ended questionnaires.

During this user testing, we also probed questions like how does practical lab session dynamics change if AR is introduced as a learning aid? Will AR application retain the collaborative environment of a laboratory session? What will be the role of laboratory instructors be if AR is introduced in the practical laboratory?

Figure 4.17 depicts the use of AR application by students in practical lab sessions and their interaction with lab instructor when AR is used. The instructor is represented with a dashed white circle in Figure 4.17 (c, d).

(a) **(b)** **(c)** **(d)**

Figure 4.17 An atypical interaction analysis of using AR in electronics laboratory session. (a) Students using 3D circuit assembly and component information feature during the experiment. (b) Students referred to animated video simulations to grasp theoretical concepts of the experiment. (c) The interaction between instructor and students regarding theoretical concepts behind the experiment. (d) A snapshot of contextual inquiry, instructor, and students discussing electronic component information.

Our observations indicate that students can work collaboratively in practical sessions using AR. In Figure 4.17 (a), a student on the left has placed an electronic component wrongly on the breadboard. The student on the right immediately drove his attention to the AR application that displayed component information and asked him to correct his mistake. The students also followed the instructions provided by the application to complete the experiment. However, if the students found any unclear guidance in the AR application, which was hard to comprehend, or if there was a break in an interaction like occlusion in AR view due to low light or AR camera not able to focus, the students would get distracted. This suggests that AR application should be engaging enough for students. Simple static content like merely depicting 3D graphics was not sufficient to hold students' interest. We also observed that students' attention was narrowed only to the AR view when interacting with the AR application. This limited them from getting the complete experience of the laboratory environment. Therefore, we posit that designers of AR also need to consider factors that control the degrees of immersion of AR users so as not to hinder the overall experience of a real environment. Perhaps a timer that can break interaction of students by asking them to set aside the AR application for some time would be useful. Further investigations should be carried out in this aspect.

Figure 4.17 (c) depicts lab instructors and students discussing a theoretical concept about RLC experiment. In a conventional lab session, the instructor is mostly involved in assisting students with troubleshooting of lab equipment like CRO. We observed that students after having received the desired output on CRO referred to the video simulation provided by AR application and made a more in-depth inquiry into the subject.

Figure 4.17 (d) is a snapshot from a contextual inquiry conducted during user-study. The students and instructors are discussing how to identify different pins of a transistor – an electronic component. This is one of the most common problems students face. A contrast between student-instructor interactions can be seen in Figure 4.17 (c) and Figure 4.17 (d). In both these cases, only the type of information being shared between students and the instructor has changed. With AR introduced, discussions are on theoretical concepts, and in the latter, it is about equipment and component.

Students also highlighted a possibility to utilize techniques through which debugging process on a breadboard could be automated in addition to AR. Since circuit debugging is also one of the major concerns that hinder the learning experience, we decided to convert existing breadboards into smart objects that were able to identify students' mistakes and assist them. This user requirement led to the development of an "intelligent" breadboard, which was categorized under smart objects. Both AR and intelligent breadboard together formed a Smart Learning System (SLS) that will be discussed in Chapter 5.

In addition to the requirement of automation for debugging circuits, it was identified that to ease the task of instructors in practical electronics laboratories, a connected system is required that can provide relevant information to instructors regarding students' progress and instructional requirements. Such a system require the collection of data regarding the experimental activity of all student groups as well as their progress in real-time. Based on these insights, a Smart Learning System was designed which was later tested amongst student users for hypothesis validation. A consolidated summary of the findings from Study -1 and Study – 2 is presented in the following section 4.5

4.5 Consolidated findings from User Research Studies

The studies provide essential insights into understanding how learning experiences can be improved in practical electronics laboratory sessions. Findings from Study -1, as discussed in Section 4.3, indicates a need for user task assistance through an intelligent or smart system that is capable of addressing the needs of both students and instructors. Study – 1 further highlights the need to facilitate teaching in the laboratory through a connected system that can enable real-time monitoring of students in the practical laboratory. Study – 2 provides insights into the functional requirements for designing AR and provide a set of design heuristics that can be utilized in designing novel learning applications. These design heuristics will be later discussed in Chapter 7. Altogether, four major themes emerge from the findings and observations of studies that can help facilitate better learning and teaching experiences in practical electronics laboratories. These themes have been generalized in Figure 4.18 below.

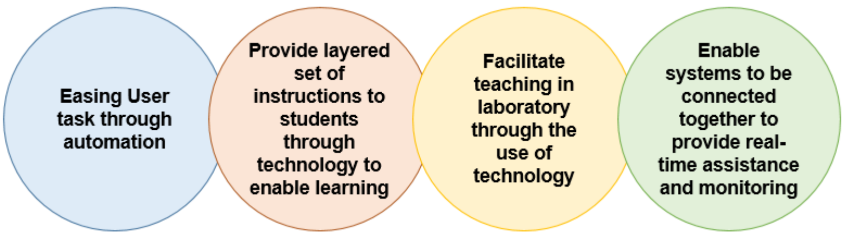


Figure 4.18 Four major themes that emerge from studies to help facilitate better learning and teaching experiences in practical laboratories.

To provide a layered set of instructions through the use of emerging technologies such as AR and smart objects, the system should be embedded with the intelligence to assist students like a human tutor. For this is important to collate all possible difficulties, mistakes and errors made and experienced by students and understand how instructors help students overcome these challenges. This thesis proposes a user-centered design method of capturing all these challenges and instructors experiential knowledge together to design an embedded intelligence for novel learning systems in practical electronics laboratory sessions. This will be discussed later on in Chapter 5.

Figure 4.19 provides a complete overview of the findings from the studies that further led to the development of SLS, discussed in Chapter 5.

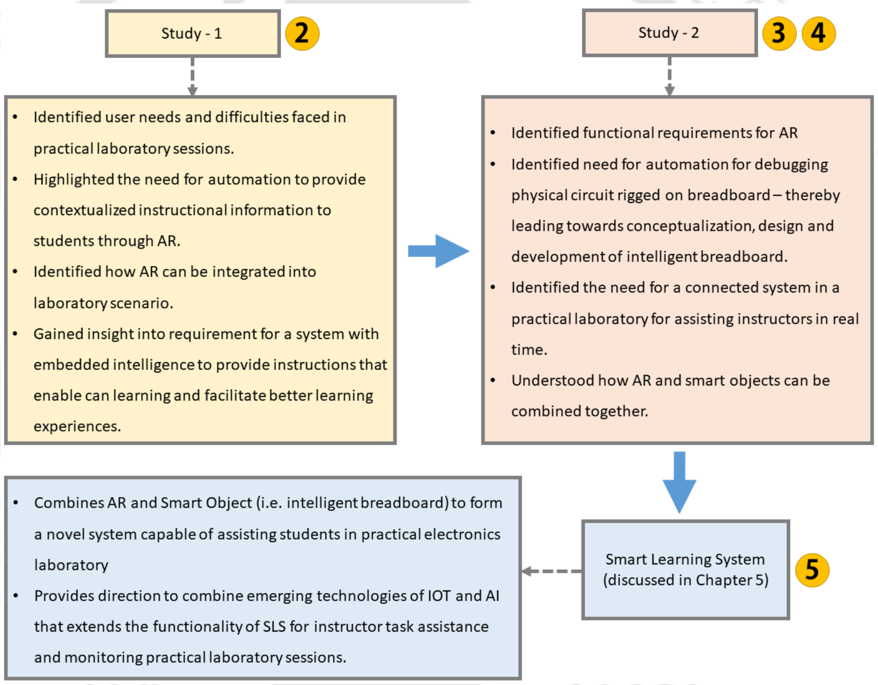


Figure 4.19 Complete overview of the findings from user research studies.

Based on the findings from studies, we proceeded towards the development of SLS prototype that synergistically combines AR and smart objects along with other emerging technologies of AI and IOT to work for the benefit of students and instructor in practical laboratory sessions.

One of our limitation during the development was resource constraints, due to which we developed lightweight prototypes to demonstrate the utility of novel aspects of our prototype. We especially faced challenges in developing the content for AR, which requires a lot of time and effort – in terms of developing 3D models, animating them and adding interactivity through software. Therefore, we used scenarios and mock-ups during design experiments (i.e., research stage 6 and 7, see Figure 3.3 for reference), along with our SLS prototype to explain to users how the end product will be like along with all its features and functionalities. Scenarios play an vital role in the evaluation of novel systems in a ubicomp scenario that is under constant design and development phase as the technology is often not well understood by developers (Abowd & Mynatt, 2000). We delivered various use-cases as scenarios during demonstrations of our prototype to student users to help them understand the primary goal of our product that was designed to assist them during practical laboratory sessions. Figure 4.20 summarizes and depict the design-develop-evaluate cycle for our prototype that resulted from our continuous interactions with users throughout the design process and design experiments.

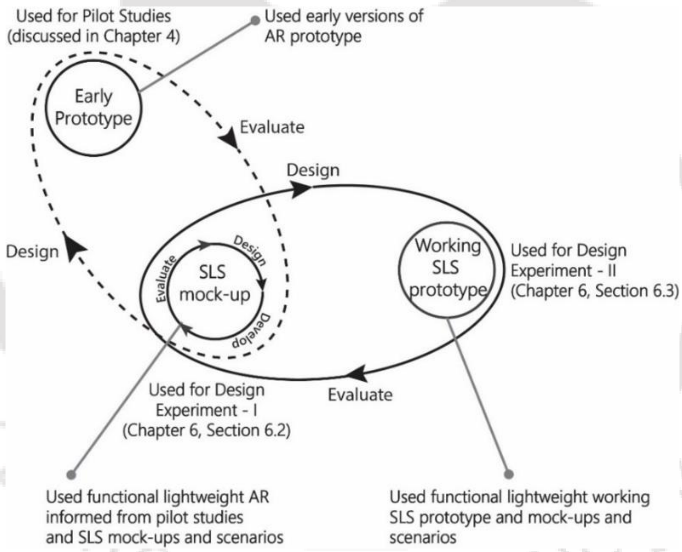


Figure 4.20 Design-develop-evaluate cycle of our prototype that resulted from UCD approach.

The cycle defines the challenges faced in developing applications for users in complex situations using a UCD approach in ubicomp scenario. Similar challenges have also been highlighted by Edwards, Bellotti, Newman, & Dey, (2003) that describe the iterative and complex nature of development process that results from UCD approach for understanding the use of cutting-edge technologies, whose working is often not easily understood by designers or developers, in various application contexts.

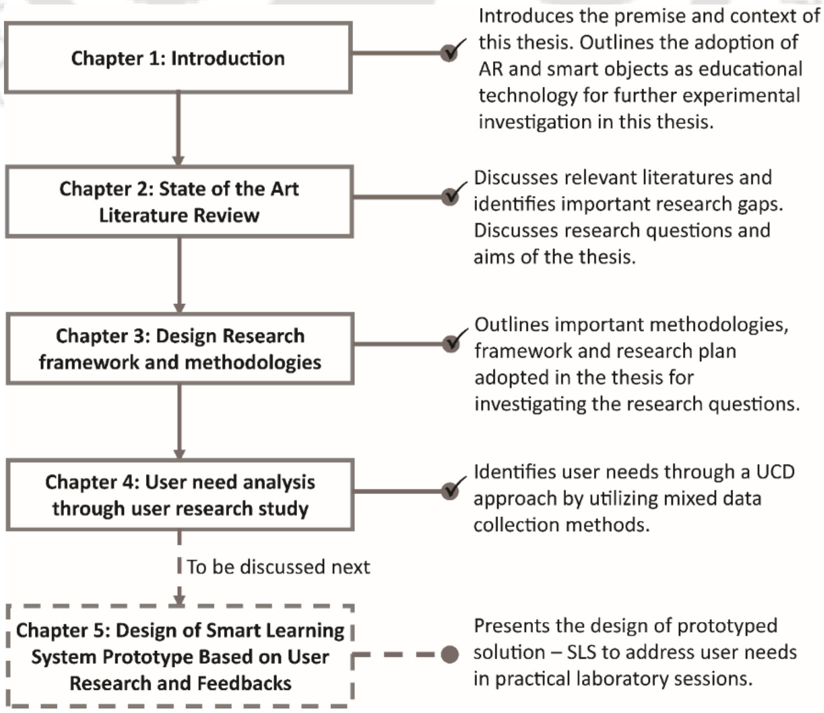
The SLS mock-up comprised of a lightweight, functional AR with mock-ups of the intelligent breadboard and IOT scenarios of its use in practical laboratories. The SLS mock-up was utilized during the first design experiment (DE - I) using Wizard of Oz technique and cognitive walkthroughs. The second design experiment (DE-II) was carried with the final version of lightweight working SLS prototype that was demonstrable to the users. Chapter 6 presents a detailed discussion on design experiments.

4.6 Chapter Summary

The chapter discusses user research studies conducted for the user need analysis and gathering design requirements. Various UCD methodologies like contextual inquiries, interviews, and scenario-based design were adopted for this experimental investigation. Early AR prototypes were developed and tested amongst users in live electronics laboratory sessions. The feedbacks provided further directions to help conceptualize, design and develop a smart learning system. The following Chapter 5 discusses the design of complete SLS prototype.

A quick recap of previous chapters:

A visual summary of the chapters covered so far is provided as follows:



Chapter 5: Design of Smart Learning System Prototype Based on User Research and Feedbacks

Chapter Abstract: This chapter discusses the working of an SLS prototype designed based on user feedback received from user research studies. Functionalities and features of AR and intelligent breadboard, that form SLS, have been discussed.

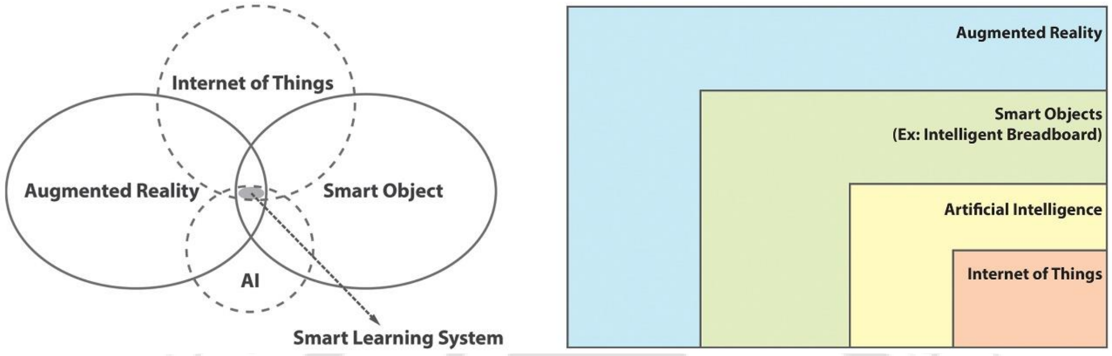
5.1 Introduction

Based on the findings and insights from user research studies, a lightweight working prototype was developed as a proof-of-concept to demonstrate how future learning systems for practical electronics laboratory sessions can be conceptualized and designed based on Mark Weser's vision of ubiquitous computing (Weiser, 1991). To achieve this, we adopted mobile augmented reality (AR) and utilized the concept of embedding commonly used objects in the laboratory with computational capabilities – based on the concept of "The MediaCup" (Gellersen et al., 1999). Such physical objects, with embedded computational and sensing capabilities, are referred to as Smart Objects (SO). AR was adopted owing to its potential to enable real-time interaction between the user, real objects and virtual objects (i.e., digital data).

Secondly, during user research studies it was observed that students mostly carry digital tablets or smartphones, laboratory manual and a journal to maintain records of the experiment during practical laboratory sessions. Therefore, mobile AR provides a cost-effective and easy to deploy way to instruct and assist students in laboratory employing already existing mediums of smartphones and digital tablets. By utilizing the concept of SO, natural affordance of physical objects can be utilized which does not create an additional learning curve on an already burdened learner in the complex environment of a practical laboratory. The SO also affords tactual interaction by retaining the physicality that helps promote better hands-on learning experience.

By coupling AR and SO, and utilizing a few features and functionalities of the Internet of Things (IoT) and Artificial Intelligence (AI), a Smart Learning System (SLS) was conceptualized and developed that could assist students effectively in practical electronics laboratory sessions and facilitates teaching. Here, we would emphasize that our

AI design is for a set of static, deterministic conditions within well-bounded situations and utilizes if-else conditional expressions for making decisions. The topic of embedded AI and its design will be discussed later. Figure 5.1 (a) depicts the synergies between different technologies adopted and integrated into the prototypes conceptualized and developed as a part of this thesis.



(a) **(b)**

Figure 5.1 Technological synergies and dominance of our proposed system. (a) Smart learning systems synergistically combine the functionalities and features of augmented reality, smart objects, internet of things and artificial intelligence to assist students in their tasks during practical electronics laboratory session. (b) Dominant technological spaces utilized in the smart learning system. The prototype predominantly utilizes augmented reality, followed by smart objects, artificial intelligence, and the internet of things.

The working SLS prototype mainly consists of AR and SO. Figure 5.2 shows a basic block diagram of its main components.

Figure 5.2 Smart Learning System components block diagram

During the design process of the prototype, laboratory course instructors were also interviewed to gain understanding regarding their needs and perspective on the use of technology in practical laboratory sessions. The insights from these interviews paved the way for the conceptualization of a system that also augments human tutoring and teaching. This led towards adopting the concept of IOT and its potential to implement AI for a large scale. Overall, the goal of the conceptualized system is to have a combined effect on improving student's activity in the laboratory, their cognitive functioning in terms of reducing workload, teacher's role and overall classroom dynamics. We believe that in such complex practical laboratory sessions, education technology should be able to balance both didactic and exploratory component of learning – thereby leading to a holistic experiential learning and teaching.

The proposed prototype (see Figure 5.6) is based on several layers of technological concepts that have explicitly been adopted from a user-centred design perspective to aid usability and utility during learning and teaching. Figure 5.1 (b) describes the technological spaces of SLS prototype concept which predominantly utilizes AR followed by the use of SO. Here a commonly used breadboard was chosen to be converted into a SO by embedding computational capabilities to it. This SO is referred to as an 'intelligent breadboard' – which was developed as a proof-of-concept to show how can existing artifacts from laboratories be adopted and made 'smart' to assist users.

Next, we considered the use of AI that can assist students in a manner similar to that of a human tutor – by encapsulating instructor's tacit knowledge and instruction patterns. We have considered AI that looks at learning from a contextual viewpoint, i.e., it is cultural and from a background of students and is only a layer in the whole scheme of things. Here, we contend that the design of AI embedded into the system should be such that it can pinpoint:

- Where is a student going wrong/ committing errors?
- Why is he/ she going wrong?
- Which concept do they need to learn to understand such case?
- How to prompt instructions through which students can derive learning on their own, self-reflect upon their actions and gain the ability to understand where they are going wrong and why they are going wrong?

Finally, we would at this point also make it clear that our final design solution to the identified need is an AI-enabled product that augments users' ability to work in the complex learning environment. We are not utilizing any AI algorithm but instead proposing a method utilizing UCD approach to design AI-enabled tool.

Lastly, we have adopted an IOT approach, which allows us to conceptualize how we can upscale this system so that it can accommodate the needs of the instructors as well as the students by enabling real-time data sharing and visualization. Therefore, by combining all the above layers of technology, our prototype provides an agile method for improving the learning experience in complex educational environments where sluggish process hampers learning. In a large-scale scenario, this system will provide quality of learning content to students. An elaborate discussion on such a scenario is carried out later on in this chapter. Privacy issues of such system fall in future work considerations.

5.2 The basic working of Smart Learning System Prototype

The SLS prototype consists of four modules that are used together in conjunction. These are highlighted below:

- A mobile augmented reality prototype module for visualizing instructions,
- A smart object – for which we designed an intelligent breadboard as a proof-of-concept,
- An AI module that provides on-screen instructions supplemented by voice regarding the practical experiment,
- A conceptualized scenario and instructor interface utilizing IOT, which helps in accessing teaching methods, activity, and learning of students in real-time.

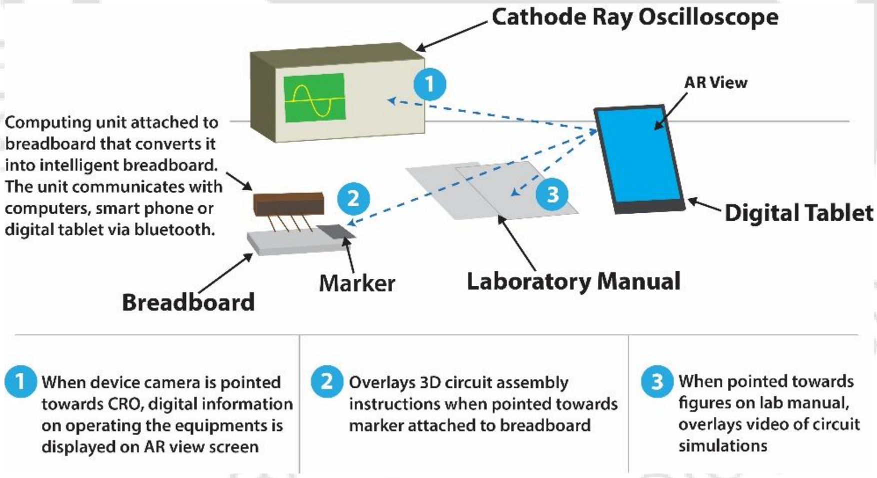


Figure 5.3 Basic setup of the smart learning system. When the camera of the mobile device is pointed towards various laboratory object, AR-based instructions are provided to students. A computational unit is attached to the breadboard that converts it into 'intelligent' breadboard that is able to identify mistakes or errors made during circuit prototyping.

Figure 5.3 depicts a basic setup of SLS and the working of AR prototype module. The mobile AR prototype provides active visualization to students by overlaying digital information regarding circuit assembly on a breadboard, operating test equipment like cathode ray oscilloscope (CRO), and, on-spot videos regarding theoretical aspects of the experiment on real-world scenarios. The application utilizes both marker and marker-less tracking techniques to overlay digital information such as 3-dimensional (3D) or 2-dimensional (2D) graphics, images, and videos onto real space.

When the camera of a smartphone or digital tablet is pointed towards a marker attached to a breadboard, or figures on a laboratory manual, or towards a CRO, instructions are overlaid onto real space in the form of 3D figures, 2D images, videos, text or sound. This helps students get contextualized instructions (see Figure 5.4 (a), (b), (c), (d) below).

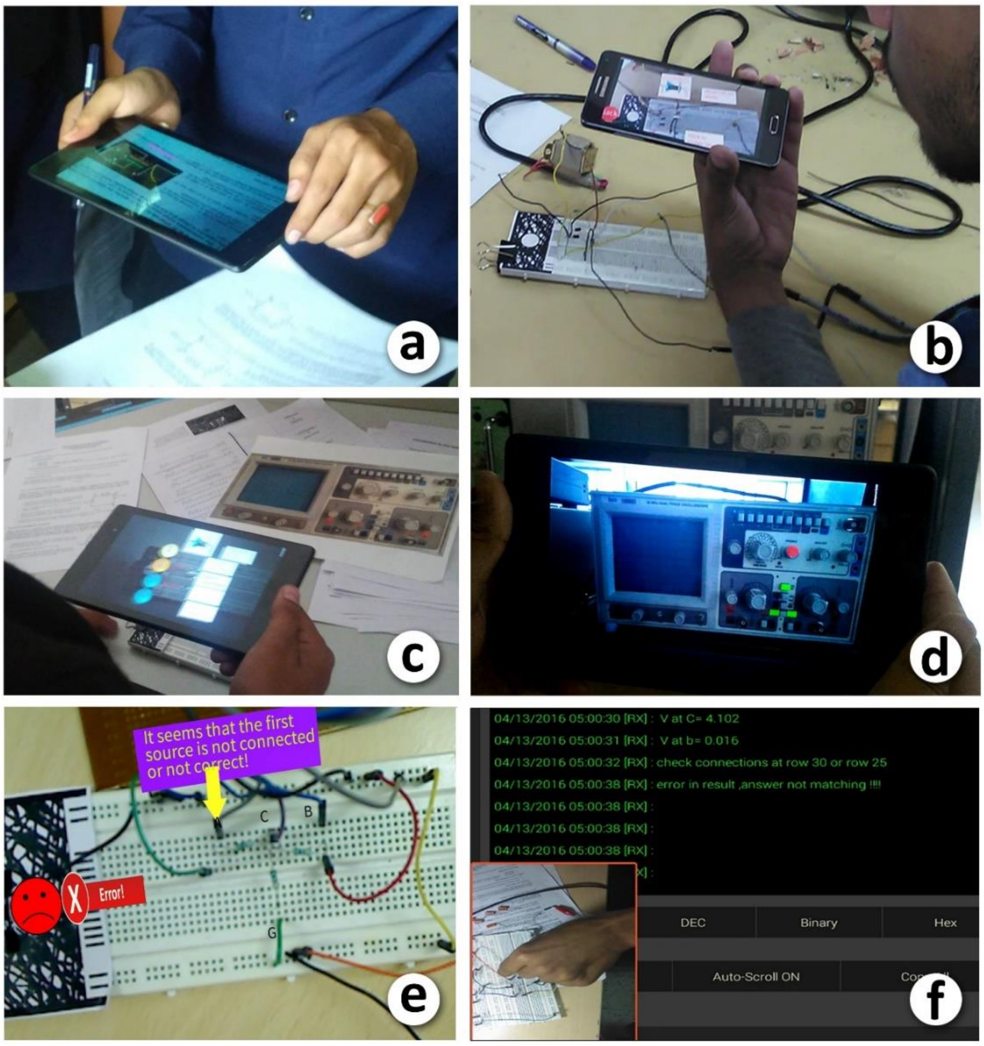


Figure 5.4 Augmented Reality and intelligent breadboard. (a) Video instructions overlaid on a lab manual, (b) Breadboard attached with marker, (c) Close-up view of the 3D graphics overlaid on a breadboard, (d) Operating instructions for CRO, (e) AR based instructions provided by intelligent breadboard on a computer screen. The exact location of mistakes or errors committed by users on the breadboard are pinpointed via AR, (f) Snapshot of instructions provided by intelligent breadboard on digital tablet.

The second module, i.e. the intelligent breadboard, senses the types of errors or mistakes that occur during prototyping of electronic circuit. These mistakes are sent via Bluetooth to our designed AI module that can be loaded on a computer or digital tablets or smartphones as a software. Based on the error or mistake received, the AI module provides required set of instruction to students to assist them with the assistance and continuation of the practical experiment. These instructions are delivered simultaneously to students on mobile screens in the form of text view and supplemented by voice and text (see Figure 5.4 (e)). Literature (Wang, Zhao, Qiu, & Zhu, 2014) on effect of emoticon in computer mediated communication was considered while designing the interface for SLS, as represented in Figure 5.4.

The system also displays, via AR view, the exact location of mistake that has happened when the device camera is pointed towards the breadboard Figure 5.4 (f). Figure 5.5 represents a basic block diagram of the intelligent breadboard process flow. We specifically designed a computational unit that could be attached with any existing breadboard to turn it into an 'intelligent breadboard' (as depicted in Figure 5.3). Further, the data on the nature of circuit errors made by students is sensed by the intelligent breadboard is also sent to instructor's interface on a digital tablet via the Internet in real time to facilitate teaching feedback by the instructor to the student. This aspect of the prototyped system will be discussed later in Section 5.4.

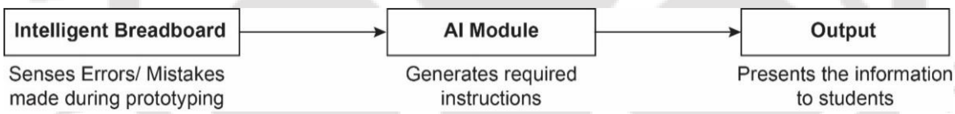


Figure 5.5 Basic flow of an intelligent breadboard module of smart learning system prototype

Overall, the functionalities of our SLS prototype includes:

- Sensing errors and predicting mistakes made during experimentation by students while they rig up while making electronic circuits on breadboards.
- Provide voice, text-based and AR-based feedbacks to students to rectify their mistakes and knowledge shortcomings via their smartphone or digital tablet mediums.
- Provide contextualized – on the spot- just-in-time, information to students such that errors made during learning become prompt for self-evaluation and self-tutoring.
- Provide active pre-visualization of specific concepts of practical experiments using mobile AR as part of pre-experimental preparation.
- Provide contextualized instructions to operate equipment and test instrument in electronics lab using AR in the form of 3D visuals close to reality.

- Provide step-wise circuit building instructions to students using AR.
- To enhance collaborative learning effort amongst peers while they conduct lab sessions in groups.
- To reduce the load on tutors and overloading of institutional infrastructure facilities and maximize teacher's teaching time.

The complete technical details of SLS prototype, which consists of AR and intelligent breadboard module, can be found in Annexure E. Figure 5.6 depicts the complete setup of SLS prototype.

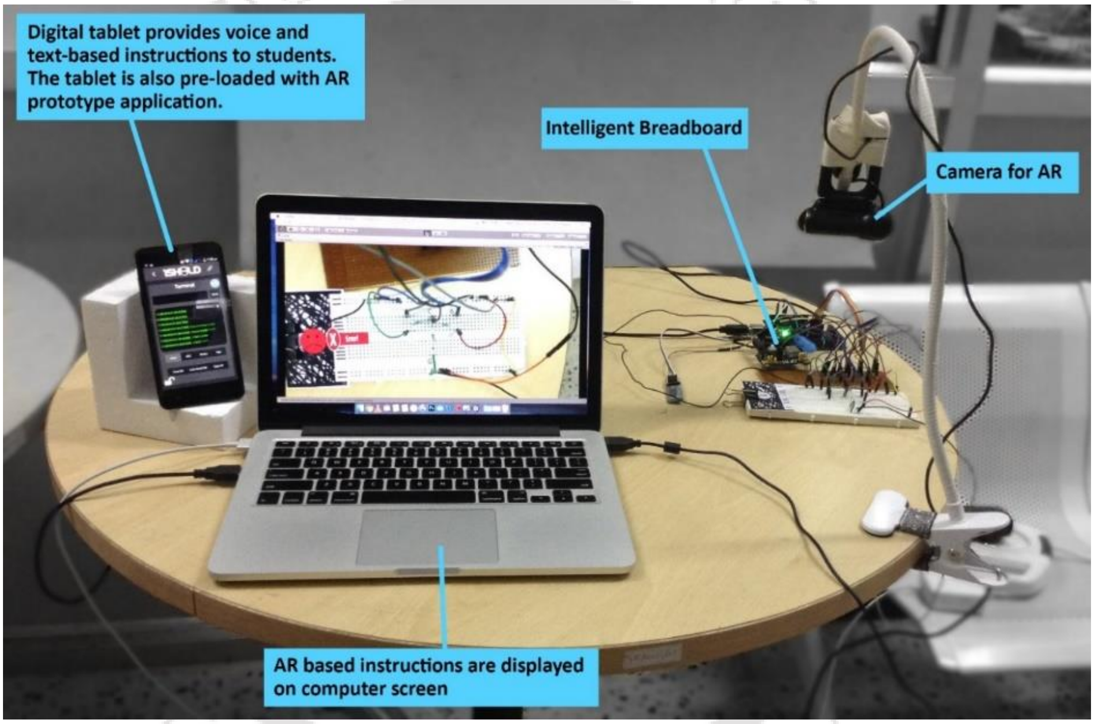


Figure 5.6 Complete setup of Smart Learning System. The prototype part of the intelligent breadboard is seen below the camera. The instructions are provided by the breadboard via digital tablet using voice and text-based modalities. Exact mistakes made by users while operating on the breadboard are shown on computer screen. The digital tablet is also pre-loaded with the prototyped AR application that assists students with various experimental tasks.

We will now explain the functionalities and features of AR prototype application followed by the features of the intelligent breadboard. Design guidelines for embedding intelligence into the SLS has been discussed in Section 5.3. Based on these guidelines the AI module was designed that could help instruct students in practical experiments. The intention was to embed intelligence into the system in a manner such that it can assist students like a human tutor.

5.2.1 Design of functionalities and features of the AR prototype based on insights from studies

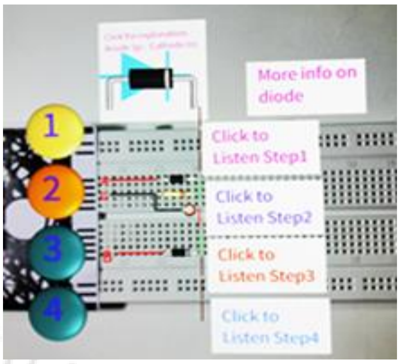
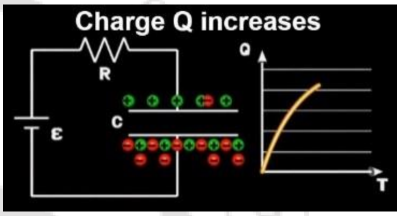
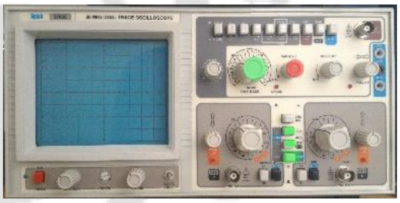
The functionalities and content of the AR application were designed based on the findings from user research studies by mapping them to each student activity during experimenting, as identified from interaction analysis (discussed in Chapter 4: Section 4.2.2). Table 5.1 depicts these functionalities.

Table 5.1 Mapping user requirements to AR prototype functionalities.

Experiment Stages	AR functionalities/ content	Description
Referencing	Animated simulation videos	The user refers to laboratory manuals for understanding procedures to follow or theory behind the experiment. AR augments this step by overlaying videos that explain the theory or animation
Assembling	3D circuit assembly guide	In this stage, the user assembles and connects various electronic components on a breadboard and connects them to test equipment. Sometimes translating complex 2D circuit diagrams is difficult for users in 3D. Providing 3D graphical representation of circuits helps in assembling and verifying circuits.
Operating Test Equipment	Equipment operation guide	After assembling, the user provides different inputs to the circuit (such as voltage or current, etc.) and measures the characteristics on an output device such as a CRO. As many users find it challenging to operate CRO, AR helps in bridging this difficulty for easy understanding.
Reporting	Screenshot, Sharing	Users make continuous note of the readings or capture data by taking photos. Our prototype can help them do this without being able to switch between camera mode and AR mode.

Table 5.2 represents the tracking used by our AR prototype along and overlaid content onto physical objects in practical electronics laboratory.

Table 5.2 Tracking techniques and virtual data used in augmentation of physical objects.

Object	Tracking	Description	Screenshot of overlaid virtual data
Breadboard	Marker-based. Tracks marker attached to the breadboard	Overlaid 3D graphics of full wave rectifier circuit. Displayed 3D models of various electronic components and their internal structure. 3D circuits were made for two experiments – RC circuit and Full-wave rectifier (see Annexure D).	
Laboratory Manual	Marker-less. Tracks natural features such as circuit diagrams of laboratory manuals.	User was presented with videos on RC, RL and RLC circuit working. The videos displayed the flow of through these circuits as well as their transfer characteristics and phasor diagrams. (see Annexure D)	
Cathode Ray Oscilloscope	Marker-less. Tracks natural features of CRO control panel.	Overlaid 2D buttons (shown in green and red) on the interface which when clicked played voice based instructions that explained various features on CRO control panel.	

During user studies, we identified that students often take pictures of the assembled circuit, output waveform from CRO, etc. for later use such as reporting the results, sharing details of experiment with friends or during the revision of the experiment before practical exams. We, therefore, added the functionality for taking a screenshot (or picture) from within the app and add annotations to it. This feature will prove helpful for AR applications in educational applications.

We also observed that although this feature is commonly available for commercial application, literature survey on the use of AR in educational scenarios did not report any such findings or functionality. Therefore, although evident, we found it fitting to embed and report such functionality for AR based applications that are designed for complex learning environments.

We also observed that students' value instructors feedback and carefully adhere to their advice in practical laboratories sessions. Instructors provide structured information to students during practical experiments that are not available on the internet. They reinforce students' learning by asking inquiry-based questions that enable them to think creatively. Although the internet is a good medium, it is unstructured and consumes much time to search for the desired information. AR has a potential to provide contextualized information. This information, if it encapsulates as instructors experiential or tacit knowledge, will be beneficial for students during experimentation activity. To capture this experiential or tacit knowledge of instructors, think-aloud sessions were conducted for two experiments to capture instructor's knowledge, and task flows were generated which consisted of instructional prompts and inquiry-based questions, see Figure 5.7.

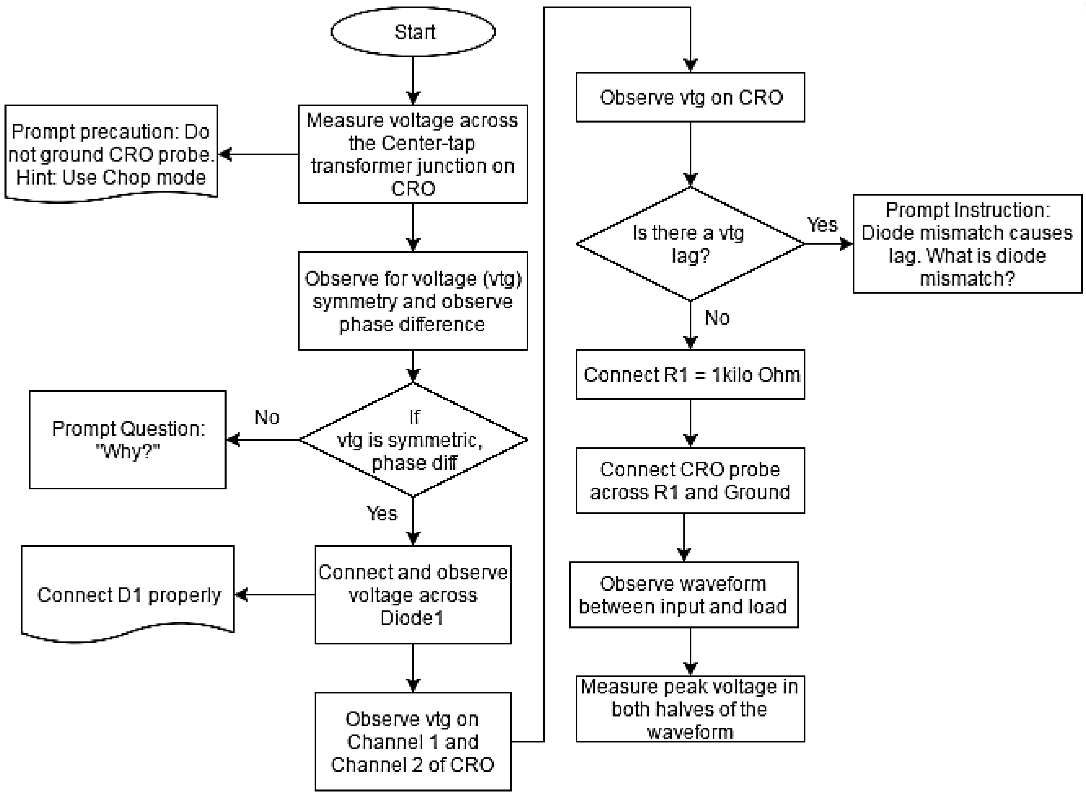


Figure 5.7 Task flow diagram for a full wave rectifier experiment embedded into AR

A group of such task-flows formed an instructional database which was embedded into AR module and SLS**.** Further discussion on how these task-flows are used for embedding intelligence will be placed later in this chapter. Figure 5.8 shows the functional block diagram of the AR module

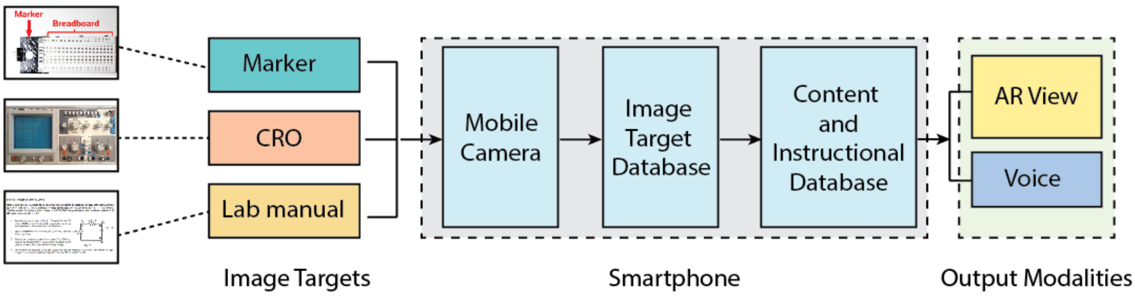


Figure 5.8 Functional block diagram of AR prototype along with image targets used.

To understand how virtual data can be overlaid over physical objects in the laboratory so that it acts an instructional medium as well provide a usable AR experience, we built several conceptual scenarios and wireframe diagrams, see Figure 5.9.

(a) **(b)** **(c)**

Figure 5.9 Stages of AR prototype development. (a) Conceptual sketch for representing information during different stages of experimental activity. (b) The concept of using AR view with CRO. (c) Wireframe of the AR module functionalities.

Wireframes provided a blueprint to help layout important user interaction elements on AR interface. Four functionalities were decided to be made available for users based on the observations from our studies on the use of AR prototype in a laboratory session. These are, (i) Flash button – which turns on smartphone's flashlight to enable user work in low light situations. As students often work in a small group of 3-4 closely, they often tend to shadow the marker. Sometimes laboratory setting is not able to provide sufficient lighting conditions for effective tracking. (ii) Screenshot button – as discussed previously, this functionality allows users to record data by capturing photographs via AR module. (iii) Share button – allows the user to share the screenshots or pictures taken from AR module with their peers or instructors via the internet or Bluetooth. (iv) Switch between voice and text-based instructions (as seen in the lower left corner of the wireframe). Student feedback from the study suggested that text-based instructions are suitable in a laboratory environment, but they can use voice-based instructions when working independently on their own. Annexure E2 presents some initial concepts and wireframe diagram of AR prototype.

The menu items conceptualized were (i) Simulation mode – that enables students to simulate virtual 3D circuits in real-time. This feature was introduced to remove the fear of getting electrical shocks or from short-circuiting the setup. (ii) Interaction log – records user's interaction with the virtual data, such as counting the number of times a user has interacted with the information presented on AR view. This featured allowed our AR module to become a part of IOT. (iii) Connect to Smart Objects – allows the user to establish interaction between AR module and smart objects (e.g., the intelligent breadboard) to allow them to use both in conjunction. A discussion on interaction log and connecting with the smart object will be presented later on in Section 5.4.

The 3D content was generated using Sketchup (SketchUp, n.d.) and consisted of (i) 3D circuit arrangement for various experiments like RC circuit and full wave rectifier, (ii) 3D electronic components such as diode, capacitors, (iii) Text-overlays and (iv) Circuit assembly instructions. The 3D instructions were primarily made for helping students with circuit assembly on a breadboard. The instructional prompts were provided to students in the form of voice. Videos regarding electron flow in a Resistor-Capacitor circuit, capacitor charging and discharging and phasor diagrams (Boylestad & Nashelsky, 2012) were used to explain theoretical concepts of the experiment and augmented the laboratory manual. Operating instructions regarding different functionalities of CRO were used as voice based instructions to assist users in operating CRO.

Figure 5.10 and Figure 5.11 represent the interaction flow diagram and the information architecture of our AR prototype.

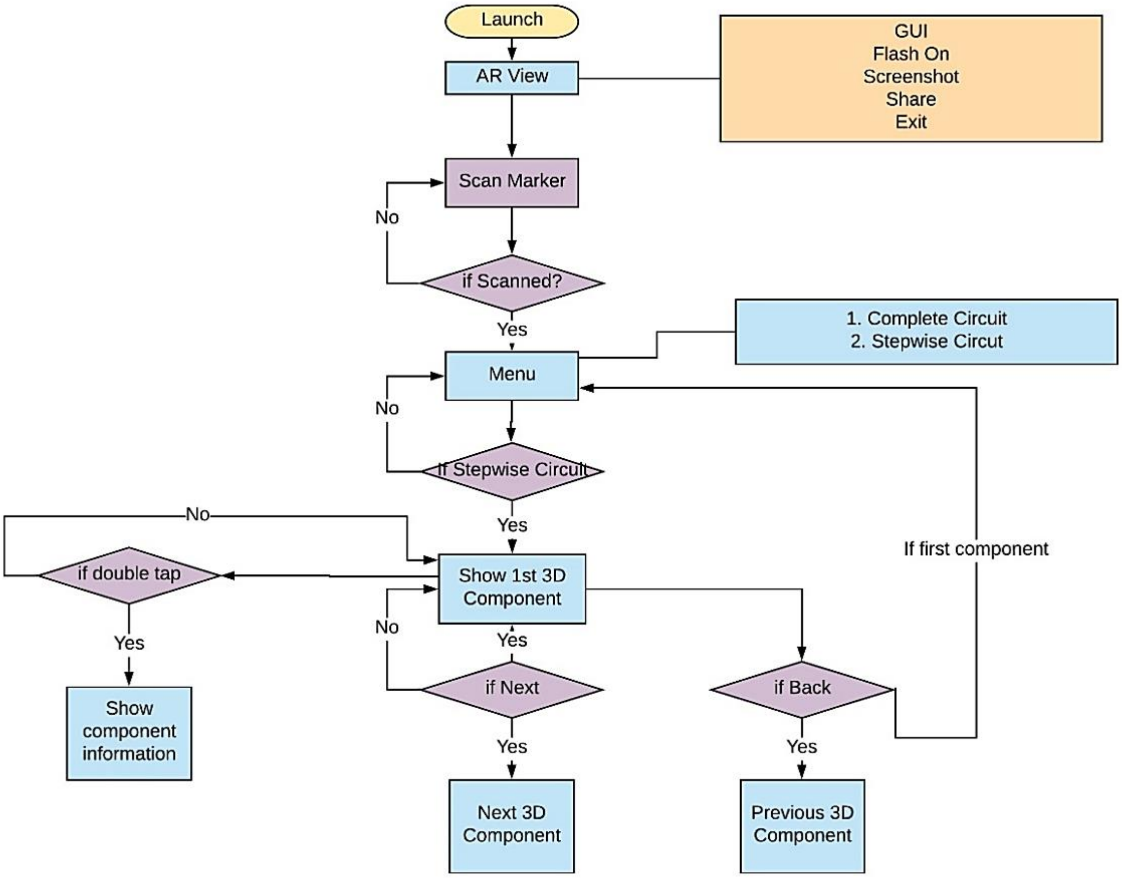


Figure 5.10 A section of interaction flow diagram of AR module.

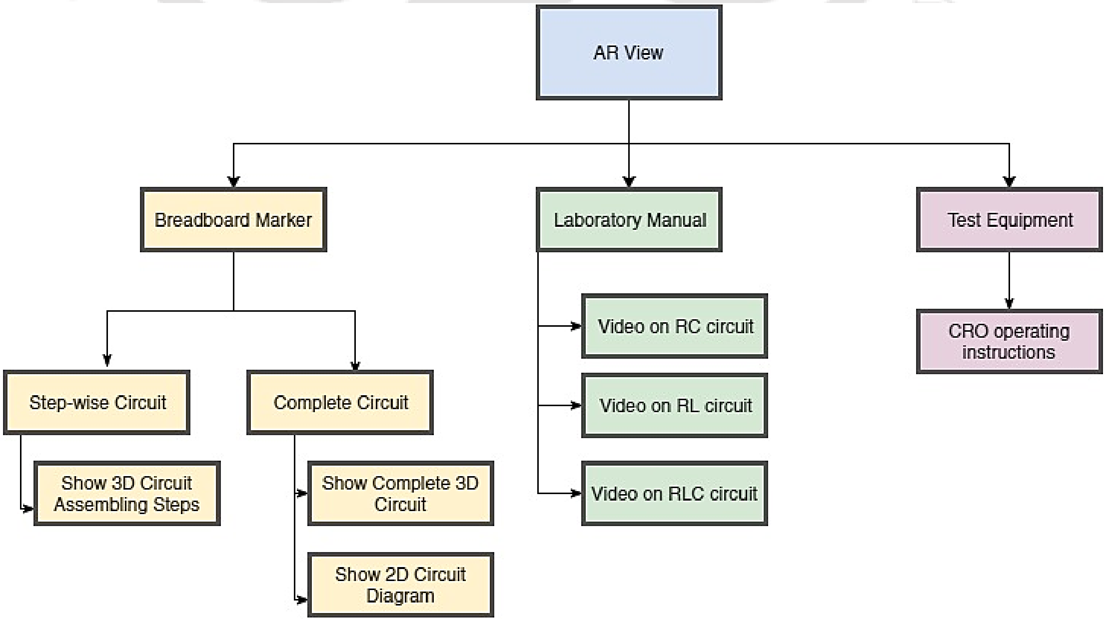


Figure 5.11 A basic information architecture of AR application.

To further aid usability and help students working on circuit assembly with debugging of circuits, an assistive instructional AI was embedded in the breadboard that sensed input and nodal voltages of the circuit. This breadboard is referred to as an intelligent breadboard and can communicate with user's smartphones or digital tablet via Bluetooth. The tablet/ smartphone acts as a mediator to provide information through text and voice-based instruction regarding errors made by users. The following Section 5.2.2 presents a detailed description of the development of intelligent breadboard prototype.

5.2.2 Design of intelligent breadboard and providing instructions to users

One of the aims of this thesis was to understand how commonly used artifacts in practical electronics laboratory session can be embedded with computational capabilities to assist users. For this, breadboard was chosen, as it is the most commonly used equipment on which students learn to prototype electronic circuits, master troubleshooting and take measurements. It is also one of the most problematic equipment reported in terms of debugging by the students. As a proof of concept to show how these computational capabilities could be embedded into a breadboard, we developed an 'intelligent breadboard.' For this, we developed a hardware module that can be attached to any breadboard to convert it into an 'intelligent breadboard.' The prototyped solution was designed for a specific use-case, i.e., Superposition theorem practical experiment (refer Annexure D3 for the experiment details), which is commonly given to first-year undergraduate students who undergo practical electronics laboratory sessions.

To embed error-sensing capabilities into our intelligent breadboard module, we observed how instructors troubleshoot and debug problems that arise during physical circuit prototypes during think-aloud sessions, as mentioned in Section 4.4. The following process briefly explains this:

- The foremost thing we observed was that instructors first make sure all the connections made on the breadboard are tight.
- Second, the power supply and the ground should be connected appropriately.
- Divide and conquers rule – debug the circuit systematically.
- A good practice, as suggested by the expert-users, is to use two different rails on a breadboard for power supply and ground (GND) to avoid confusion. This also keeps a circuit manageable for debugging.

- Try your best not to make messy connections.
- Use of proper colour coding while wiring the circuit, i.e., use red for power, black/ brown for ground.
- Check for shorts using a continuous mode on digital multi-meter. Check the voltage at each node of a circuit using a multimeter.
- In many cases, especially when dealing with active components like transistors, use CRO.

Based on these insights, we decided to adopt the method of measuring node voltages of a circuit as it was well within our prototyping reach and could be made using readily available off-the-shelf electronic components. Further, as we were implementing a proof-of-concept lightweight prototype to demonstrate our proposed use case of making lab artifacts smart, a nodal analysis method was a quick and easy way to debug help resistive electrical network circuits like superposition theorem – for which the prototype was developed.

We designed a sensor module that could sense and compare voltages at different nodes of the electronic circuit prototyped onto the breadboard. After comparisons of voltage between nodes, the module can sense the type of mistake that occurs on the breadboard for that particular circuit. The module can detect overvoltage, loose connections on breadboard, source or input voltage and nodal voltages. Figure 5.12 presents a block-diagram of the intelligent breadboard prototype. The hardware details have been described in Annexure E.

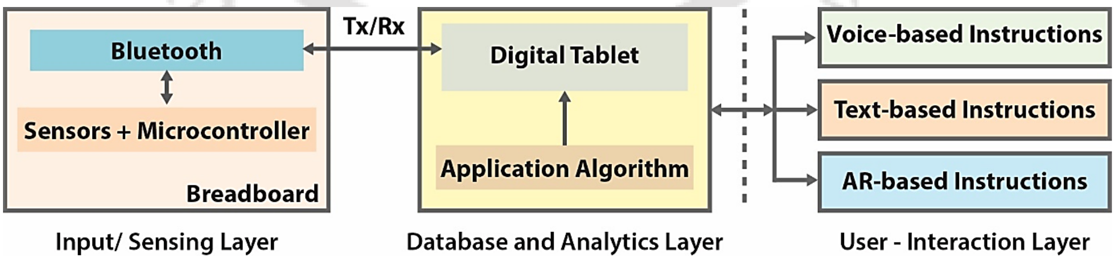
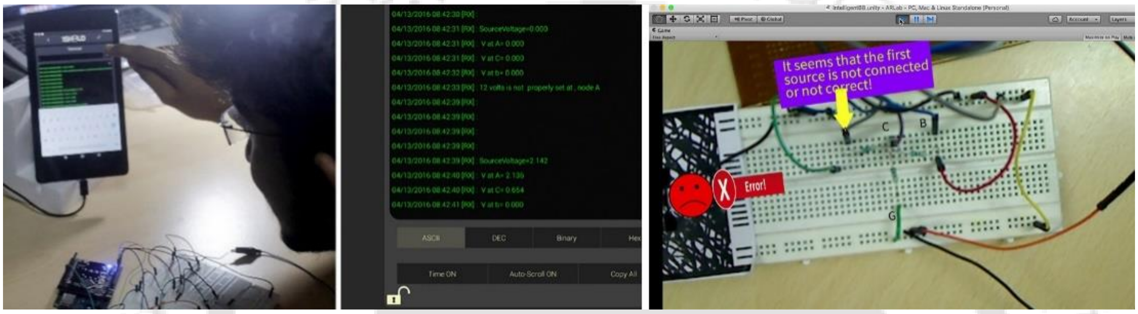


Figure 5.12 Block diagram showing the working of the intelligent breadboard.

Based on the type of errors sensed by the intelligent breadboard, corresponding instructions are generated for the user. Figure 5.13 depicts screenshots of instructions presented to the user via tablet screen and AR view of computer presenting instructions to the user. These instructions are provided to the user through text-based and voice-based functionalities on a smartphone and via AR view on a personal computer (see Figure 5.13 (c)). A set of pre-defined instructions are embedded into the code on microcontroller attached to the intelligent breadboard. The code triggers these instructions when the sensor module senses a particular mistake/ error. In case of instruction via AR, a Bluetooth serial communication is established between intelligent breadboard and the computer software. Based on the types of errors sensed, 3D instructions are augmented on the breadboard via AR view.



(a) (b) (c)

Figure 5.13 Screenshots of instructional prompts from intelligent breadboard setup. (a) A user is interacting with the screen based interface on a smartphone. (b) Errors and instructions are displayed on the screen of a smartphone. (c) AR interfaces on a personal computer to provide instructions by tracking mistakes on each row of the breadboard.

The instructions presented on a tablet screen (see Figure 5.13 (b)) are “check connections at row 30 or row 35, answer not matching”. These text-based instructions help users to troubleshoot their mistakes while electronic prototyping. Figure 5.13 (c) shows AR based instructions that pinpoint the place where the user has made a mistake.

The following pseudo-code, Figure 5.14, partially defines the steps used to detect loose connection on a breadboard for circuit debugging. Our primary aim was to design the type of intelligence such that it can guide students in practical laboratory session in a manner similar to that of a human tutor. For this, the system should be able to not only deduce the type of mistakes made by the student but also be able to provide prompts that can guide them through learning. Therefore, we adopted to integrate the feedbacks of user research into our codes. Detailed discussion on this approach has been presented in Section 5.5 that follows. Figure 5.15 describes a pseudo-code of circuit debugging algorithm utilized by SLS.

```
Algorithm circuit-debugging for loose connection is

Input: Check connection on breadboard

Output: Voice, text and AR based prompts

for each circuit connection on breadboard do

    scan for loose connections by comparing node voltages with predefined
value

if node voltages match predefined values on breadboard do

Output: Good work using voice, text and image prompt

elseif node voltages do not match predefined values on breadboard do

check database for required set of instruction for the mistake

Output: Instructions using voice, text and AR prompt
```

Figure 5.14 Pseudo-code describing a segment of circuit debugging algorithm.

```
Terminal.println ("what will be value resistance between node A and C if Vc
= 2.222 V?");
   Terminal.println ("A. 2.2 K.ohm");
   Terminal.println ("B. 1.1 K.ohm");
   Terminal.println ("C. 5.6 K.ohm");
   Terminal.println ("D. 4.6 K.ohm");
       .
       .
       .

   if(Ans=='a')
   {
     Terminal.println("You are correct !!!");
     Terminal.println("now you can proceed to next part");
   }
   if(Ans=='b' || Ans=='c' || Ans=='d')
   {
    Terminal.println("Sorry, wrong answer! Please read more about circuit
analysis in Chapter 3 of your course book.");
    }
```

Figure 5.15 A segment of code depicting the type of instructions asked by intelligent breadboard to the user.

Having described the functional aspect of our prototyped solution, we now proceed to understand the rationale behind developing an embedded intelligence component using a UCD approach. The following section presents this discussion.

5.3 Design Heuristics for Embedding Intelligence

5.3.1 Mapping Errors and Instructions to Experimental Task-Flow

Through interaction analysis, (discussed in Chapter 4: Section 4.2.2), laboratory activity of students for experimenting has been broadly categorized into four steps (refer to Figure 5.16).

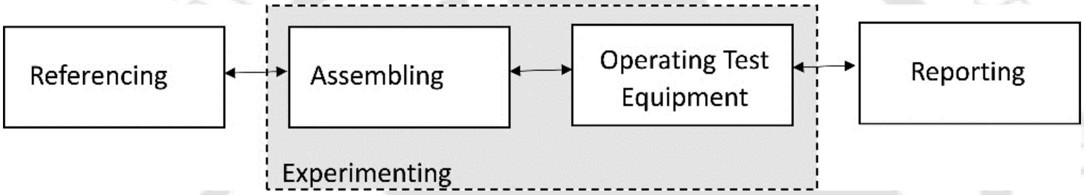


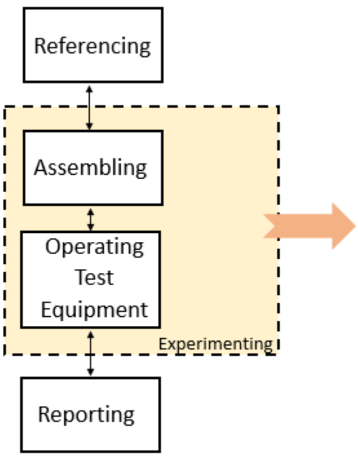
Figure 5.16 Block diagram of students' activity in a practical lab session. Assembling and operating test equipment form a significant part of this process.

It is during assembling and operating test equipment stages that significant errors or mistakes are made by students that increases their effort, mental demand, and frustration levels. As observed from videos, interviews, think-aloud sessions and open-ended questionnaire, such errors can be classified into four categories. These are – (i) Physical errors, (ii) Perceptual errors, (iii) Theoretical errors and (iv) Technical errors. Physical errors and perceptual errors can partly be categorized under the interactional errors, i.e., errors that happen while interacting with the experimental setup. While not all physical errors contribute to mistakes made by students (e.g., loose connections), wrong connections or placement of components does. Perceptual errors are mostly visual. These can occur during any of the four stages of experimental activity. However, while conducting a practical experiment, they happen when students visually misperceive connections or components. Table 5.3 describes these errors mapped to students' activity in a practical electronics lab.

Table 5.3 Types of errors made by students while doing practical experiments mapped to the activity.

Type of Error	Description	Activity
Physical	Break in connection not visible to human eye, Loose Connections, Wrong arrangements of components.	Assembling, OTE
Perceptual (Visual Perception)	Wrong Connection, Use of faulty electronic component.	Referencing, Assembling, OTE, Reporting
Theoretical	Wrong understanding regarding electronic component, test equipment or experiment.	Referencing, Assembling Reporting
Technical	Faulty lab equipment and objects	Assembling, OTE

Figure 5.17 below depicts various modes of interaction and different modalities through which it is possible to address various difficulties experienced during experimenting phase.



Type of Errors	Description	Interaction Modality	Type of Interaction
Physical	• Break in connection not visible to human eye • Loose Connections • Wrong arrangements of components	Augmented Reality + Smart Object (SO) • AR for pointing errors • SO sends data to AR application regarding errors	Mobile AR-User Interface (AR-UI) + Tangible User Interface
Perceptual (Visual Perception)	• Wrong Connection • Use of wrong electronic component		
Theoretical	• Wrong understanding regarding electronic component, test equipment or experiment	Augmented Reality • Visualizing working and practical applications	AR – UI
Technical	• Faulty lab equipment and objects	• Augmented Reality based operating manual for students • Intelligence embedded during manufacturing process to detect technical fault with equipment	AR – UI + Product Interface (e.g. control panels with notifications)

Figure 5.17 Guidelines for embedding intelligence through various modes on the interaction of AR, smart objects, and product interfaces.

We posited that if a system can guide students through this process while minimizing the number of trial and error efforts required in debugging circuits or operating test instruments, an effective learning experience can be created for students. Such a system would then be capable of reducing the amount of frustration and cognitive load of students.

Studies (Sweller et al., 1998; Van Gog & Paas, 2008) from cognitive science show that for knowledge assimilation and schema formation to take place, cognitive load experienced by students should be minimal. Hence, developing physically intelligent agents capable of embodying highly structured information and instructions can help students learn effectively in a lab. The basis of this statement sprouts from work on AR (Yuen et al., 2011), tangible interaction (O'Malley et al., 2004) and human ideation (Oviatt et al., 2012) that highlight the importance of physicality, natural affordance and interface of objects. As reported in the interviews, a major concern for course instructors in these labs is to be able to relate theoretical aspects of the experiment to practical, real-life applications. For this is it necessary to provide highly situated and contextualized instructions for students which can help them relate to such concepts. Hence, there is a need to generate suitable instructional algorithms that embody tacit knowledge of instructors which is highly structured in nature. For doing so, Task flow diagrams (TFD) were created (refer to Figure 5.7, Section 5.2.1) from think-aloud sessions and observational studies for experiments reported to be difficult for students. These TFDs highlighted various instructions that should be generated when a specific type of error is encountered, and that invoked inquiry-based learning in students during various steps of the experiment. The instructions were captured from interviews of lab instructors. Figure 5.18 describes the process of collating this database through a UCD approach.

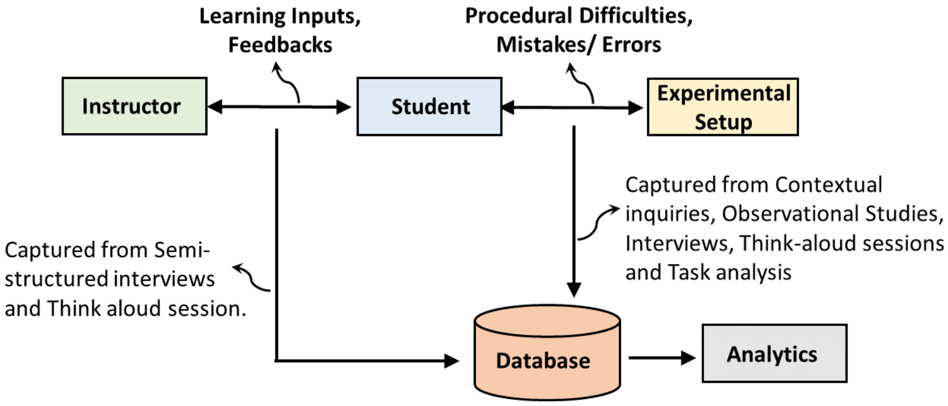


Figure 5.18 A UCD approach can be adopted to capture different experiences of users along with experiential knowledge component of expert users. These can form a database that can be used to assist learners in complex environments.

Through UCD approach, we can capture a large number of user experiences in laboratory session that can be used to augment the learning of students. These experiences can be collated into a database, which can be used for such a purpose.

5.3.2 Defining Intelligent Systems

The complete experimental setup usually consists of various objects and equipment in labs. Students while working with this setup interact with various objects in this scenario and also distribute a part of their intelligence into those tools (Salomon, Perkins, & Globerson, 1991). Mapping errors to the task-flows help in cataloging the types of interactions that are likely to happen between the experimental setup and students. By identifying objects that are used mostly by students and have a high likelihood of producing interactional errors can be chosen to be embedded with computational capabilities to sense such mistakes. Doing so creates a tangible user interface (TUI) that acts as an input mechanism for error and task sensing. From such system, further developments can be made to define what types of instructions are most suitable for students depending upon the state sensed by TUI.

To adequately convey these instructions to students, various types of output modalities can be defined. These have to be chosen such that students get the most out of their learning experience (in this thesis we utilize AR, smart objects, voice, and text-based interaction modalities.). Hence, as we move towards increasing the experiential learning value, we are also tending towards increasing the Degrees of Intelligence (DOI) to be embedded into our tutoring system.

Figure 5.19 represents a block diagram of the proposed model of DOI that conveys how intelligence is being embedded into the objects which when used in combination or with other equipment and instruments in a lab, form a smart learning system (SLS) for students in the lab. The sensing layer contributes towards a first degree of intelligence (1-DOI) and is mainly responsible for sensing and computing functions (for example intelligent breadboard senses user's errors or mistakes during physical circuit prototyping). Developing adequate instructions and learning content corresponding to task-flows and errors is the second degree of intelligence (2-DOI). Designing rich learning experience and interactions with the system is a third degree of intelligence (3-DOI) and in this thesis has been achieved by utilizing AR as interaction and visualization modalities.

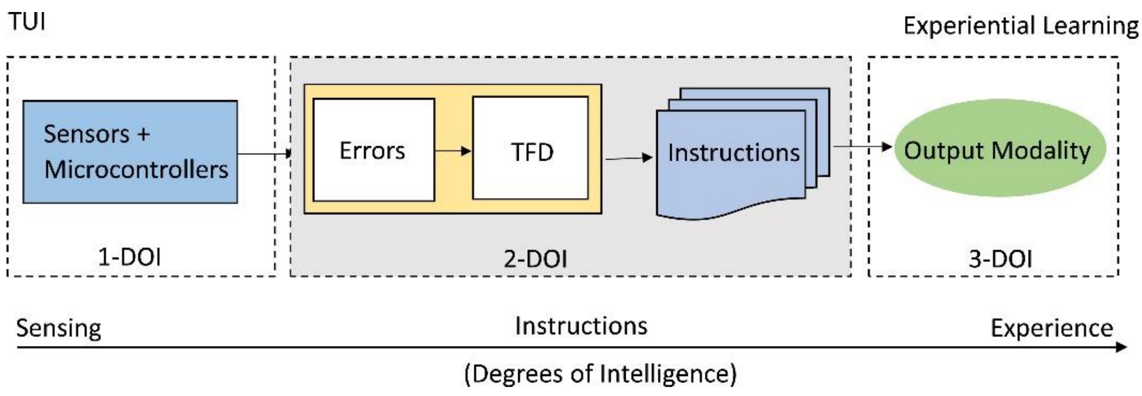


Figure 5.19 Block diagram representing increasing degrees of intelligence embedded into the learning system.

It is important to note that such systems have distributed intelligence, i.e., an object embedded with specific computational capability alone cannot act like a complete medium for learning. It is through multiple modes that it interacts and provides necessary instructions and experience to students. Our SLS prototype is based on this rationale. When we further consider how an SLS can be upscaled to further cater to the need of instructors and students on a large scale, the potential of IoT can be leveraged. In the following Section 5.6, we describe this conceptual scenario.

5.4 Facilitating teaching through SLS using an IOT approach: A conceptualization for upscaling the SLS

So far, we have discussed how SLS functionalities have been adopted to assist student users in practical electronics laboratory session. We now extend the use-case of SLS to augment human tutoring by adopting an IOT based approach. This approach will not only help teachers and instructors enrich their teaching in the classroom, but also provides a potential use of AI to upscale the SLS to cater to a large number of users in laboratories with a paucity of teaching assistants and infrastructure. According to NMC Horizon report (2017), IOT is already being adopted in institutions to generate data on student learning for informing directions for content delivery and improving teaching methods. Although IOT based approach has been adopted in remote lab scenarios, there is a dearth of literature on implementation of an IOT approach in practical electronics laboratory sessions. Research studies (Jones & Jo, 2004; Jou & Wang, 2013; Virtanen, Haavisto, Liikanen, & Kääriäinen, 2017) have presented conceptualization of ubiquitous learning environment in practical laboratories that can be possibly implemented on IOT approach. However, these studies mostly focus on understanding the context of the user regarding their physiological or location-based context.

In a conventional laboratory environment, instructors obtain feedback on student learning experiences in face-to-face interactions with students. This helps them in continual evaluation of their teaching methods. However, in case of a large batch of laboratory sessions, this face-to-face interaction often gets limited to very few student groups as the instructors often need to spend much time with small debugging issues in one group. This often leaves few other groups, that require more assistance of instructors, waiting in queue for long time durations.

Sometimes, these groups are not able to receive the attention of their instructor at all in a time restricted laboratory session. This causes a burden on the instructors in the next practical session to help the lagging group to catch up with the rest of the class. To overcome this difficulty, we conceptualized the following model to help instructors get assistance and feedback on teaching. The following paragraphs describe how Educational Data Mining (EDM) used with SLS can help tackle these difficulties.

We present a conceptualization of IOT scenario based on the approach of interconnected smart devices and applications. The concept derives its understanding from the field of EDM that relies on user-interactions with a learning portal (mostly web and MOOCs based) to create various interaction and time logs (Khasawneh, Box, & Chan, 2006; Romero & Ventura, 2007). These logs can be analyzed to inform the instructors to tailor-suit the content to individual students needs to improve their overall learning experience. These logs also help instructors monitor and assess their teaching methods. We extend this concept for use into our designed SLS prototypical solution that utilizes AR and intelligent breadboard based smart objects.

Figure 5.20 depicts a conceptualized model of integrating IoT for practical electronics laboratory along with SLS.

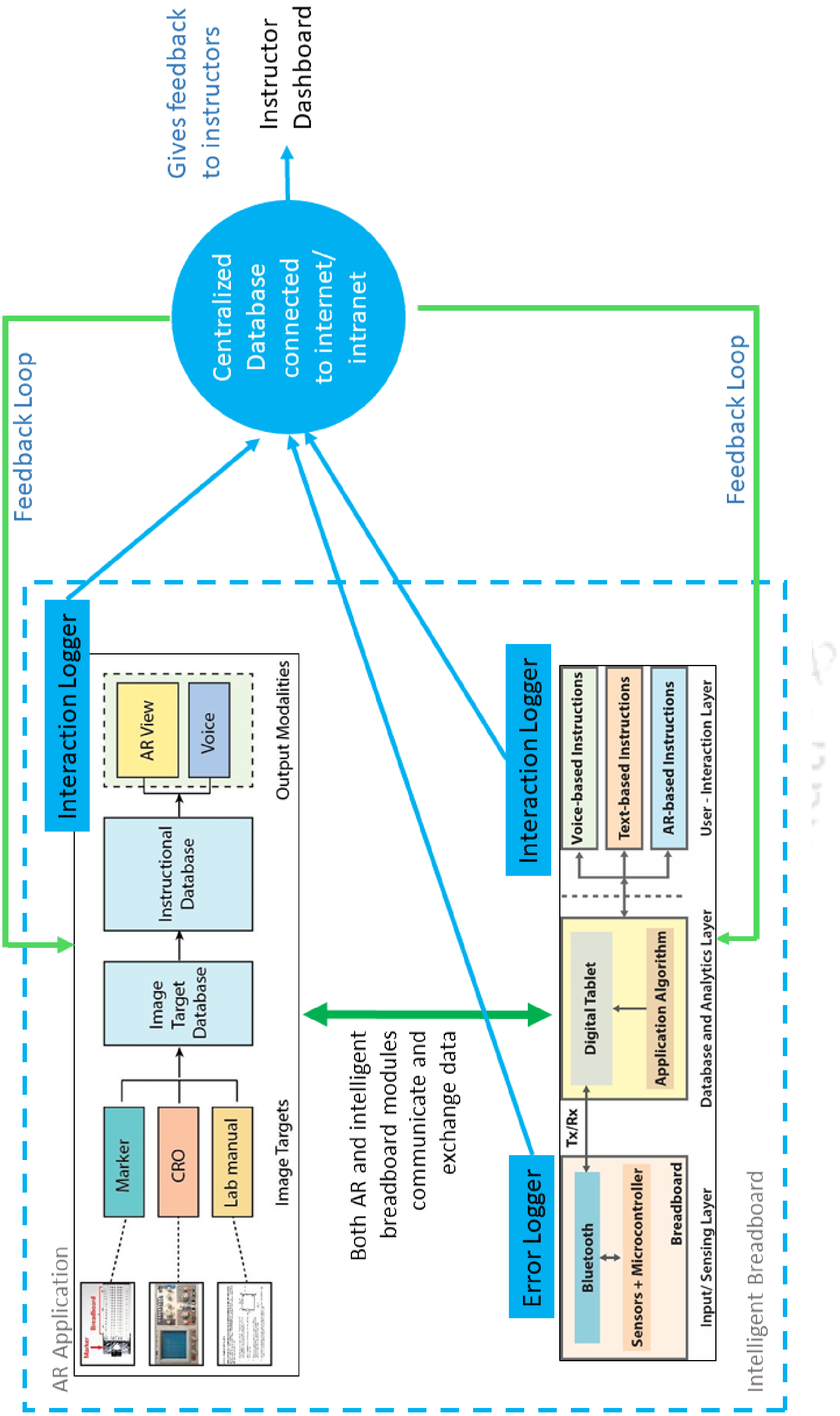
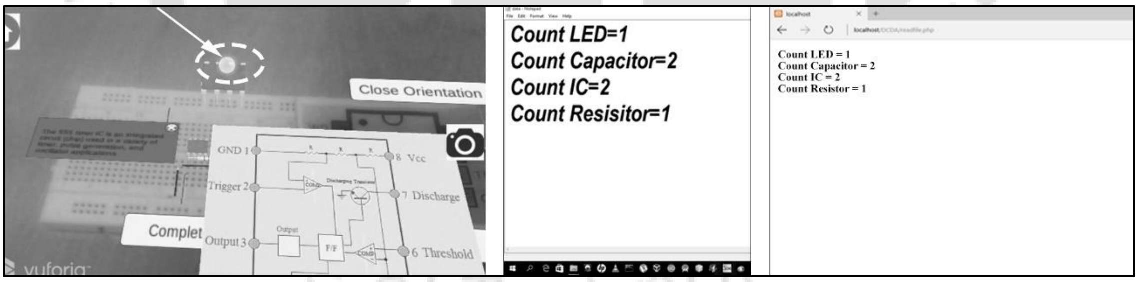


Figure 5.20. Complete Conceptualization of the Smart Learning System in IOT scenario.

In case of our AR application prototype, the user interacts with the application via AR view output modality. We propose to use an interaction logger (see Figure 5.21) with this modality to track how users interact with the content of AR application and for how long does a user interacts with the content. This log can help instructors understand how users interact with information to understand an experiment. If a group of such logs generated from a number of student users using AR application is presented to the instructors visually, it can help them discover interesting patterns that can help in continual assistance and evaluation of groups. The instructor will be able to understand what type of information is being accessed most by students in lab sessions. How much time is the being spent by students to consume this information? Perhaps the information being accessed most requires more attention thereby requiring more tutoring and pre-lab sessions. This information log can be presented to instructors visually through a digital tablet interface to help them get a better visualization of class behaviors. This will be elaborated soon in a few paragraphs to come,

As a proof of concept, we developed a simple model to count the number of taps (user interaction in the form of clicks) on individual 3D elements of our AR application prototype and then send this information from smartphone (loaded with our AR application) to a web-based interface. Figure 5.21 presents screenshots of this demonstration.



(a) **(b)** **(c)**

Figure 5.21 Screenshots from a simple demonstration of generating user-interaction log via AR. (a) User interacting 3D element on screen via AR view, see the arrow pointing towards a white circle. (b) A counter keeps track of the number of clicks on individual 3D and the graphical element of AR application and stores them as a log file in text format. (c) This log file can be sent to a web-based interface and presented to instructors visually

For intelligent breadboard, the user utilizes both input/ sensing layer and interaction layer for interaction. In the input/ sensing layer, we add an error logger and an interaction logger at the interaction layer. Error logger can keep track of all the mistake that occurs while prototyping the physical circuit on a breadboard and categorize them into different types of mistakes as discussed in Table 5.3 of Section 5.3.1.

All the logs are sent to a centralized server or “the cloud.” This is where the potential for AI comes into the picture. The cloud contains a massive data on the types of mistakes that commonly happen for particular experiments in practical lab session and the type of information accessed by the students in that practical experiment. Is there a certain category of mistakes and information that is being used by the student? Are these students categorized based on regions, colleges, academic performance? If so, what is the most suitable type of instructions that can be provided to these students? What recommendations should be given to the instructors? These are some of many questions that need to be answered by AI. The AI’s task is to find a suitable type of instructions based on the logs sent by the devices. It should be able to predict the right type of instruction and recommendations for both students and instructors for augmenting learning and teaching experiences in the complex learning environment of a practical laboratory session. This segment of our thesis is a doorway for future work in this area.

We now explain the concept of an instructor’s dashboard on a digital tablet for assisting the teaching of student groups in labs.

5.4.1 Instructor interface

This section briefly discusses the conceptual interface for laboratory instructors. The aim of this interface is to act as an information platform that provides real-time feedback to laboratory instructor regarding students’ performance and difficulties. This platform can be used by instructors to aid them in teaching large batches of students.

Based on the observations from practical electronics laboratory sessions, various activates in which instructors are involved in were observed – which mainly consist of assisting students, accessing their progress and evaluating them. It was observed that although instructors play a crucial part in laboratories to give guidance and feedback to students, no mechanism does the same for instructors. With our proposed conceptual scenario of integrating SLS with IOT and AI, it is possible to develop a platform for instructors that can provide them with timely feedback and ability to monitor a large batch of students in practical laboratories. Figure 5.22 depicts the steps involved in conceptualizing instructor interface.

Various techniques such as experience mapping, paper-prototypes and wireframes were utilized, see Figure 5.23. A dashboard was designed as a concept to show how instructors can get assistance through the use of AR and SO in an IoT scenario. The complete interaction flow diagram of the dashboard has been presented in Annexure E3. The dashboard, shown in 5.23 (c), presents information that is required by instructors to assist and monitor students' progress and activities related to practical experiment. These include, students' assignment status, progress in class, top errors or mistakes made by them in experiments and completion status of experiments. The instructor can either choose to view individual progress of the students or group-wise progress. Top errors and mistakes section helps instructor get feedback on the most commonly occurring errors/ mistakes by students while conducting the experiment. Based on this information, the instructor can decide upon the type of instructions to be given to students. The interface assists instructors in identifying students who are lagging or facing difficulties in performing the experiment.

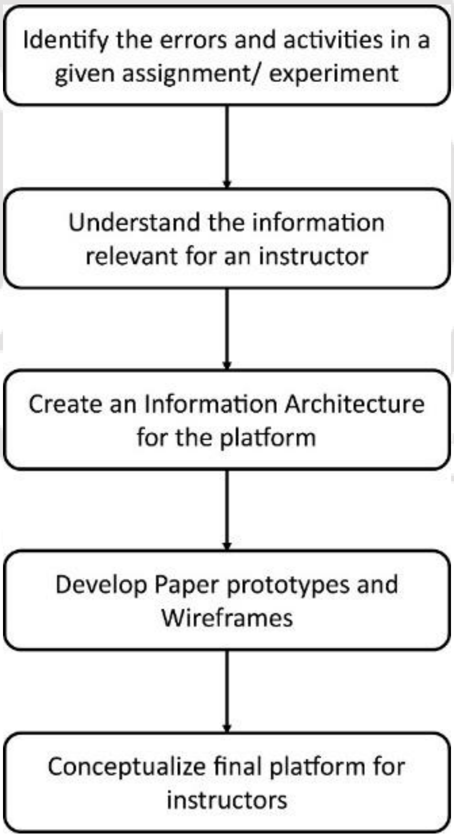


Figure 5.22 Steps followed for the conceptualization of instructor interface.

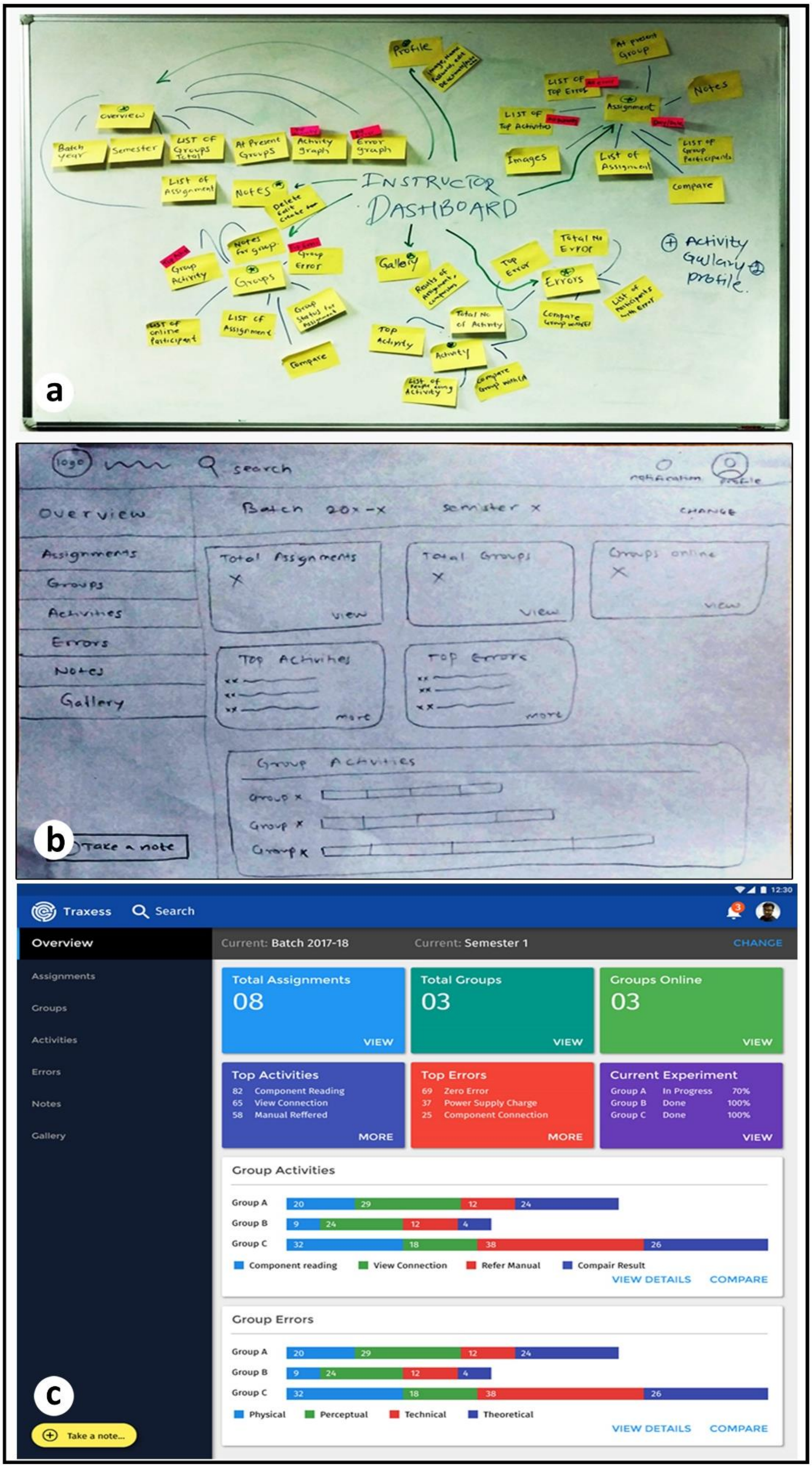


Figure 5.23 Steps followed to obtain instruction interface. (a) Experience mapping (b) Paper prototype and wireframes (c) Final concept.

5.5 Formulating posits and working hypotheses to test the SLS prototype

We posited that the SLS prototype would influence the learning experiences of students in practical laboratories and affect their workloads. Two Design Experiment (DE) studies were planned and conducted to test our SLS prototype, posits and validate our hypothesis as a part of research stage 6 and 7 (refer to Figure 3.3). Chapter 6 that follows next describes these studies in details. The posits were tested in Design Experiment – I through formative evaluation using a UCD approach. Hypotheses were tested in Design Experiment – II through within group experiment design.

Following posits were under test in the Design Experiment - I:

P1: SLS will improve the learning experience of students in practical electronics laboratory sessions

P2: SLS will improve student's concentration and readiness to work in a practical laboratory session.

P3: SLS will improve students' understanding of practical experiments.

P4: SLS will improve timesaving of students in practical laboratory sessions.

The following hypotheses were formulated and tested during Design Experiment -II was:

- **H1:** SLS will affect the overall Workload of students on the NASA-TLX scale.
- **H2:** A positive relationship exists between learners' satisfaction and the reuse intention of SLS.

In addition to H1 and H2, the following hypotheses were also tested for factors that also affect the workload of students in laboratories:

- **H3:** SLS will affect the Mental demand of students on the NASA-TLX scale.
- **H4:** SLS will affect Physical Demand of students on the NASA-TLX scale.
- **H5:** SLS will affect the Temporal Demand of students on the NASA-TLX scale.
- **H6:** SLS will affect the perceived Performance of students on the NASA-TLX scale.
- **H7:** SLS will affect the perceived Effort of students on the NASA-TLX scale.
- **H8:** SLS will affect the perceived Frustration of students on the NASA-TLX scale.

Figure 5.24 summarizes the research stages involved in the development of SLS prototype.

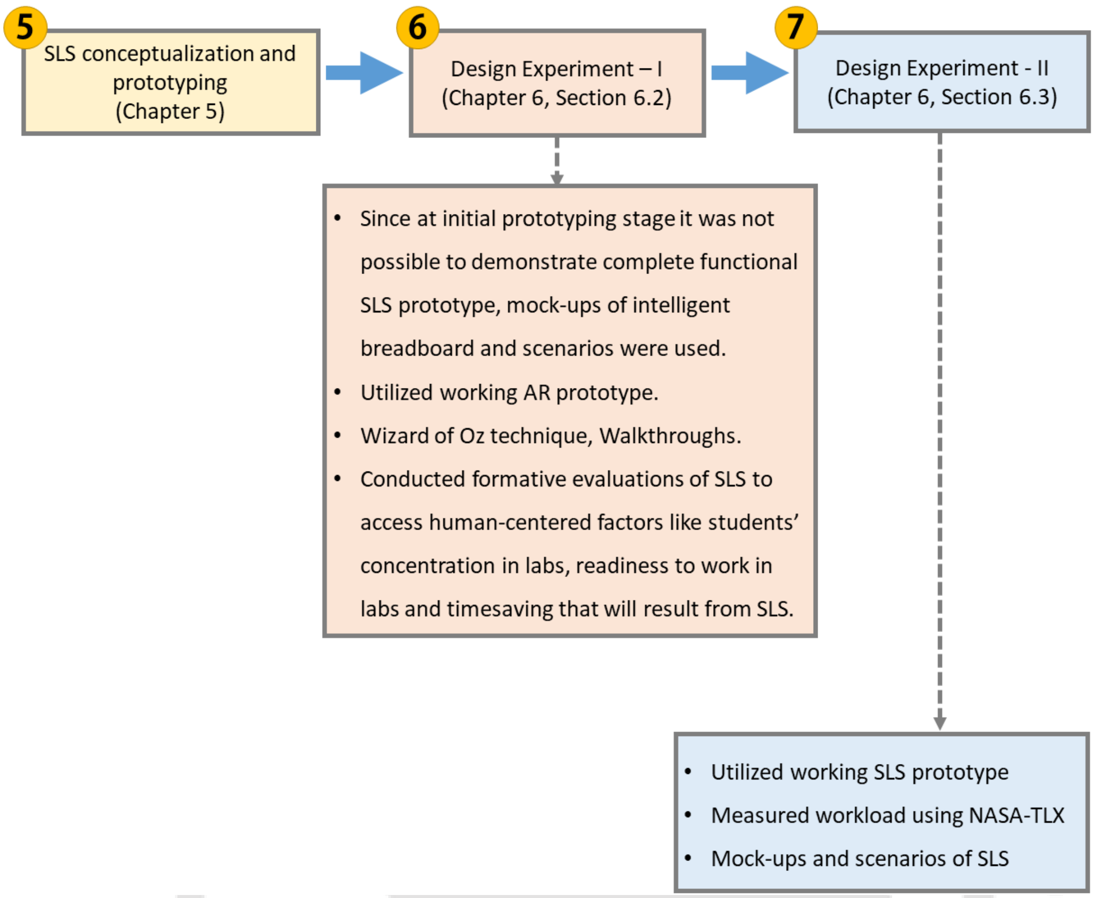


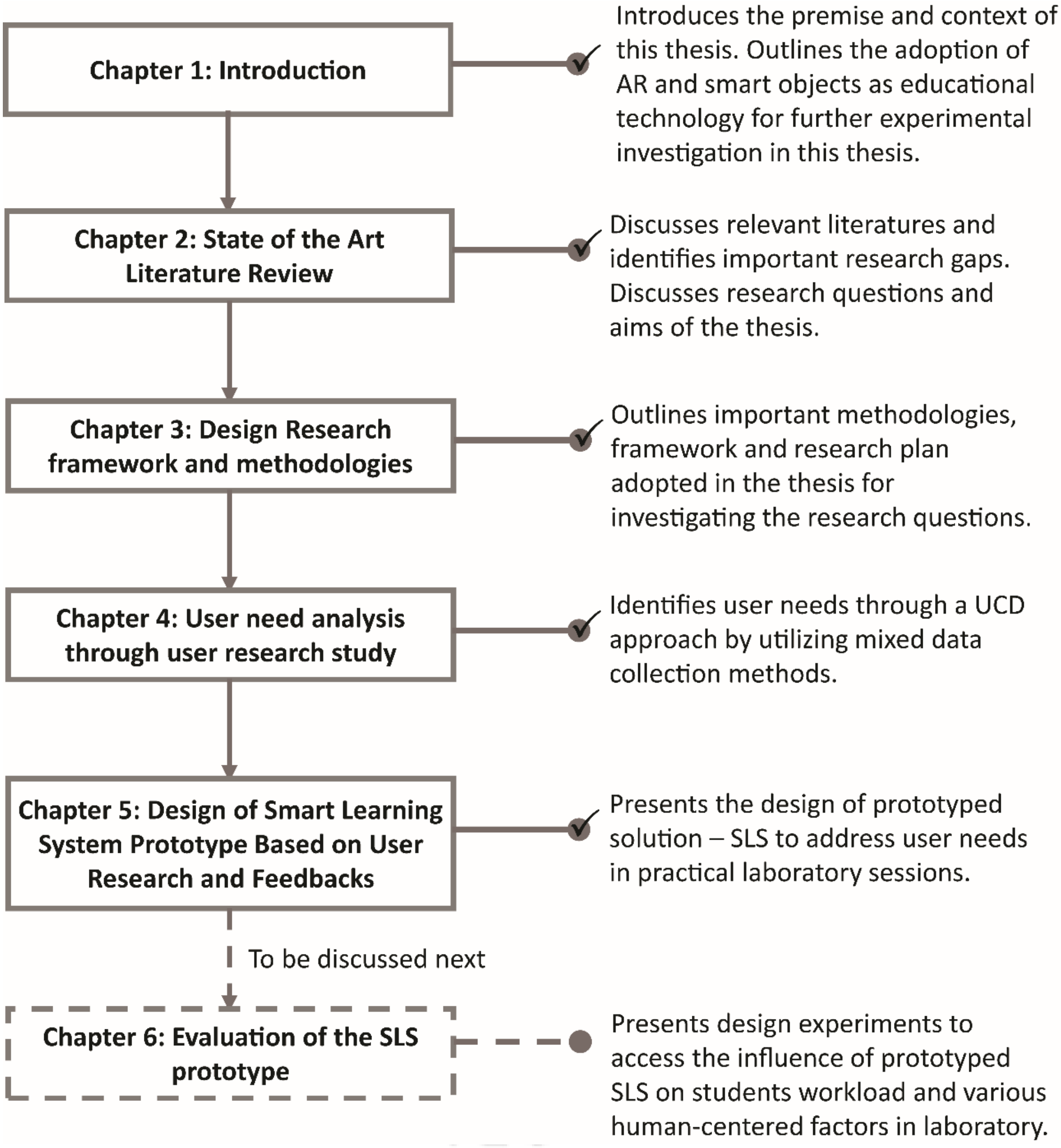
Figure 5.24 Summary of research stages for testing SLS prototype.

5.6 Chapter Summary

The chapter presented a detailed description of the functional aspects of the SLS and provided a conceptual scenario that extends its use by converging technologies of IOT and AI. The chapter also highlights the posits under test in the thesis as well as the working hypotheses. In the following Chapter 6, we present the further experiments conducted to test our prototype and conceptual design amongst a heterogeneous user group.

A quick recap of previous chapters:

A visual summary of the chapters covered so far is provided as follows:



Chapter 6: Evaluation of the SLS Prototype

Chapter Abstract: This Chapter 6 presents design experiments conducted amongst a heterogeneous sample student population of various engineering institutes across India. The design experiments were conducted to test our SLS prototype, posits made around the use of SLS in practical laboratories and validate working hypotheses. The sample population ensured a versatile pool of students for the experiments with students participating from all engineering branches from various engineering institutes.

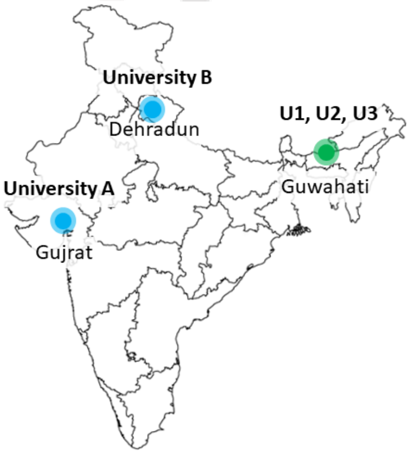
6.1 Introduction

Design Experiments were conducted to investigate and test the utility and usability of our designed, prototyped solution, as well as gain more insights into the types of challenges faced by students in practical electronics laboratories across India. Design Experiments (DE) help characterization of messy situations by allowing flexible design revisions and evaluations (F. Wang & Hannafin, 2005).

Gathering different types of user needs in complex learning environments of practical electronics laboratory cannot be restricted within well-established institutes (for example Indian Institute of Technology (IITs)). Many institutes across India lack the full infrastructure to deliver proper learning experiences and satisfaction to students. Design solutions in such situations need to be robust enough to overcome challenges posed by varying user requirements that emerge from various constraints – posed by learning environments, infrastructure, and human resources. Adopting a design-based methodology helped us gain insights into different types of user needs and allowed revisions in our prototype design to meet user requirements that emerged as the studies unfolded – i.e., the evolutionary perspective of a user-centred design approach.

The investigations employed a mixed methodology approach utilizing qualitative and quantitative methods of data collection and analysis. Qualitative aspects of these design-based experimental investigations helped us to capture learner's experiences and inductively derive relations between various complex subjective parameters experienced by students' in practical electronics laboratories. This aspect of our design experiment is mainly rooted in grounded theory (Berg, 2001). Capturing learning experiences of students is crucial and has not yet been explored in any literature that we have reviewed in this thesis. The need for research in this direction has also been highlighted by Cheng & Tsai (2013) in their detailed review paper on augmented reality for education. Secondly, the workload has been cited as one of the major influencer on students' learning in practical laboratory sessions (Chandler & Sweller, 1991; Johnstone, 2006). We therefore also investigated the effect of SLS on students' various workload load factors by using NASA-TLX questionnaire.

The first design experiment (DE-I), see Figure 6.1, was carried out amongst a total of N = 43 student participants (users) from the state of Gujrat (15 participants) and Dehradun (28 participants) with SLS mock-ups depicting the use of intelligent breadboard in conjunction with AR, scenarios and working AR prototype. The mock-ups were mainly utilized as the SLS prototype was in its initial development phase and could not be functionally demonstrated to users. DE-I mainly utilized design methods like Wizard of Oz technique and walkthroughs for formative evaluation of SLS prototype. DE-I mainly accessed human-centered factors that have not been investigated in any kinds of literature reviewed in this thesis.



Participants	No.	Experiment Type	
University A, Gujrat	15	Formative Assessment of SLS **Setup: AR, Mock-ups, Scenarios**	DE-I
University B, Dehradun	28		
University 1 (U1), Guwahati	94	Usability Evaluation and Task Load Assessment **Setup: SLS, Mock-ups, Scenarios**	DE-II
University 2 (U2), Guwahati	22		
University 3 (U3) Guwahati	10		

Total Participants = 169

Figure 6.1. User usability testing studies carried out as a part of design experiments across three different states of India.

The second design experiment (DE-II) was carried out in the state of Assam with a total of N = 126 student participants from three different colleges with the complete working lightweight SLS prototype that was also informed from the responses of the participants received during DE-I. Effect of SLS on student users' workload was accessed in this experimental user study to test and validate our hypothesis.

Figure 6.1 depicts the location of these design experiments along with the number of participants and experiment description. These multiple user groups were chosen consciously to formatively access our prototyped solution amongst users of varying academic disciplines of engineering institutes. All participants were familiar with electronics and had studied or been studying courses related to electronics engineering. Having multiple user groups of varying background allowed us to make observations and evaluation of utility and usability of our prototypes.

6.2 Design Experiment – I: Formative assessment of SLS prototype

DE-I formatively accessed human-centered factors that were found missing in literature survey. These factors are students' perceived concentration level, readiness to work on experiments and timesaving in laboratory sessions. User-centered design methods of cognitive walkthroughs and Wizard of Oz techniques were utilized in this experimental investigation. This section discusses DE-I in details.

6.2.1 The population of interest and posits under test in the experiment

DE-I was conducted across two different states of India (15 from Gujrat, 28 from Uttrakhand) amongst randomly selected 43 student participants ($Mean_{age}$= 20.95, SD = 1.43) based on convenience sampling and comprised of 66.7% male and 33.3% female. All selected participants were familiar with electronics and had undergone or were undergoing practical electronics labs sessions as a part of their curriculum. The students belonged from various courses and branches like M.Sc. Electronics (66.6%), B. Tech Electrical Engineering (14.3%), M. Tech Electrical Engineering (9.5%), B. Tech Civil Engineering (4.8%) and Ph.D. Material Science (2.4%). The sample population ensured a versatile pool of students for the experiments with students participating from all engineering branches from various engineering institutes of India.

Following posits were under test in the Design Experiment - I:

P1: SLS will improve the learning experience of students in practical electronics laboratory sessions

P2: SLS will improve student's concentration and readiness to work in a practical laboratory session.

P3: SLS will improve students' understanding of practical experiments.

P4: SLS will improve timesaving of students in practical laboratory sessions.

6.2.2 Procedure, Material, and Setup used in Design Experiment – I

Since DE-I was conducted across different engineering institutes of India based on convenience sampling, it was not possible to engage students in real-time practical laboratory sessions and then gauge the effectiveness of our SLS prototype. We therefore utilized the technique of cognitive walkthroughs to help student participants identify and realize the difficulties experienced by them while conducting practical experiments in electronics laboratories. Cognitive walkthroughs (CW) use explicitly detailed procedures to simulate user's problems at each step through written forms or dialogues (Nielsen, 1994). This technique is commonly used in usability engineering to give researchers a chance to identify or describe potential user's problems that arise or might arise in interactions with a system or environment without requiring a fully functional setup or the involvement of user (John & Packer, 1995; Rieman, Franzke, & Redmiles, 1995). Figure 6.2 depicts the complete DE-I process.

The participants were first asked to describe their experiences during each stage of the experimentation in practical electronics laboratory session through an open-ended questionnaire form. The form was specially designed for CW session and helped participants gather their experiences and identify difficulties faced by them in practical sessions without requiring them to work on a physical experimental setup. The stages for which participants were asked to describe their experiences were Referencing, Assembling, Operating test equipment and Reporting as derived from hierarchical task analysis described in Chapter 4: Section 4.2.2. This form was also analyzed later using content analysis to get a consolidated finding of difficulties reported by student participants. Annexure F1 presents the form given to participants during cognitive walkthrough session to help identify difficulties experienced in laboratory sessions.

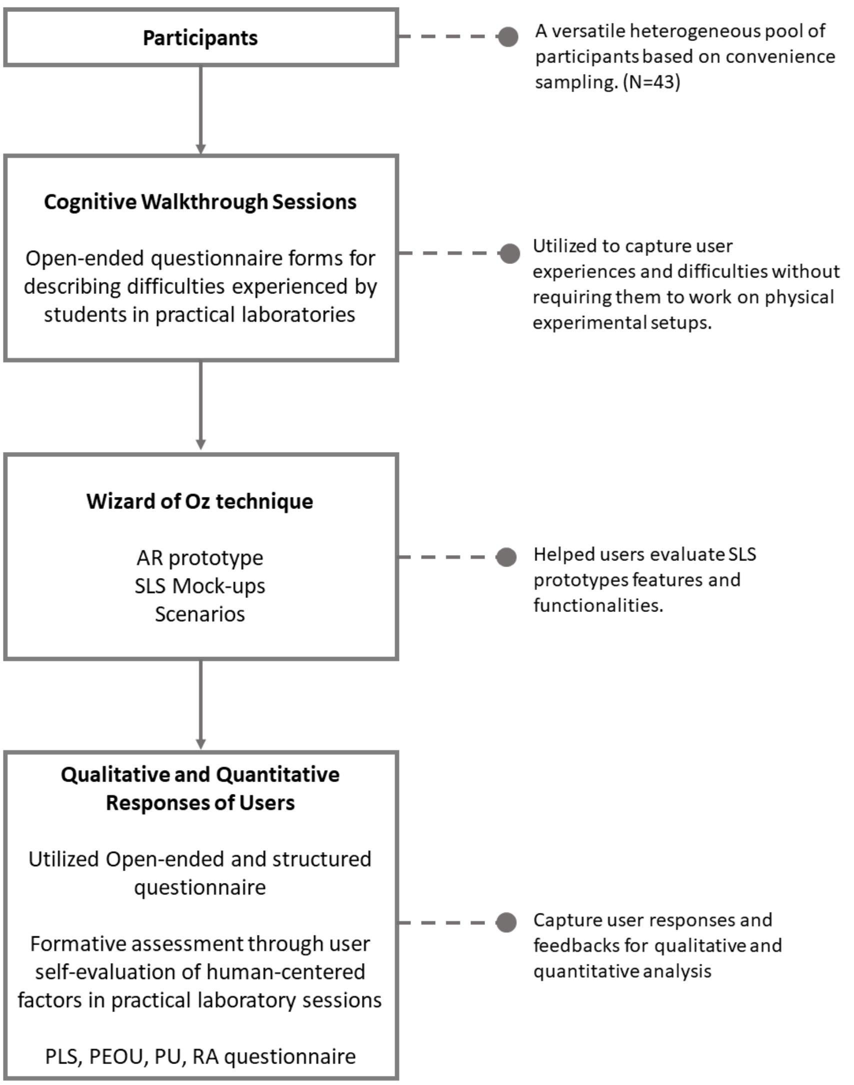


Figure 6.2 DE-I process that utilized Cognitive Walkthroughs and Wizard of Oz techniques for evaluation of the prototyped solution for practical electronics laboratory sessions.

The participants were also asked to self-evaluate their understanding behind the experiments that resulted from various activities such as reading lab manual, getting help from instructors and through peer interaction in practical electronics laboratory sessions, see Table 6.1.

Table 6.1 Students self-assessment (N=43) regarding their understanding, on a scale of 1 to 10 (1=Low, 10=High) gained in the lab from various activities.

Item	Mean	SD	Median	Q1	Q3	IQR
Reading the lab manual	6.60	1.35	7	6	7	1
Getting instructions from lab teacher	6.91	1.73	8	5	8	3
Discussing and taking hints with our batchmates	7.49	1.68	8	6	9	3

After the cognitive walkthroughs, we utilized the Wizard of Oz (WOz) technique during which the participants were demonstrated the features and functionalities of our prototyped solution and asked to interact with it. The participants were also presented with scenarios (see the box represented as Figure 6.3) and mock-ups of SLS that explained various use cases of our AR prototype, what further functionalities will be encapsulated by it to aid utility and usability in laboratory sessions and how it can be used in conjunction with intelligent breadboard to assist students with practical experiments. Annexure E2 presents these mock-ups. The WOz technique is an experimental evaluation mechanism that allows observation of a user operating an apparently fully functioning system whose missing features, functionalities or services are supplemented by a hidden wizard – often presented in the form of narratives, scenarios or mock-ups (Salber & Coutaz, 1993). Since at this stage of our experimental investigation the prototype was under development and was not fully demonstrable to users, the WOz technique helped us evaluate it amongst different users without requiring complete prototype setup.

> "The AR application is able to project 3D graphics and other digital information like 2D images, videos onto real space, as you are seeing in our demonstration. In case of 3D circuit assembly guide, you can select multiple configurations and arrangements to be projected onto the breadboard. In certain cases, users also fear trying new methodologies in lab by varying various parameters such as voltage or current going into the prototyped circuit due to risk of getting electric shock. In this AR application, you will be able to simulate the circuit in real-time, by varying desired parameters and see its effect in real space. Supposing you increase the voltage input in a circuit to an extremely large value and see the capacitor actually blow up in 3D! It's just like a circuit simulator, but using AR and 3D graphics. We also plan to add various functionalities like (i) snapshots and share, and (ii) we plan to increase the interactivity in the application wherein you can interact with 3D electronic components. Further, when you point the application towards various test equipment like CRO – as you can see from this mock-up, the application will point out how to make various connections and which knobs to rotate through AR view. For example: the AR application will show visualizations on where to insert CRO probe – in Channel 1 or Channel 2 in 3D.
>
> We are also exploring ways through which mistakes made during circuit prototyping can be pinpointed exactly via AR and the system is able to guide students by asking them various questions and suggesting them to read relevant chapters related to the experiment to strengthen their concept. Similar to a manner in which a human tutor guides students. Our other functionalities will include feature like – switching between voice-based instruction and text-based instruction. Enabling mobile flashlight so that AR can also be used in dim light situations. A provision for connecting the application with internet is also planned so that structured information, as selected by course instructors, is presented to you."

Figure 6.3 Scenario delivered to student participants during design experiments.

Figure 6.4 depicts the complete experimental setup. The goal was to qualitatively assess the effect of SLS on participants learning experience and how it influences them in practical laboratory sessions. This qualitative assessment helped us gain an in-depth understanding of participants' situation in a practical laboratory, which is not generally captured in quantitative assessments. After interacting with our prototype and experimental setup used during WOz technique process, participants were asked to describe their usage experiences in an open-ended questionnaire. The questionnaire also asked students to present a formative-evaluation on their perceived increase in understanding, concentration and timesaving in practical electronics laboratory sessions that will result from the use of our prototype in laboratory sessions.

(a) **(b)** **(c)**

Figure 6.4 Experimental setup of DE-I. (a) A computer containing video demonstration of AR application and digital mock-ups and scenarios, a breadboard attached with marker, digital tablet, lab manual and a paper printed mock-up of analog CRO. (b) Participants interacting with prototype and mock-up. (c) A digital mock-up of the application and its use-case was shown and explained to student participants. The mock-up depicts future functionalities that AR will include and was presented to participants along with the scenario.

In addition to the qualitative data, quantitative data were also collected using structured questionnaires. As practical laboratory sessions are a collaborative environment where students work in close groups, the medium of instructional format and the content play an important role in affecting their learning satisfaction (Chandler & Sweller, 1991). We therefore used Perceived Learner's Satisfaction (PLS) scale to access this parameter.

Further, to quantitatively access our prototype's usability, Perceived Ease of Use (PEOU), Relative Advantage (RA) and Perceived Usefulness (PU) scale were used. All questionnaires have been presented in Annexure F1.

6.2.3 Results of qualitative analysis of data collected through open-ended questionnaires

An in-depth content analysis of the 15 (out of 43) responses received from open-ended questionnaires forms (see Appendix F1) from CW was performed. In the open-ended questionnaire, the participants were asked to identify and write the difficulties experienced by them in a practical laboratory session. Figure 6.5 highlights the difficulties indicated by the participants in the CW forms.

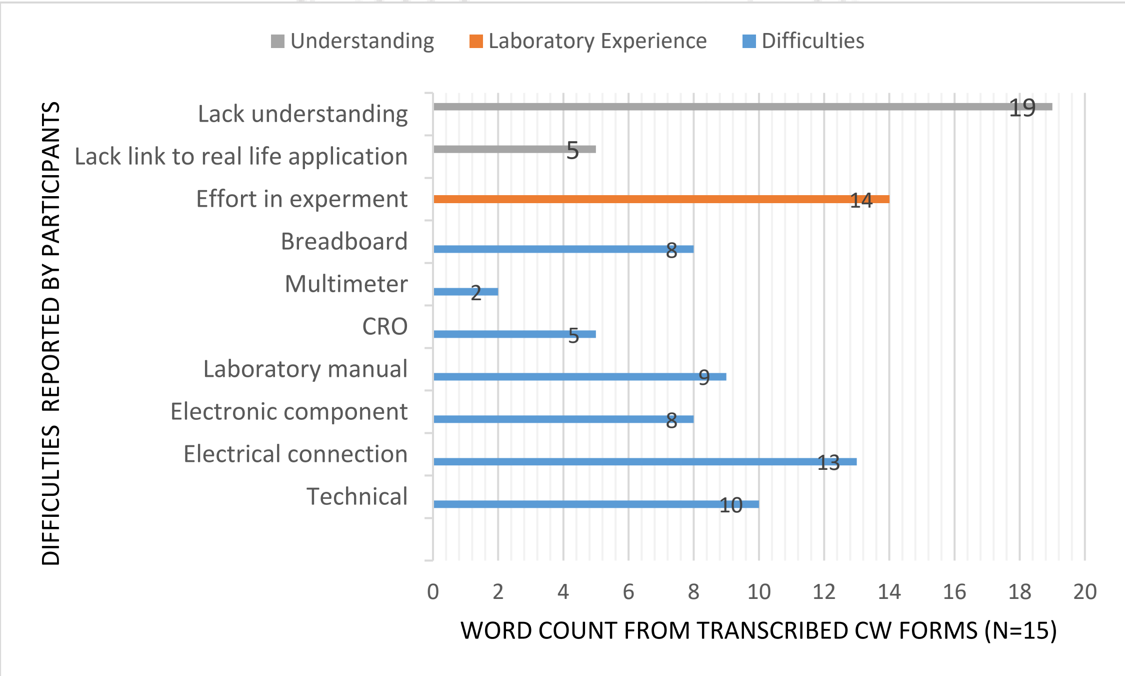


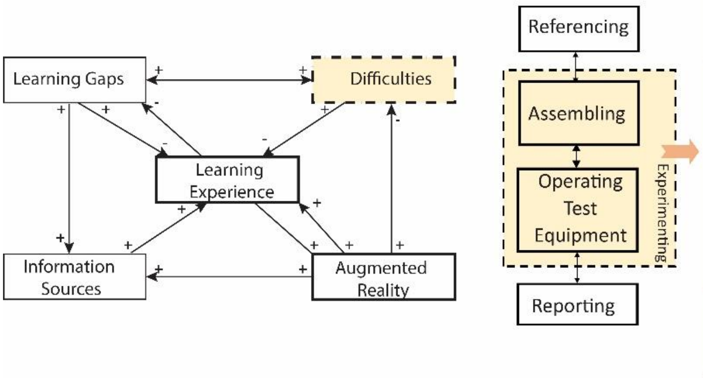
Figure 6.5 Word count from transcribed CW form responses of students' experience and difficulties experienced in the practical electronics lab session.

The participants were also asked to provide feedback on their experiences after using our prototypes in an open-ended questionnaire. The responses were transcribed and analyzed using content analysis. The transcribed data were coded by the author and categorized in five categories namely (i) Learning gaps, (ii) Difficulties experienced in labs with different equipment, (iii) Learning experience, (iv) Information sources and (v) AR learning experience. Following codes were included in the mentioned categories of learning gaps and difficulties:

- **Learning gaps:** lack of understanding about theory, experiment or equipment, and, lack of a link to practical (or real life) example.

- **Difficulties:** technical, electrical connection, lab manual, test equipment, breadboard, effort. Difficulties experienced in the laboratory can further be categorized into different types as shown in Figure 6.6 (b).

We wanted to identify how SLS can influence overall aspects of learning experiences of students in practical electronics laboratory sessions. Figure 6.6 (a) depicts an impact relation diagram (Blessing & Chakrabarti, 2009) that was inductively derived from the content analysis. The model shows the effect of various factors on the learner's experience and how AR can improve these experiences.



Type of Errors	Description
Physical	• Break in connection not visible to human eye • Loose Connections • Wrong arrangements of components
Perceptual (Visual Perception)	• Wrong Connection • Use of wrong electronic component
Theoretical	• Wrong understanding regarding electronic component, test equipment or experiment
Technical	• Faulty lab equipment and objects

(a) (b)

Figure 6.6 Relation between different categories on student learning experience. The plus '+' indicates an increase and '-' indicates decrease. (b) Different types of difficulties identified in practical laboratory sessions.

Participants reported that introducing AR in practical laboratory session would help improve their learning effectively and efficiently. It will also help them in reducing fear, saving time and getting proper information during the experiment. Students used adjectives like 'good,' 'helpful,' 'interesting' and 'fun' to describe their learning experience with AR. Keywords identified from the transcribed data that described usability aspect of AR were – 'easy,' 'efficient,' 'would like to continue' - which was coded to a willingness to continue usage, and 'time.' Table 6.2 presents a few excerpts from students' responses regarding lab experience and on the use AR application in practical electronics lab sessions. From the responses, it can be seen that AR affects learners' experience positively and they perceive it to be effective and easy to use.

Table 6.2 Excerpts from students' responses regarding lab experienced and their experience on the use of SLS prototype mainly consisting of AR interaction modality.

Participant	General responses on lab experience	Response on AR experience
P1	"…I would like to mention that the one circuit has to be made by the instructor before experiment so that we can learn and understand the results even if we face problem in making the circuit due to some equipment fault…"	"The AR application is going to be very helpful. It is very promising. With a few upgradations, it will become an essential part of electrical and electronics lab."
P2	…At least the circuit connected on breadboard must be given so that students can get some hint….	"Basically this application provides us the most appropriate position to connect components on a breadboard which will drastically reduce the error of connecting wrong circuit components and reduce the debugging time for a complex circuit.
P3	"…during the circuit designing part on a breadboard, taking correct values of resistor and capacitor is a big problem because if we take some random value then circuit won't work…"	"Very good and interesting application…it is very helpful not only for experiments but for the basic knowledge we need to understand the experiment for…it will be fun."
P4	"…CRO is a bit difficult to operate like we can solve the problem of common ground in output or make it user-friendly…"	"The use of CRO and breadboard becomes easy by using this AR application"
P5	-----	"It was a very good experience because it showed us the behaviour of transfer of current as well as its graph"
P6	"…Details about the experiment, circuit diagram, and purpose of the experiment, limitations and how to perform without referring the lab manual should be told before the experiment…"	"The reasons displayed for derivation from ideal conditions was informative and gave us a practical feeling for the situation"
P7	-----	"Make this app for windows platform too so that I can do experiments on my own"
P8	"…often experiment too tedious such that focus foes on finishing it somehow in quest for result often learning/ concept etc. gets diluted and one simply becomes happy with the fact that results have come…"	"It will be very helpful and work will be efficient rather than difficult. Learning becomes easier and we won't have to worry about unexpected things like burning of ICs or explosions."
P9	-----	"This AR application make students to get more and more correct information during the experiment time itself."

Table 6.3 describes the formative self-assessment of students regarding the additional understanding of principles behind the experiment, time-saving in the lab and concentrating on an experiment that will result if AR application is made available to them in practical laboratory sessions.

Table 6.3 Descriptive statistics of students' self-assessment on their perceived understanding, timesaving and concentrating on an experiment that will result from using SLS application in the lab. Q1, Q3, IQR represent the inter-quartile and quartile ranges.

Item	Mean (%)	SD	Median	Q1	Q3	IQR
Understanding the principle behind the experiment	56.51	21.81	60	40	75	35
Time-saving in lab	67.70	23.12	75	50	80	30
Readiness for lab	67.91	19.77	70	60	80	20
Concentrating on experiment rather than involving in debugging part of experiment	71.40	20.57	80	60	90	30

It can be seen that students perceive that introducing SLS would help them increase their understanding in laboratories, help save time, improve concentration and readiness to conduct various practical experiments. Thereby proving that our contention and posits hold true.

6.2.4 Verifying insights from qualitative analysis through quantitative responses

A 15-item questionnaire relating to perceived learner's satisfaction (PLS) scale was used. The questionnaire was adopted from Wang (2003) and modified for our study. The questionnaire used learner interface (I), content (C), personalization (P), and, peer collaboration (L) to measure learner's satisfaction (for complete questionnaire refer to Appendix F1). The participants were asked to rate their SLS prototype based learning experiences by indicating their agreement or disagreement with the questionnaire items on a 7-point Likert scale where 1 = strongly disagree and 7 = strongly agree. Figure 6.7 shows the model for measuring learner's satisfaction using AR. Questionnaire items PLS14 and PLS15, are criterion questions that are considered as global items as per the guidelines provided by Wang (2003).

A 7-item questionnaire consisting of perceived ease of use (PEOU), perceived usefulness (PU) and relative advantage (RA) scale were also administered to students wherein the respondents were asked to mark their responses on a 5-point Likert scale where 1=Strongly Disagree, and 5=Strongly Agree. The questionnaire was adapted from Sun et al., (2008) and was modified for our study. Table 6.4 shows the descriptive statistics of PLS, PEOU, PU, and RA.

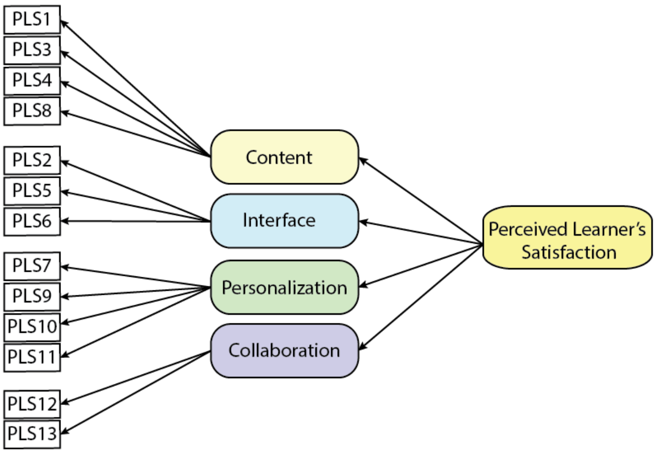


Figure 6.7 Model for measuring learners' satisfaction using AR. Adopted from Wang (2003).

The students showed a high level of perceived learners' satisfaction, Mean = 5.97; SD = 0.29 which is good. In addition to that, the usability aspects of AR application were also rated high, and students found AR to be useful in practical lab sessions.

A correlation between the total score of PLS questionnaire items (i.e., the sum of items PLS1 to PLS13) and the sum of criterion questions (i.e., PLS14 and PLS15) was accessed as per the guidelines provided by Wang (2003). A Spearman's rho correlation value of 0.597 significant at $p < .01$ was received thereby indicating that a positive relationship exists between perceived learners' satisfaction and reuse intention of SLS. This indicates that our prototyped solution will positively influence learner's satisfaction in practical electronics laboratory sessions, thus validating our qualitative findings.

The findings of DE-I indicate that the proposed SLS prototype will positively influence human-centered factors of students that affect their learning experiences. After formatively accessing our prototype in this DE-I through a UCD approach, we proceed towards measuring the effect of our prototype on students' various workload factors in DE-II. By this time, the complete working prototype was developed which was demonstrable to users. However, this working SLS prototype was lightweight and used as a proof-of-concept.

Table 6.4 Descriptive statistics of PLS, PEOU, PU, RA

Item Code	Item Description	N	Mean	SD
Perceived Learner's Satisfaction				
PLS1	The AR application provides content that exactly fits your needs in conducting specific lab practical at the right time.	43	5.56	.959
PLS2	The AR application is easy to use.	43	6.19	.794
PLS3	The AR application makes it easy for you to find the content you need in your own way of exploring.	43	5.84	1.022
PLS4	The content provided by the AR application is easy to understand.	43	6.19	.664
PLS5	The AR application is user-friendly in term of its user-interface.	43	5.98	.831
PLS6	The AR application responds to your request fast enough.	43	5.72	1.008
PLS7	The AR application makes it easy for you to evaluate your progress and learning performance and become confident.	43	5.63	1.176
PLS8	The testing methods provided by the AR application in understanding the experiment are easy to follow and interact with.	43	5.91	.895
PLS9	The AR application provides secure testing environments in which you are not afraid to make mistakes involving circuits, blown devices and short-circuits.	43	5.98	1.080
PLS10	The AR application enables you to choose what you want to learn and when you want to learn when you are deeply concentrating in the experiment.	43	5.88	.762
PLS11	The AR application provides a personalized learning support just as an instructor/tutor/lab assistant would do.	43	5.86	1.082
PLS12	The AR application makes it easy for you to discuss questions and doubts with your teachers and batch mates during the experiment itself.	43	5.65	.997
PLS13	The AR application makes it easy for you to share what you learn with your peers and batch mates.	43	6.23	.751
PLS14	As a whole, you are satisfied with the advantages provided by the AR application.	43	6.37	.787
PLS15	If made available in your institute, you will definitely this AR application.	43	6.63	.655
Perceived Ease of Use Scale				
PEU1	The AR application was simple and easy to use.	41	4.66	0.530
PEU2	I feel comfortable using this AR application.	41	4.54	0.636
PEU3	It was easy to learn to use this AR application.	41	4.61	0.542
PEU4	I believe I became more productive using this AR application during my experiment.	41	4.44	0.634
Perceived Usefulness				
PU	I can effectively complete my lab practical on my own using this AR application.	41	4.27	0.742
Relative Advantage				
RA1	Performing lab practical, using this AR application is more effective than using only traditional paper and simulation based formats.	41	4.46	0.596
RA2	This AR application is better that other lab instructional systems like Internet and simulation software I have used so far.	41	4.32	0.756

6.3 Design Experiment – II: Effect of SLS on Students' Workload

This experiment was conducted to access the effect of SLS on students' extraneous cognitive load (or workload) in practical laboratories. The experiment was conducted in three different institutes of Guwahati, Assam (India), see Figure 6.8, with the complete prototyped SLS system. The institutes were (i) University 1 – a national teaching institute, (ii) University 2 – a state engineering college, and (iii) University 3 – a private sector university. All participants belonged from electronics background or were undergoing basic electronics-related courses and laboratory sessions. A purposeful randomized sampling method and within-subject design were adopted. The study was conducted during live practical electronics laboratory sessions while the student participants were performing experiments. This was purposefully done to measure different types of workloads experienced by students' using NASA TLX – which has to be administered during or immediately after the task (S. G. Hart & Staveland, 1988).

Figure 6.8 Participants from various institutes participating in usability testing.

NASA-TLX is the most widely used measure of the workload in human factor research (S. G. Hart & Staveland, 1988). It is a multi-dimensional rating scale that has six dimensions: mental demand (MD), physical demand (PD); temporal demand (TD); own performance (P); effort (E); and frustration (F). The dimensions reflect task-related (MD, PD, TD), subject-related (P), and behavior-related (F and E) factors (Wilson et al., 2011). Table 6.5 describes these dimensions. These multidimensional measures provide strong diagnosticity (i.e., the ability to discriminate between different types of workload (Bowers, 2013)). However, a limitation of this scale is that it is created for a specific task or environment, and therefore may not reflect different dimensions of the workload in another environment (Wilson et al., 2011).

Although the NASA-TLX has been adopted to measure workload in many HCI research (Dhar et al., 2012; Salve, 2016) by aggregating individual dimension scores to provide a total mean weighted workload measure. This process ignores the primary advantage of multidimensional scales: their ability to discriminate between different sources of workload. As identified from user research studies (in Chapter 4:), students have reported to face a lot of frustration and effort while handling various equipment or in different experimental stages in practical electronics laboratories – thus indicating that they face different types of workloads. Hence, to determine the effect of SLS on various types of workloads experienced by students in practical electronics laboratory, we utilized the multi-dimensional NASA-TLX scale. In addition to this, PLS, PEOU, PU and RA questionnaires were also administered. See Annexure F2 for the questionnaires.

Table 6.5 Description of NASA-TLX subscales. Source: adapted from (S. G. Hart & Staveland, 1988)

NASA-TLX Subscales	Description
Mental Demand (MD)	Mental demand scale gives the subjective measure of how much mental and perceptual activity was required to perform the task (e.g., thinking, deciding, calculating, and remembering)
Physical Demand (PD)	How much physical activity was required to perform the task (e.g., pushing, pulling, turning, controlling)
Temporal Demand (TD)	How much time pressure students felt due to the rate or pace at which the task was performed
Performance (P)	How successful was the student in accomplishing the goals of the task
Effort (E)	How hard did the student feel she/he had to work (mentally and physically) to accomplish the level of performance
Frustration (F)	How insecure, discouraged, irritated, stressed, and annoyed did the students feel during the task

The study was carefully planned so that the running practical experiments in these institutes matched the content and setup of our working prototype. However, due to several constraints like institutes' timetables, availability of students and instructors – we had to conduct the studies in several laboratory sessions that did not entirely match with our demonstration setup. In such cases, we utilized scenario-based design techniques (Davidoff et al., 2007; Rosson et al., 2002; Carrol, 2000) to explain the participants about our prototyped setup, its functionalities, how it can be used in their current practical laboratory sessions. The participants were also described how SLS could also be generalized for other practical laboratories and disciplines. The scenario as described previously in Figure 6.3 was also delivered. Since all student participants of the study were familiar with electronics, they were able to relate completely with our prototypes. Figure 6.9 represents the type of experiments running in these institutes and the questionnaires that were administered to the participants during this usability study.

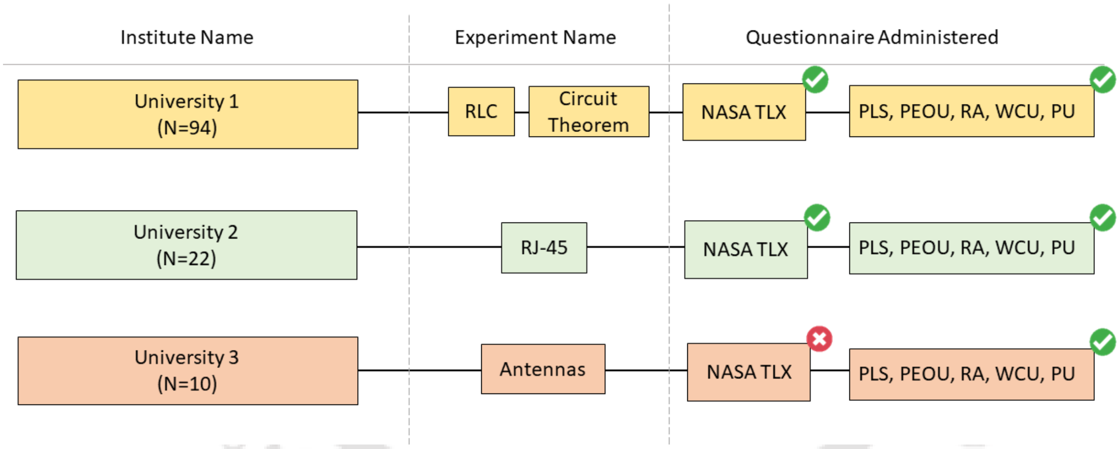


Figure 6.9 Institute names, name of running practical laboratory experiments for which the study was conducted and the types of questionnaire administered.

We did not administer the NASA-TLX for the Antenna experiment at University 3 as it was an introductory class, theoretical in nature, and the students were not required to work on an experimental setup. Therefore, the NASA-TLX could not be used as per the guidelines (S. G. Hart & Staveland, 1988) as there was no task involved. We however administered other questionnaires (PLS, PEOU, PU, and RA) about various usability aspects after demonstrating our prototyped setup and letting students interact with it.

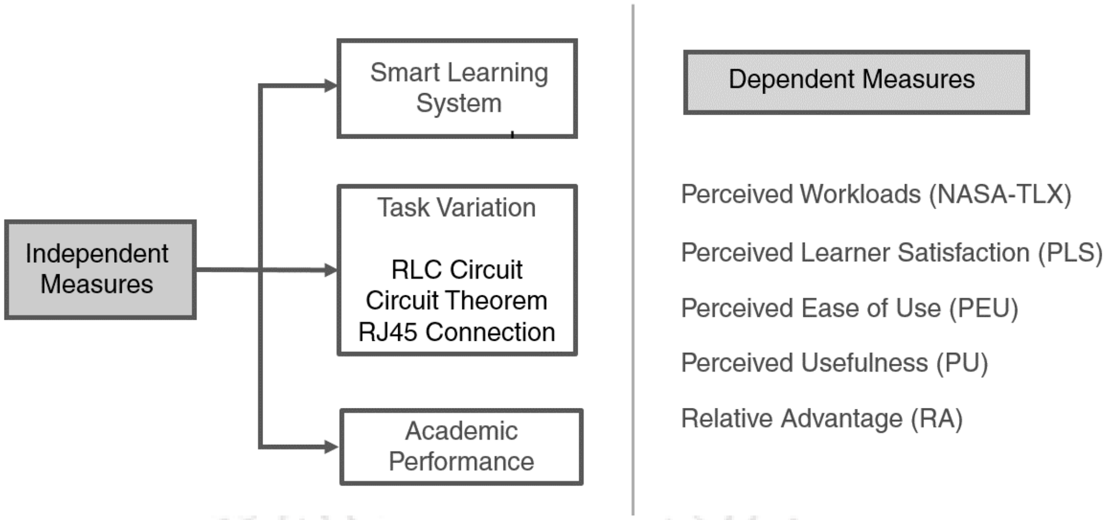


Figure 6.10 Dependent and independent measures of the study.

Figure 6.10 represents independent and dependent measures of these experimental studies conducted as a part of DE-II. Three different practical laboratory sessions running different experiments (RLC, Circuit theorem, and Familiarization with RJ-45 connector) were considered for which NASA-TLX was administered. These practical experiments have been considered as different task-variations. A brief description of these tasks is described as follows:

i. **RLC Circuit** – In this experiment, students are required to measure the input and output characteristics of passive components such as resistor, capacitors, and inductors in different combinations. The output measurements are taken from a CRO. Input source for assembled circuits is a function generator. See Annexure D2 for the lab manual use by students in this experiment.

ii. **Circuit theorem** – In this experiment students are required to learn about different types of resistor circuit and its related Superposition and Thevenin's theorems. The students measure various nodal voltages of the circuit, which mainly comprises of different resistors. Variable DC power supply is used as an input device, and a Digital Multi-meter is used to measure output. See Appendix D3 for the lab manual use by students in this experiment.

iii. **RJ-45 Cable Connection** – This experiment is mainly a part of diploma students' electronics workshop. The students are required to strip the RJ-45 cable (i.e., an Ethernet cable) from the end and attach CAT6 RJ-45 plug on it using crimp connector. Students use hand tools like coaxial cable strippers and crimper strippers.

Owing to lightweight nature of the working SLS prototype – designed as a proof-of-concept, a summative study accessing academic performance of students in terms of obtaining test scores was not feasible. Therefore, we relied on subjective and qualitative measures that assess the usability of our prototype and its effect on students' perceived workload load for various practical experiments in the laboratory.

6.3.1 The Hypothesis tested during DE-II

From the literature review, as discussed in Chapter 2, it was identified that difficulties in practical laboratories affect the extraneous cognitive load (or the mean weighted workload on NASA-TLX scale) of students. To test the effect of SLS prototype on students' overall workload and its reuse intention, the following hypotheses were formulated and tested during DE-II:

- **H1:** SLS will affect the Mean Weighted Workload (MWWL) of students on the NASA-TLX scale.
- **H2:** A positive relationship exists between learners' satisfaction and the reuse intention of SLS.

In addition to testing H1 and H2, the following hypotheses (H3 to H8) were also tested for individual factors (MD, PD, TD, P, E, F) that influence the mean weighted-workload of students in practical laboratories. For the sake of brevity and maintaining continuity in the thesis, the results of these hypotheses have been discussed in Annexure G.

- **H3:** SLS will affect the Mental demand of students on the NASA-TLX scale.
- **H4:** SLS will affect Physical Demand of students on the NASA-TLX scale.
- **H5:** SLS will affect the Temporal Demand of students on the NASA-TLX scale.
- **H6:** SLS will affect the perceived Performance of students on the NASA-TLX scale.
- **H7:** SLS will affect the perceived Effort of students on the NASA-TLX scale.
- **H8:** SLS will affect the perceived Frustration of students on the NASA-TLX scale.

6.3.2 Experiment Procedure

A within-group experiment was conducted amongst three different student groups for different tasks (RLC, Circuit theorem, RJ45), see Table 6.6.

Table 6.6 **Experiment type for conducted amongst different student groups.**

Task Name	Participant Group	Experiment type	Questionnaire
RLC Circuit	A	Within-group	Pre/ post-NASA-TLX, PLS, PEOU, PU, RA
Circuit Theorem	B	Within-group	Pre/ post-NASA-TLX, PLS, PEOU, PU, RA
RJ45	C	Within-group	Pre/ post-NASA-TLX, PLS, PEOU, PU, RA

Demographics information of the participants was collected, and a pre-test NASA-TLX questionnaire was administered during their experimental tasks (RLC, Circuit theorem, RJ45). This was done by the guidelines provided by Hart et al., (1988) which suggests that NASA-TLX questionnaire should be filled during the task or immediately after it. After the participants had finished their task, a demonstration was given to the students about our prototyped setup.

During the demonstration, the participants were briefed about the SLS prototype. Various usage scenarios of the prototyped setup were also explained to the participants. Next, the students were asked to use and interact with our prototype. After the demo session and hands-on interaction with our prototypes, the participants were asked to estimate the workload generated by using SLS for their respective experimental tasks on the post-test NASA-TLX. Usability questionnaires – PLS, PEOU, PU, and RA, were also administered. Figure 6.11 presents a complete description of the experiment design and procedure along with the dependent and independent measures.

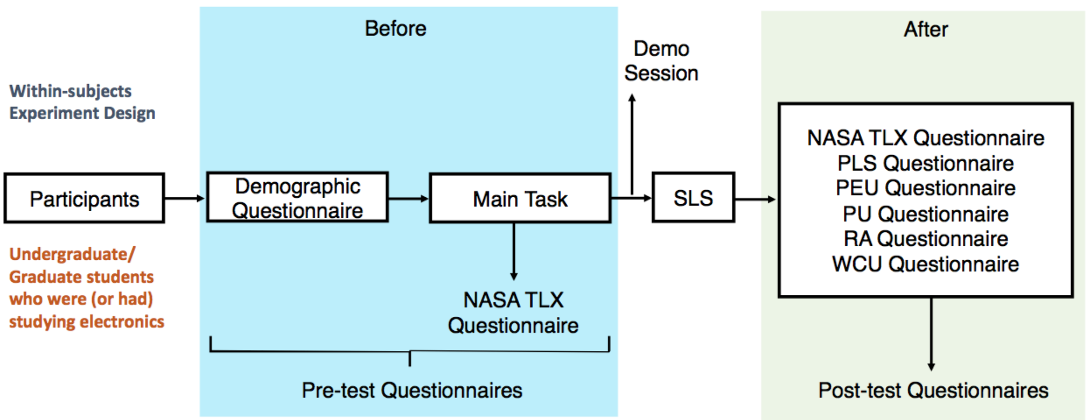


Figure 6.11 A within-group experiment design was adopted for DE-II.

6.3.3 Participants

Total N = 126 students participated in the usability study. The participants were undergraduate students from various branches of engineering who were enrolled into basic electronics laboratory courses. Diploma students from state engineering university who were enrolled in electronics and telecommunication branch also participated. All student participants were undergoing or had undergone basic electronics course. The mean age of participants was 19.28 ± 1.55 (22.2% Female, 77.8% Male). The demographics of the participants are given in Table 6.7.

Table 6.7 Demographics of students gender, age, degree courses, disciplines and awareness of technologies like AR and smart objects.

Descriptive Statistics		Disciplines	Frequency
Male	98	Chemical	62
Female	28	Biotech	16
Total	126	Bio-science	10
		ECE	12
Age	19.29 (M)	ETC (Diploma)	22
	1.55 (SD)	Mathematics	4
		Total	126
B.Tech	104		
Diploma	22	Heard of AR and related	Yes (32)
		technologies?	No (94)

6.3.4 Material and Setup used in Experiment

A demonstration setup was prepared comprising of our novel working prototypes based on an intelligent breadboard and augmented reality prototype as shown in Figure 6.12. Mock-ups printed on papers that explained additional use cases and functionalities of our demonstration setup were also utilized to give users a complete perspective of SLS usage scenario. Paper-based questionnaire on learner satisfaction and task load were given to users. Scenarios, as shown in box represented by Figure 6.3, was delivered and explained to the participants during the demonstration.

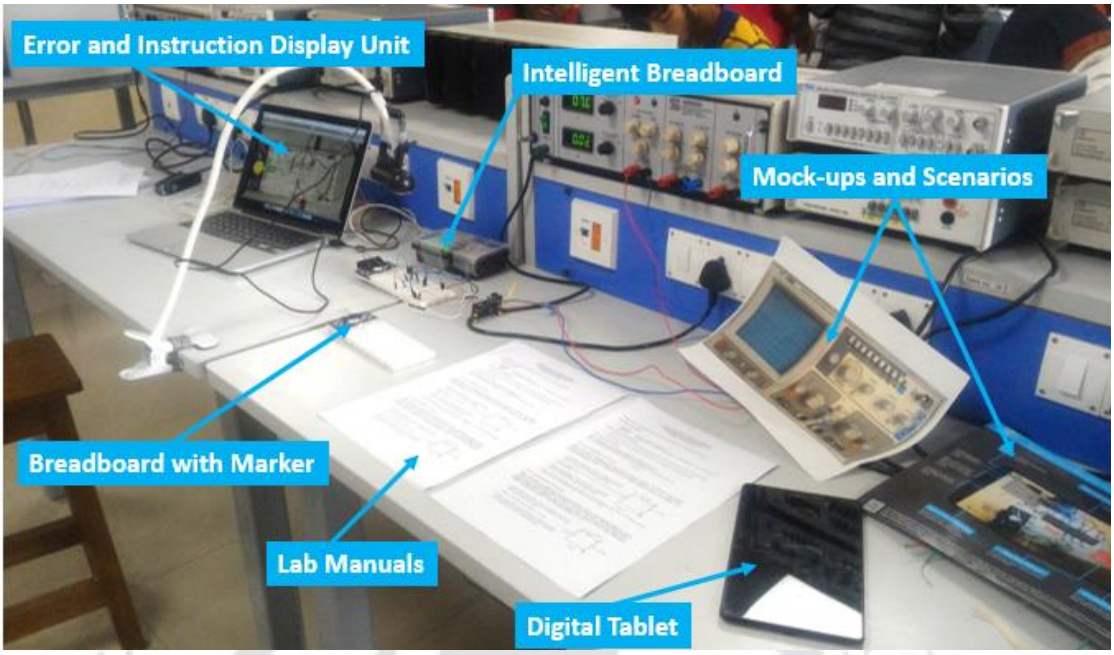


Figure 6.12 SLS demonstration setup comprising of tablet loaded with AR prototype, intelligent bread-board setup connected to a computer and conceptual mock-ups of the prototype.

The subsequent sub-section enlists the detailed results of hypotheses testing.

6.4 Results and Analysis from DE-II

This section presents the results on testing hypotheses regarding the influence of SLS on overall extraneous cognitive load (or MWWL) of students and its reuse intention.

The effect of SLS on MWWL and related workload factors (MD, PD, TD, P, E, F) were measured in three ways, (i) Based on overall workload factors for all participants. (ii) Based on the academic performance of students, and (iii) Task-specific effect on various workload factors of NASA-TLX questionnaire (discussed in Annexure G). The MWWL was calculated as per the guidelines given by Hart et al., (1988).

A total of N = 90 valid responses of the participants were obtained after list-wise deletion from 116 NASA-TLX questionnaires. Paired t-tests were carried out to compare means between the groups for within-group study. Before conducting the analysis, the assumption of normally distributed difference score was examined, and the data was found to be normally distributed. The results of these tests are described as follows.

6.4.1 Influence of SLS on students workloads

Overall descriptive statistics of all NASA-TLX dimensions for traditional laboratory without the use of SLS and with the use of SLS are presented in Table 6.8. Individual workload factors and MWWL were measured. H1 pertains to MWWL. H3 to H8 pertain to additional workload factors. Table 6.9 depicts the results of paired sample t-tests conducted to test the hypotheses framed around various factors that affect students workload in practical laboratories. The results indicate that SLS reduces the MWWL and other workload factors affecting students in practical laboratory sessions. Figure 6.13 depicts a comparative graph between the means of different dimensions of NASA-TLX scale.

Table 6.8 Descriptive statistics for different dimensions on NASA-TLX scale (0 = Low to 100 = High)

		Traditional Lab		Smart Learning System	
Workload Type	**N**	**Mean**	**SD**	**Mean**	**SD**
Mental Demand	90	35.56	21.09	19.42	17.38
Physical Demand	90	11.34	12.71	8.53	10.41
Temporal Demand	90	19.80	9.29	12.78	9.48
Performance	90	19.24	15.84	21.02	14.23
Effort	90	49.47	18.29	24.21	17.30
Frustration	90	30.72	20.29	10.32	8.28
MWWL	90	11.03	2.69	6.43	2.89

Table 6.9 Results of paired t-tests conducted for hypotheses testing.

Task name	Result from paired *t*-test	Null Hypotheses	
MWWL	$t(89) = 10.923,\ p < .0001,\ d = 1.15$	Failed to Accept H_{01}	Overall cognitive load
Mental Demand	$t(89) = 7.145,\ p < .0001,\ d = 0.75$	Failed to Accept H_{03}	Hypotheses pertaining to various workload factors effecting the overall cognitive load.
Physical Demand	$t(89) = 2.906,\ p = .005,\ d = 0.31$	Failed to Accept H_{04}	
Temporal Demand	$t(89) = 5.629,\ p < .0001,\ d = 0.59$	Failed to Accept H_{05}	
Performance	$t(89) = -2.042,\ p = .044,\ d = -0.22$	Failed to Accept H_{06}	
Effort	$t(89) = 9.446,\ p < .0001,\ d = 1.00$	Failed to Accept H_{07}	
Frustration	$t(89) = 9.281,\ p < .0001,\ d = 0.98$	Failed to Accept H_{08}	

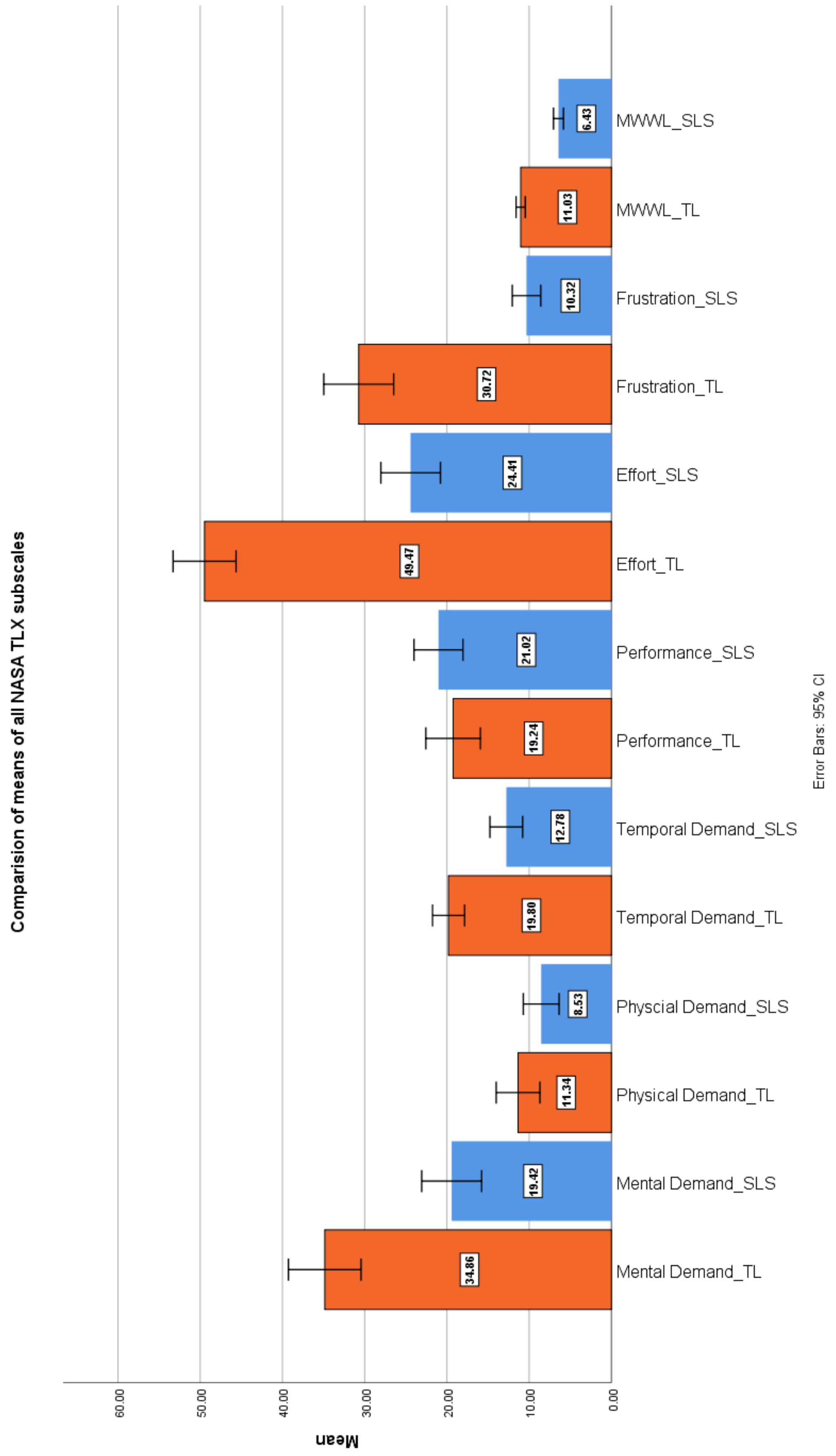


Figure 6.13 Comparison of means of all NASA-TLX subscales

6.4.2 Influence of SLS on MWWL of students according to academic performance

The following hypotheses (H1) has been tested to understand the effect of SLS based on academic performance of students.

H_1: SLS will affect the overall Workload of students on the NASA-TLX scale.

Influence of SLS on MWWL of students according to their academic performance was also measured. Table 6.10 present the descriptive statistics MWWL according to students' rated academic performances. Table 6.11 presents the results from a paired t-test. Figure 6.14 depicts the overall means of NASA-TLX scales and MWWL according to students' academic performance. Further task-specific measures of workload factors have been discussed in Annexure G.

Table 6.10 Descriptive statistics of Weighted Workload for different tasks on NASA-TLX scale (0 = Low to 100 = High)

		Traditional Lab		Smart Learning System	
Academic Performance	**N**	**Mean**	**SD**	**Mean**	**SD**
Up to 50%	19	11.65	2.42	6.74	2.96
Up to 70%	20	11.01	2.80	8.00	2.95
Above 70%	51	10.80	2.76	5.7	2.61

Table 6.11 Results of paired t-test for different academic performance.

Academic Performance	Result from paired *t*-test	Null Hypotheses
Up to 50%	$t(18) = 4.973,\ p < .0001,\ d = 1.14$	Failed to Accept H_{07}
Up to 70%	$t(19) = 3.035,\ p = .007,\ d = 0.68$	Failed to Accept H_{07}
Above 70%	$t(50) = 10.134,\ p < .0001,\ d = 1.42$	Failed to Accept H_{07}

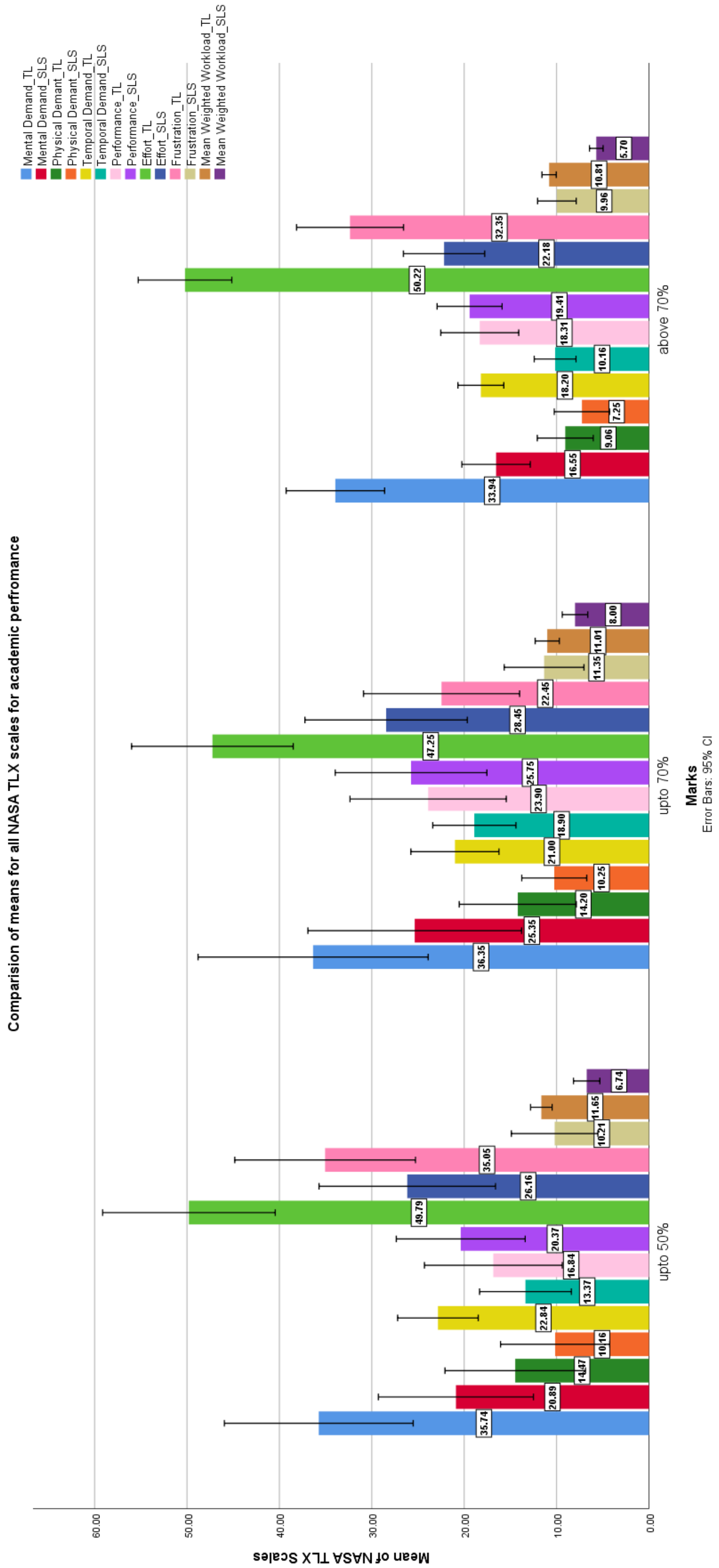


Figure 6.14 Workloads experienced according to academic performance.

6.4.3 Reuse intention towards SLS and Perceived Learners' Satisfaction

H_2: A positive relationship exists between learners' satisfaction and the reuse intention of SLS.

To test the hypothesis (H2) a Spearman's rho correlation analysis between the total score of PLS questionnaire items (I, C, P, L) and the sum of criterion questions was accessed as per the guidelines provided by Wang (2003). Spearman's rho correlation shows a statically significant positive relation, $r_s(93) = .751$, $p = .01$, thereby validating the hypothesis H_2.

Table 6.12 shows a strong Spearman's rho correlation between PLS, PEOU, PU, and RA. It can be interpreted that a strong significant positive correlation exists between these parameters.

Table 6.12 Spearman's rho correlation between PLS, PEOU, PU, and RA

	PLS	PEOU	PU	RA
PLS	1			
PEOU	.769**	1		
PU	.655**	.589**	1	
RA	.661**	.670**	.525**	1

** Correlation Significant at 0.01 level

Table 6.13 presents a descriptive statistics of PLS, PEOU, PU, and RA. It can be seen from the table (PLS15) that students show a high willingness to adopt SLS as a learning aid in practical laboratories, M = 6.12, SD = 1.113.

Table 6.13 Descriptive statistics PLS, PU, PEOU, RA (N = 95)

Item Code	Item Description	Mean	SD
Perceived Learner's Satisfaction			
PLS1	The SLS provides content that exactly fits your needs in conducting specific lab practical at the right time.	5.78	1.314
PLS2	The SLS is easy to use.	6.04	1.148
PLS3	The SLS makes it easy for you to find the content you need in your own way of exploring.	5.83	1.048
PLS4	The content provided by the SLS is easy to understand.	5.93	1.142
PLS5	The SLS is user-friendly in term of its user-interface.	6.00	1.111
PLS6	The SLS responds to your request fast enough.	5.80	1.048
PLS7	The SLS makes it easy for you to evaluate your progress and learning performance and become confident.	5.78	1.150
PLS8	The testing methods provided by the SLS in understanding the experiment are easy to follow and interact with.	5.84	1.142
PLS9	The SLS provides secure testing environments in which you are not afraid to make mistakes involving circuits, blown devices and short-circuits.	5.93	1.104
PLS10	The SLS enables you to choose what you want to learn and when you want to learn when you are deeply concentrating in the experiment.	5.68	1.331
PLS11	The SLS provides personalized learning support just as an instructor/tutor/lab assistant would do.	5.81	1.179
PLS12	The SLS makes it easy for you to discuss questions and doubts with your teachers and batchmates during the experiment itself.	5.68	1.178
PLS13	The SLS makes it easy for you to share what you learn with your peers and batch mates.	5.77	1.180
PLS14	As a whole, you are satisfied with the advantages provided by the SLS.	5.87	1.160
PLS15	If made available in your institute, you will definitely this SLS.	6.13	1.113
Perceived Ease of Use Scale			
PEU1	The SLS was simple and easy to use.	4.41	0.751
PEU2	I feel comfortable using this SLS.	4.43	0.753
PEU3	It was easy to learn to use this SLS.	4.38	0.801
PEU4	I believe I became more productive using this SLS during my experiment.	4.17	0.930
Perceived Usefulness			
PU	I can effectively complete my lab practical on my own using this SLS.	4.34	0.881
Relative Advantage			
RA1	Performing lab practical, using this SLS is more effective than using only traditional paper and simulation-based formats.	4.37	0.768
RA2	This SLS is better that other lab instructional systems like Internet and simulation software I have used so far.	4.33	0.881

6.5 Inferences

Hypotheses H_1 and H_3 to H_8 deal with testing the influence of SLS on various workload factors of students on NASA-TLX scale. As seen from previous results presented in Section 6.4.1 and 6.4.2, and Annexure G, the hypotheses testing for different tasks indicate that all hypotheses are supported for RLC experiment. In case of Circuit theorem, H_1 and H_7 are supported. For RJ45, H_4 is supported. Table 6.14 depicts the consolidated results of hypotheses for various tasks. Refer Annexure G for results on the task-specific effect of SLS on various workloads of students.

Table 6.14 Consolidated results of hypotheses testing of workloads for various tasks.

	RLC	Circuit Theorem	RJ45
H_1	Supported	Supported	Not Supported
H_3	Supported	Not Supported	Not Supported
H_4	Supported	Not Supported	Supported
H_5	Supported	Not Supported	Not Supported
H_6	Supported	Not Supported	Not Supported
H_7	Supported	Supported	Not Supported
H_8	Supported	Not Supported	Not Supported

When considering the influence of SLS overall by combining all tasks, see Section 6.4.1, it is observed that the SLS influences various workload factors significantly. Factors such as effort (E), frustration (F), mental demand (MD) and mean weighted workload (MWWL) are influenced strongly by the SLS and have a large effect size ($d \geq 0.8$). It can be stated that the SLS reduces these workload factors among students. The SLS also effects the temporal demand (TD) with a medium effect size ($d = 0.6$) implying that students perceive that SLS will help them save time in the laboratory. The performance (P) shows a relatively small effect size ($d = -0.2$) implying that students perceive that it will not influence their performance much. It can also be observed that students with different academic performance perceive that the SLS will reduce the overall workload in practical electronics laboratories.

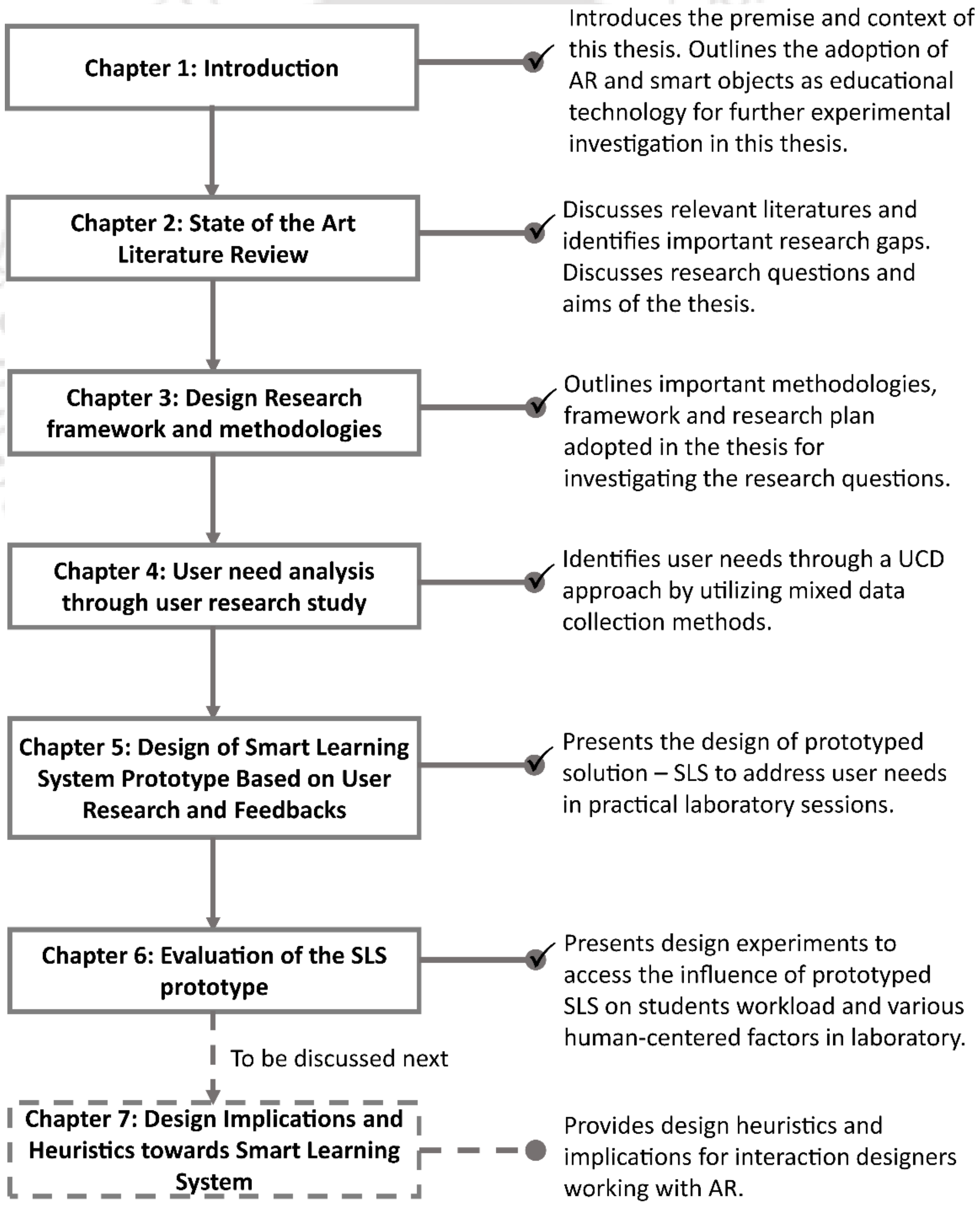
Overall, from H2, it can be seen that the students are willing to reuse the SLS in laboratories.

6.6 Chapter Summary

The chapter presents the results of DE-I and DE-II conducted across India. The results indicate that the SLS influences the workload of students and reduces factors such as effort, frustration, mental demand, temporal demand and overall workload.

A quick recap of previous chapters:

A visual summary of the chapters covered so far is provided as follows:



Chapter 7: Design Implications and Heuristics towards Smart Learning System

Chapter Abstract: This chapter presents design implications and heuristics derived from experimental investigations carried out in the thesis.

7.1 Introduction

The thesis attempts to state that it is possible to interweave different emerging technologies such as – augmented reality, smart objects, artificial intelligence, and the internet of things together into a holistic system to enrich students' learning experiences. The designed SLS, discussed in Chapter 5, can assist students with their experimental tasks by utilizing AR and intelligent breadboard. SLS provides instructional prompts to reinforce student's learning and can facilitate teaching in laboratory sessions by providing real-time student monitoring capabilities to instructors.

The thesis also argues, in Chapter 6 under Sections 6.2 and Section 6.3, that that the proposed SLS reduces the workload and enhances collaborative learning effort amongst students while they conduct practical electronics laboratory sessions in groups. The conceptualized instructor dashboard system, proposed in Chapter 5 under Section 5.4, can also reduce the load on tutors and overloading of institutional infrastructure facilities and maximize teacher's teaching time.

Based on the insights gathered from experimental investigations and prototype development process reported in this thesis, design implications and heuristics towards developing a learning system for practical electronics laboratory sessions have been derived and reported in the following Section 7.2. These heuristics will be helpful for Interaction Designers and HCI researchers working on AR or mixed reality (MR) in their effort to develop effective learning mediums to improve learning experiences for students. Further investigations to test and validate these heuristics can be carried out as future work.

7.2 Design Heuristics and Implications for Designers

In Design, heuristics refer to a set of broad rule or prompts that can be useful for designers to design user-interfaces and explore variations in design solutions. According to Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez (2014):

> "Design heuristics are intended to help designers move through a "space" of possible solutions, helping designers to intentionally introduce variations within their designs to generate non-obvious ideas that are also different from one other. They are also likely to support designers in becoming "unstuck" or removing fixation when they have worked on a task for a long time, and are struggling to generate more, and different, ideas. Design Heuristics can repeatedly be applied, and in combination, to produce a variety of novel and original design ideas. As a tool, Design Heuristics can help a designer generate multiple creative and diverse ideas so that they will have explored the full space of potential designs."

The design of learning system (SLS in this thesis) in the context of practical electronics laboratory sessions requires understanding about (i) the kind of activities users be involved in while conducting a practical experiment, (ii) how users are going to interact with the system, (iii) the appropriateness of different interaction modalities and arrangement for user-interface on AR. A set of heuristics have been derived in the thesis as under. These heuristics will be useful for designers working towards utilizing AR as a learning medium for the educational practical laboratory.

These design heuristics fall under broad HCI factors of User-Interface (UI) design, Utility, Enjoyability, and Functionality and lead towards overall usability and usefulness of the AR-based learning system. The UI design pertains to the AR application interface with which the users interact. Utility refers to the tools that should be embedded in the AR application and will be useful for users in a practical laboratory scenario. Enjoyability means the degrees to which the instructional content created for AR is entertaining and pleasurable for the user so that it leads towards playful engagement and learning. Functionality refers to technical features that should be considered while developing the AR application for practical laboratory context. Figure 7.1 depicts these broad HCI factors and their relation to the derived heuristic for AR learning system in the practical laboratory.

These design heuristics have been derived from field observations, user research studies, and prototype development and can be used by AR content and interface designers for developing mobile AR experiences for practical laboratory sessions. These have been discussed as follows:

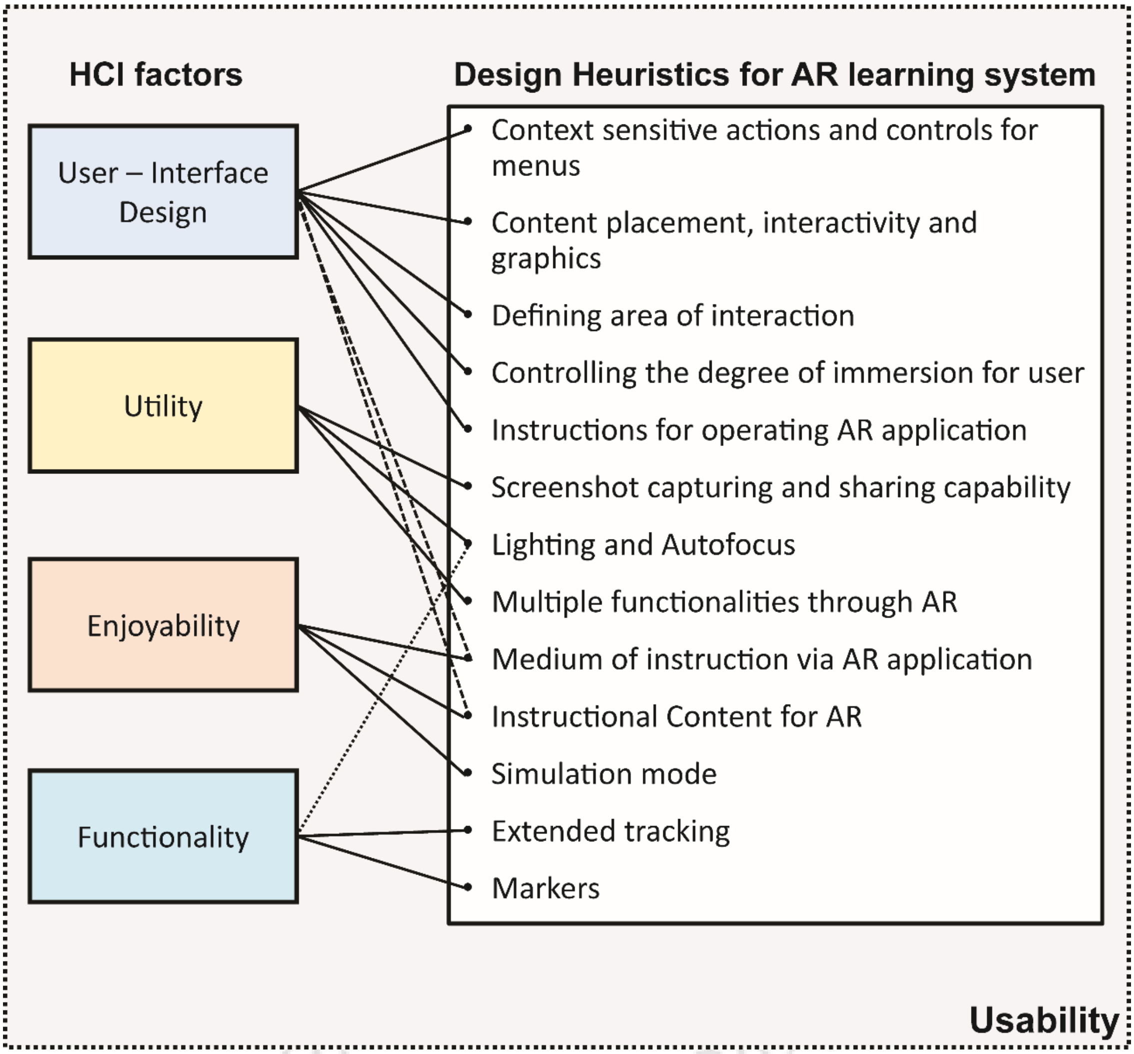


Figure 7.1. Broad HCI factors of derived design heuristics

- **Instructional Content for AR**

Experiment with a variety of ways in which content can be overlaid onto real world (practical laboratory environment) using AR. Do not just restrict to 3D graphics – as has been observed in many research literatures. Experiment by overlaying relevant videos, 2D images (both static and animated) and audios to help the user learn better in practical laboratory sessions.

- **Context sensitive actions and controls for menus**

A single AR application may contain many functionalities that need to be superimposed over different contexts - like a breadboard, lab equipment, markers, laboratory manuals, etc. Designing menu items for each of these becomes challenging, as we need to take into the account the geometries of the object over which the content is superimposed and occlusion effects. A standard way is to implement a ray cast menu – which is AR based marker specific menus, unlike fixed GUIs. Figure 7.2 depicts an example of a ray-cast menu. Appendix E2 depicts the wireframe of AR application with fixed GUI elements.

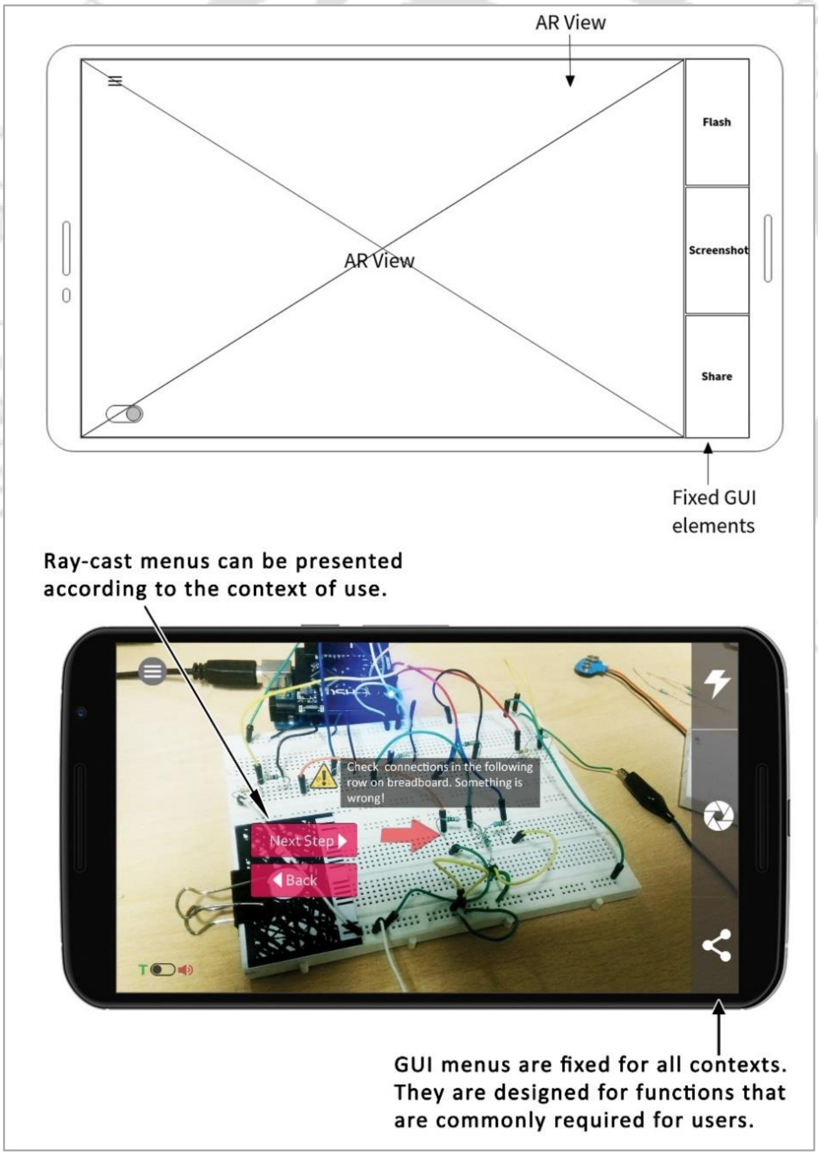


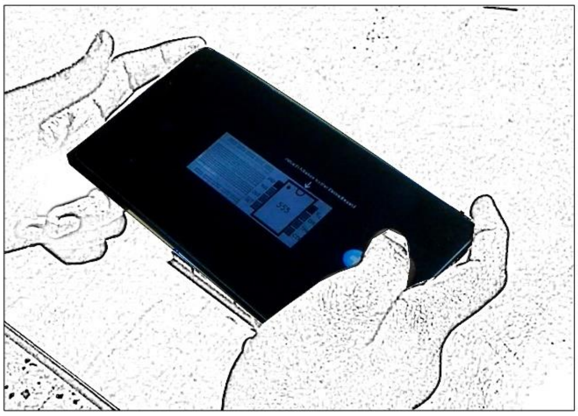
Figure 7.2 Ray cast and GUI menu elements of AR application. Top image shows a wireframe of AR applicatoin. The image below shows a mock-up of AR with ray cast and GUI menus.

Menu elements should be designed such that user's depth perception is taken into consideration along with the surface geometry for better interaction between user and content. The menu items should also be placed within the field of view of user's screen. Users find it difficult to navigate content and menu items that fall outside the screen area or visual field of view. Affordance of the 3D objects and super-imposed digital content is also of prime importance. Authors (Dünser, Grasset, Seichter, & Billinghurst, 2007) have highlighted several design guidelines that can be useful in this regard.

- **Overlay screens providing instructions to operate AR application**

Many users, at present, are still not familiar with the AR technology and how it works. An overlay screen (or splash screen) providing instructions about how AR has to be used when application starts will be helpful. Figure 7.3 shows one of the overlay screens of our updated version of AR application. When initialized, the AR application screen provides instructions to users regarding how to attach a marker on a breadboard, augment digital content over objects by tracking image targets and inform them about various functionalities of the application. Annexure E2 presents a complete interaction flow diagram of AR with splash screen.

Authors (Rolim, Schmalstieg, Kalkofen, & Teichrieb, 2015) have presented a set of AR guidelines to provide instructions to users based on the classic mode by superimposing text, images, and graphics. These guidelines can also be integrated to improve the usability of AR.



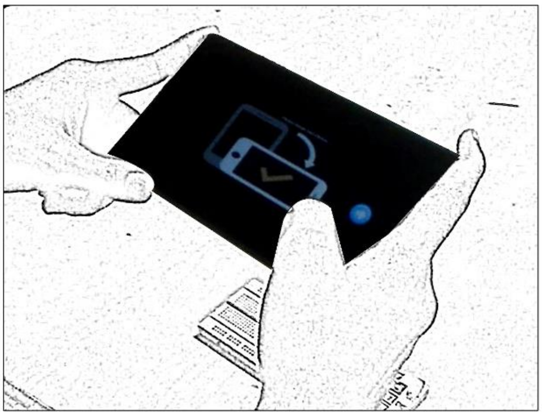


Figure 7.3 Additional AR application features. Overlay screens provide information to users on how to operate AR application.

- **Designing multiple functionalities through AR**

Utilize the complete experimental setup workspace of the user in a laboratory for overlaying instructional information via AR. There are a number of test equipment and devices whose functioning is arcane to users. AR can help users unravel them. This thesis reported three main functionalities for AR, i.e., equipment operation guide augmented laboratory manuals and 3D circuit building guide. A suggested wireframe for overlaying instructions over CRO using AR is shown as an example in Figure 7.4. Similar functionalities can be created for other test equipment or devices and manuals in the laboratory.

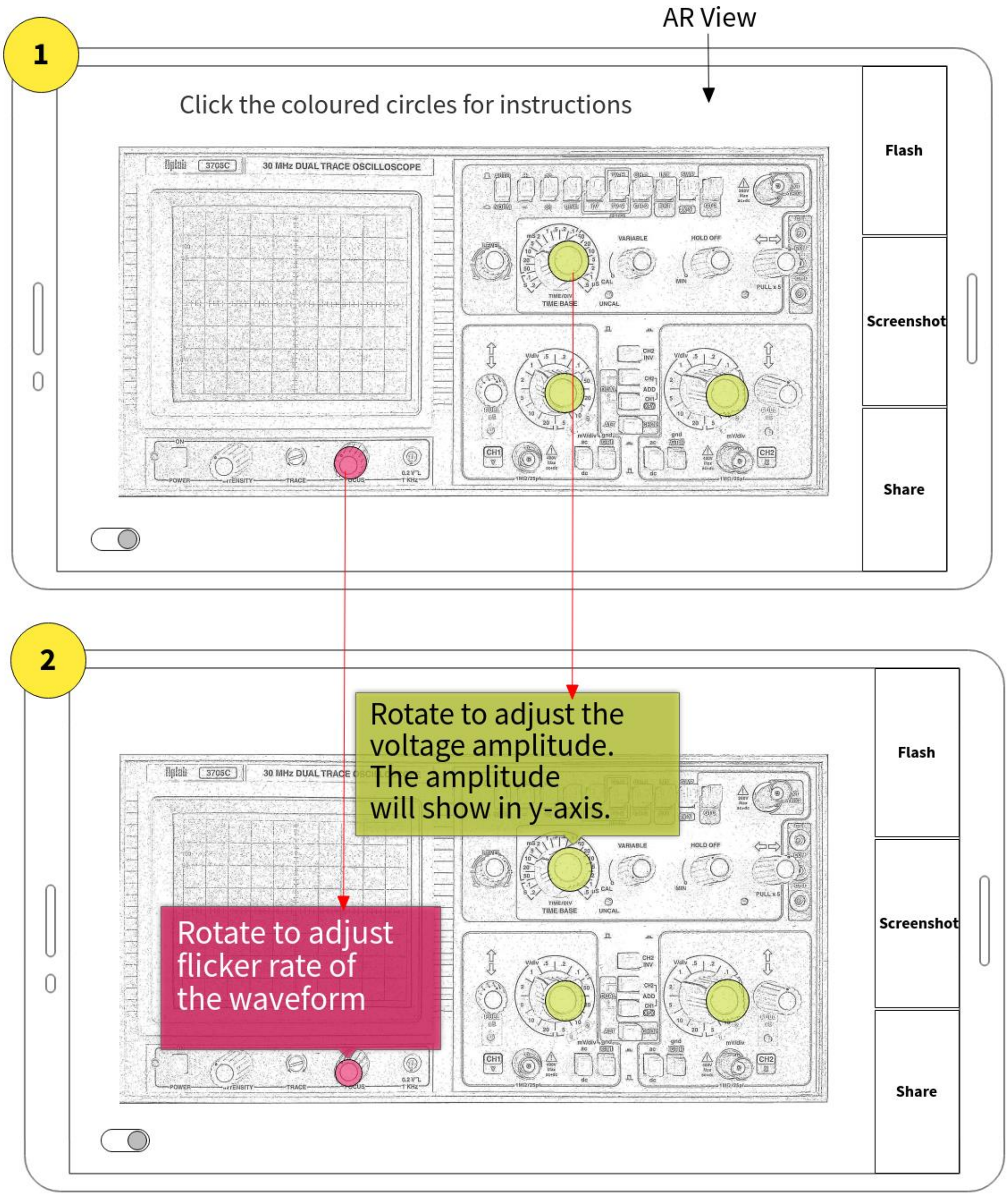


Figure 7.4 Wireframe of AR functionalities overlaid on CRO

- **Screenshot capturing and sharing capability**

This functionality has mainly been used in many commercial AR applications for entertainment purpose (for example Snapchat[2], Instagram[3]). Although an obvious feature, it was found that many studies on AR design guidelines have not highlighted this functionality or mentioned its usage.

From our user research studies (see Chapter 4, Section 4.4) it was observed that students, as well as lab instructors, often used their smartphones as a data collection device in the laboratory by taking the photographs of the experimental setup and output on CRO. These photographs are used as a reference during reporting of experiment or later use, such as exam preparation or discussing with peers of different laboratory group. Since our prototype initially lacked this functionality, we observed that it caused a break in the interaction between the user and AR application, which was time-consuming and cumbersome. Having the ability to take photographs or screenshots from within the AR application can leverage its capabilities further as a data logger and reporting tool thereby improving its utility and usability in practical laboratory sessions. This functionality was added purposefully in our AR prototype for a demonstration after the observations made by user-studies as shown in Figure 7.5. Complete wireframes, GUI, and interaction flow diagram for AR application are presented in Annexure E.

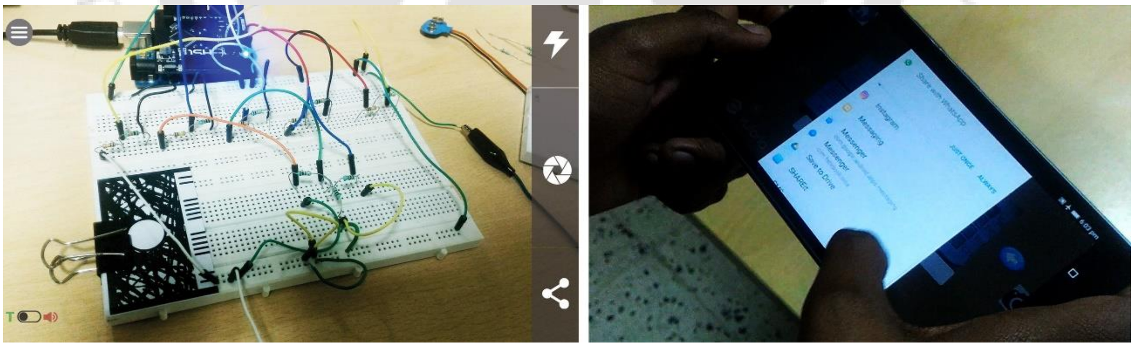


Figure 7.5 Screenshot and sharing capabilities in AR application prototype. Left image shows a GUI of AR application. The last button at bottom right is for sharing screenshots. Right image shows sharing options that popped up upon pressing the share button on GUI.

- **Lighting and Autofocus**

Proper lighting is a major concern for AR without which the detection of marker and content augmentation is not possible. Since students often work in groups on an experi-

[2] https://www.snapchat.com , [3] https://www.instagram.com,

ment, chances of shadowing the marker increases. Having a proper light source or utilizing correct markers for the application will be helpful in such cases. Mobile AR Application for labs should provide functionality to turn on inbuilt LEDs in smartphones. Further, an autofocus feature should be added so that the camera can adjust in low-light conditions. Autofocus is also helpful in detecting markers quickly and will save user's time while operating the application by avoiding them to restart the app again. This feature was not also reported in any kinds of the literature of AR for educational uses. A complete GUI has been presented in Annexure E2 that depicts these functionalities.

- **Controlling the degree of immersion for user**

Students often narrow their attention on mobile AR view while interacting with the application. This limits them from getting the complete experience of the laboratory environment. AR designers need to consider factors that control the degrees of immersion of AR users to harmoniously synchronize AR experience with the overall experience of a real environment and does not tunnel the user's vision to AR view. Perhaps a timer that breaks interaction of students by asking them to set aside the AR application for some time can be used as a stopping queue. Figure 7.6 depicts a possible wireframe that monitors student's onscreen activity and disables the AR view so that they can concentrate more on the physical setup. This should perhaps also prevent students from relying on AR too much.

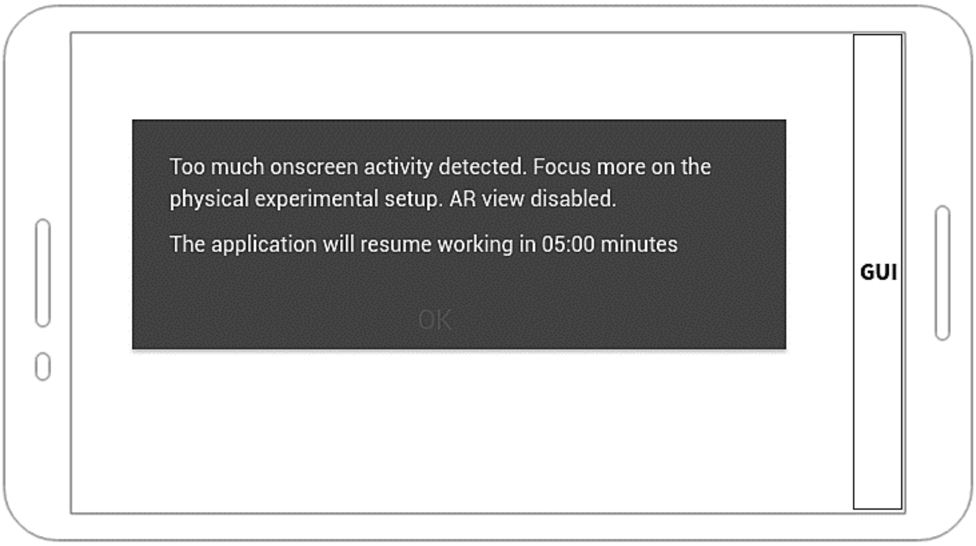


Figure 7.6 Wireframe depicting onscreen activity monitor notification to keep a check on AR application usage.

- **Content placement, interactivity, and graphics**

Sometimes multiple contents need to be superimposed onto a single image target. This poses a challenge regarding (i) placement of content with respect to the mobile screen and user's field of view, (ii) designing navigation to select the content and (iii) switching between one content to another within a confined spatial limit. The content should not be scattered across the image target to roll out of user's AR view on mobile screen and should fall within user's field of view.

If however, the content is too large to be displayed over a single area, navigational queues should be added for users as a prompt to move the mobile device to the required location of the content. Further, care should be taken while designing the graphics to be superimposed over objects so that it does not merge with the real world background – this will hide the content from the user.

In the context of the practical laboratory, the 3D content needs to be distinct and easily visible to students. For example, while designing 3D component with dark shades that merge with the real-world background, add a contrasting background graphics, see Figure 7.7.

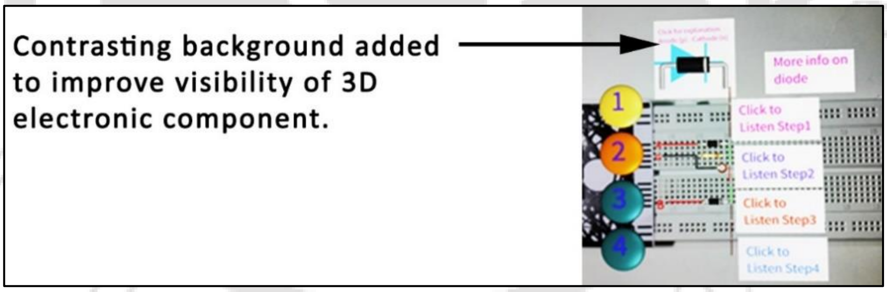


Figure 7.7 Contrasting background should be added behind 3D electronic components when required to improve the visibility

- **Defining area of interaction**

In the context of practical electronics lab sessions, students' workspace interactions are mostly confined to their equipment, experimental setup, and peers with limited physical movement. It is for this workspace that mobile AR applications need to be designed. However, while designing AR instructions, the area of interaction is not just limited to the device screen. Given the spatial freedom for virtual content in AR, Designers need to be careful about the placement of superimposed digital content so that it does not fall outside user's field of view. AR interactions taking place within the user's field of view would retain an engaging interaction with AR and collaboration amongst students. If the users require physical movement to access the content beyond the field of view, they start feeling uncomfortable. Therefore, menus and contents need to be designed accordingly.

- **The medium of instruction via AR application**

Voice-based instructions were reported to a useful feature for independent learning that takes place individually or outside of the lab sessions. During lab sessions, students preferred visual and text-based instructions. Students also suggested including more language options for voice-based instructions in the application as they feel more comfortable getting inputs in their native language.

- **Markers**

While conducting experiments in laboratories, it is often difficult to focus on markers. This creates a problem for users, as AR content cannot be displayed. Suitable markers should be designed depending on the application context, usage environment, and lighting conditions. In scenarios where markers cannot be used, markerless AR techniques can be explored.

- **Extended tracking**

Students viewing projected virtual information through AR often try to see it in conjunction with other real-world objects that do not have required markers or virtual information attached. For example, students viewing a superimposed video of the theoretical waveform on laboratory manuals on AR view tried to drag it using long-press finger interaction towards CRO screen to compare it with actual output waveform. Extended tracking features (Vuforia, n.d.-a) can give students the flexibility to move the virtual content over the desired physical space through AR requiring image target in AR camera's field of view.

Figure 7.8 depicts a wireframe and a conceptual view of extended tracking where students can compare the theoretical waveform overlaid on laboratory monitor by overlaying if near CRO screen. Students can overlay content from one marker to another using this feature to compare results or content.

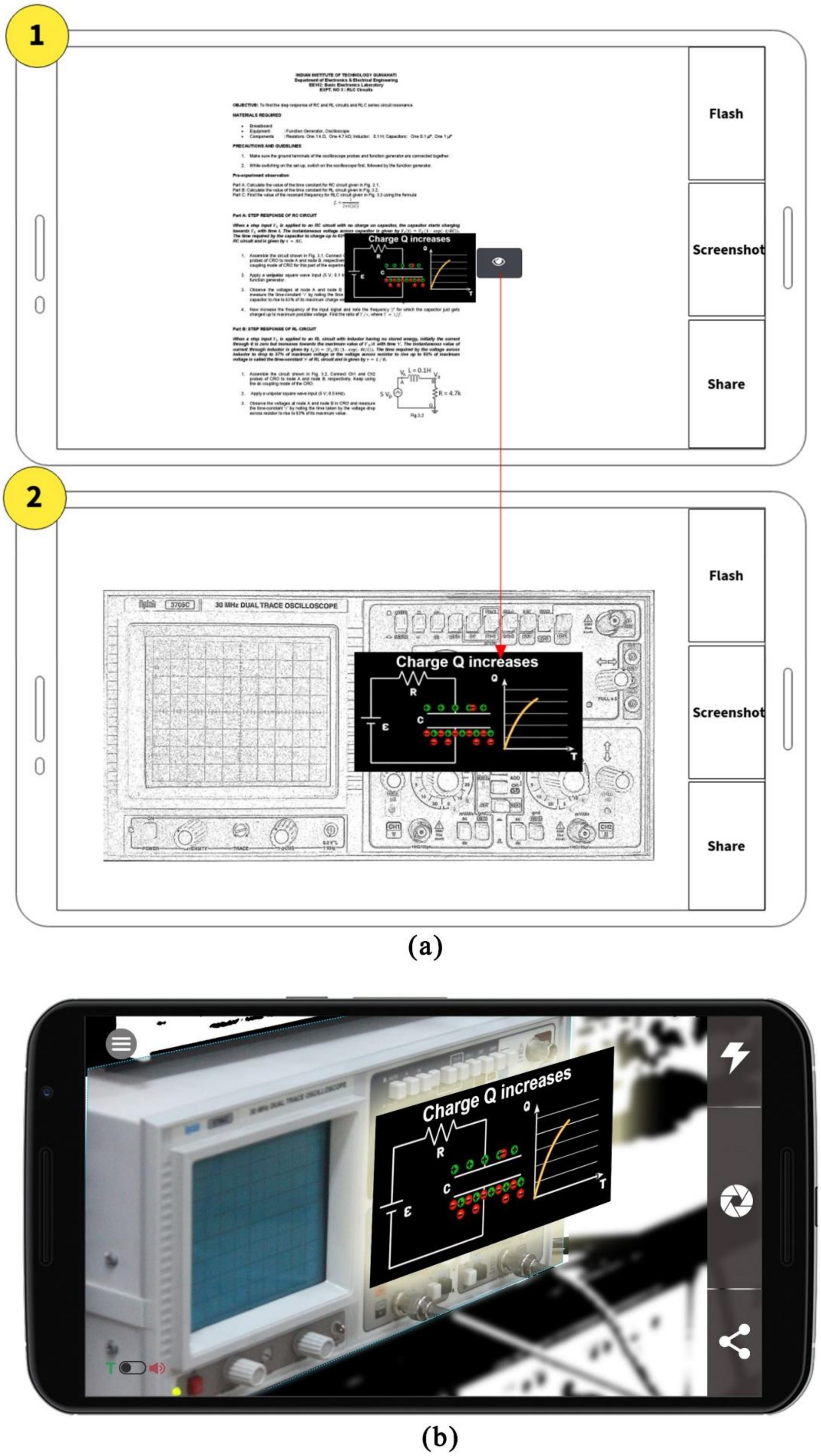


Figure 7.8 Extended tracking feature. (a) Possible wireframe of extended tracking feature. (b) Conceptual representation of extended tracking view on AR application interface. Theoretical waveform can be displayed next to CRO screen. This will allow students to compare theoretical and practical results simultaneously.

- **Simulation mode**

Based on our observations in practical lab sessions, we found that students are often reluctant to try new methodologies while experimenting due to safety concerns like a risk of getting an electric shock, short circuits, blowing up electronic components or equipment. This fear hinders their process of experimenting in a practical lab session. A simulation mode feature can be used by students to experiment freely without fear. This feature can enable students to simulate and visualize electronic circuits in 3D visuals close to reality where they can input any circuit conditions based on real-world situations and view the output on AR view. Figure 7.9 depicts a suggested wireframe for simulation mode.

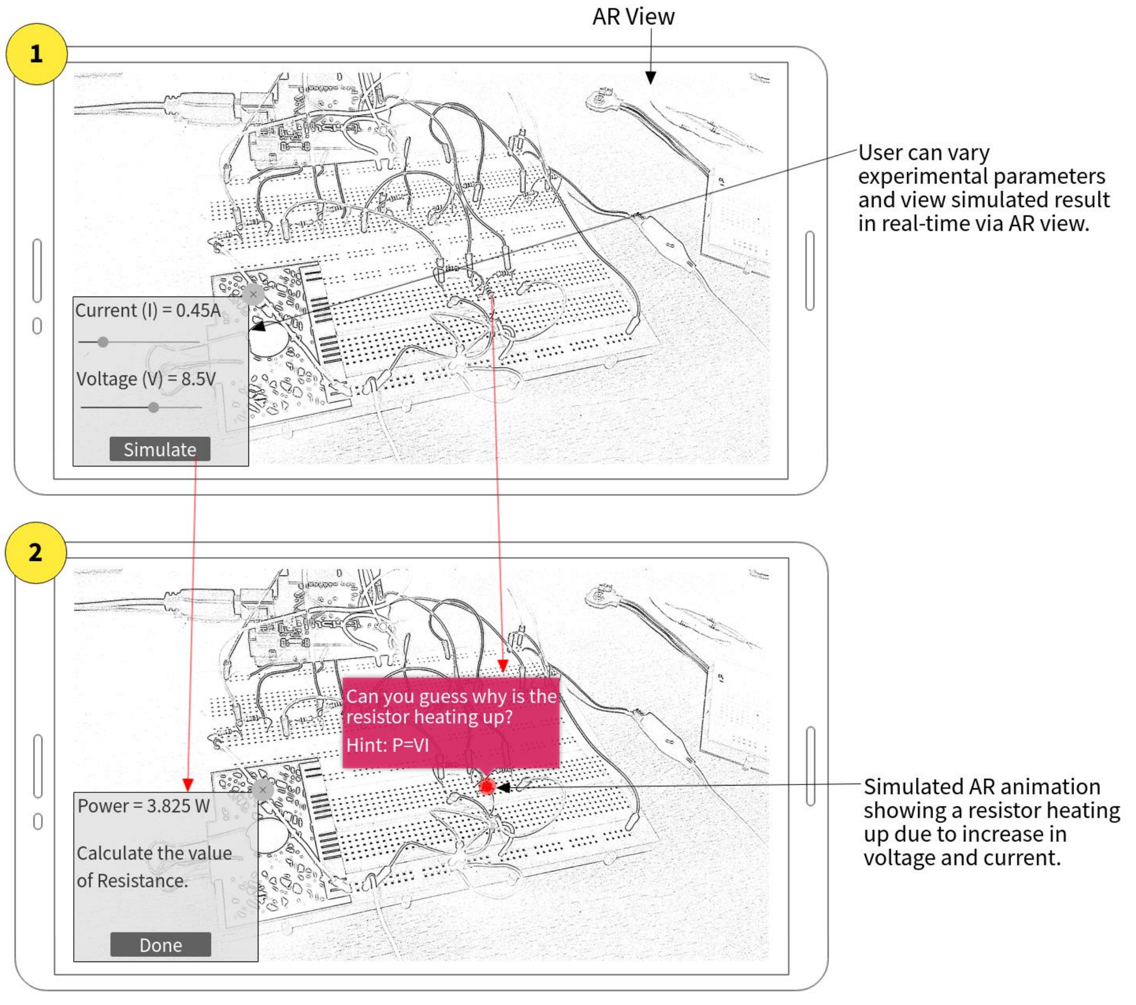


Figure 7.9 Possible wireframe for simulation mode using AR. The user can manipulate various experimental parameters, as shown in the wireframe image on top, and view the effect of variations of these parameters on circuit in real-time as animations super-imposed on actual circuit. The wireframe image below shows a possible way in which this animation can be shown to the user.

7.3 Advantages of SLS in simplifying instructor's task when implemented

A typical laboratory instructor of a fully supported large national institute (such as IITs) with proper infrastructure and resources addresses around 30 – 35 students in practical sessions. Two to three teaching assistants are also involved in instructing and assisting students in a practical laboratory with the instructor in these institutes. This means that the total of 2 to 3 instructors (including TAs) are involved in a laboratory session. Even with all the facilities available, instructors need to devote a lot of time to help students in practical sessions. From the calculations presented in Table 7.1, it can be seen that in a three hours laboratory session, an instructor needs to spend around 45 minutes per student group.

Table 7.1 A hypothetical calculation on instructor's time consumed in a practical laboratory session

<table>
<tr><th>Traditional laboratory without the use of SLS</th><th>Laboratory with the use of SLS</th></tr>
<tr><td colspan="2">Total time for a laboratory session per week = 3 hours
Total number of students in laboratory session = 30
Total number of student groups (30/5 students) = 6
Number of instructors available for 30 students in a large institution = 2 to 3</td></tr>
<tr><td>Total number of actual contact time spent by an instructor on a student group = ~ 15 minutes

The frequency of instructor attention required by a student group in one lab session = 2 to 3 times (as observed from contextual inquiries, see Chapter 4, Section 4.2.1)

Extra contact time if instructor addresses a student group multiple times = ((Contact Time spent on each student group) x (Frequency of instructor attention)) = ~ 30 minutes

Overall time spent by instructors on a student group in a laboratory session = Actual contact time + Extra contact time = ~ 45 minutes

Add to these other time-consuming factors like faulty equipment, troubleshooting time, insufficient instructional materials available to students (all factors have been discussed in Chapter 4)</td><td>As the SLS addresses most common difficulties of students, therefore instead of dividing contact time individually for each group, instructors will be able to focus more on the groups that require help. Thus increasing contact time based on student group requirement.

As the instructors are provided real-time information regarding students' progress and difficulties on instructor dashboard (discussed in Chapter 5, Section 5.4) frequency of instructor attention required by a student group in one lab session will decrease to 1 to 2 times.

Spending extra contact time per student group will depend upon the level of difficulties. Instructors can spend more time monitoring how activities are being performed instead to

Overall time spent by instructors on a student group will reduce as SLS provided necessary automation to assist students. Overall instructor time spent on lagging student group will increase.</td></tr>
</table>

This implies that while the instructor tends to one student group, other students are kept waiting in queue for their difficulties to be addressed. This factors contribute towards an increased workload on the instructor and leads towards frustration amongst students who are unable to understand the experiment. Thus the quality of instructor-student interaction and the contact time of instructor and students is affected.

From DE-I, as reported in Chapter 6, Section 6.2, it was found that students perceived that they would save around ~ 67% of their time (see Table 6.3) while using the SLS in the practical laboratory. The students also perceived that they would understand better (~ 56% improvement compared to previous understanding level) and will be able to concentrate more (~ 71% improvement) on a practical experiment by utilizing the SLS. What these percentages imply is that as students become more self-reliant in a laboratory owing to the use of SLS, instructor's workload reduces. If the SLS instructor dashboard, as described in Chapter 5, Section 5.4, is implemented, instructors will be able to understand the classroom dynamics better and will be able to address students in a much more fruitful way. Thus, the quality of instructor-student interaction and the quality of contact time spent by instructor per students will improve.

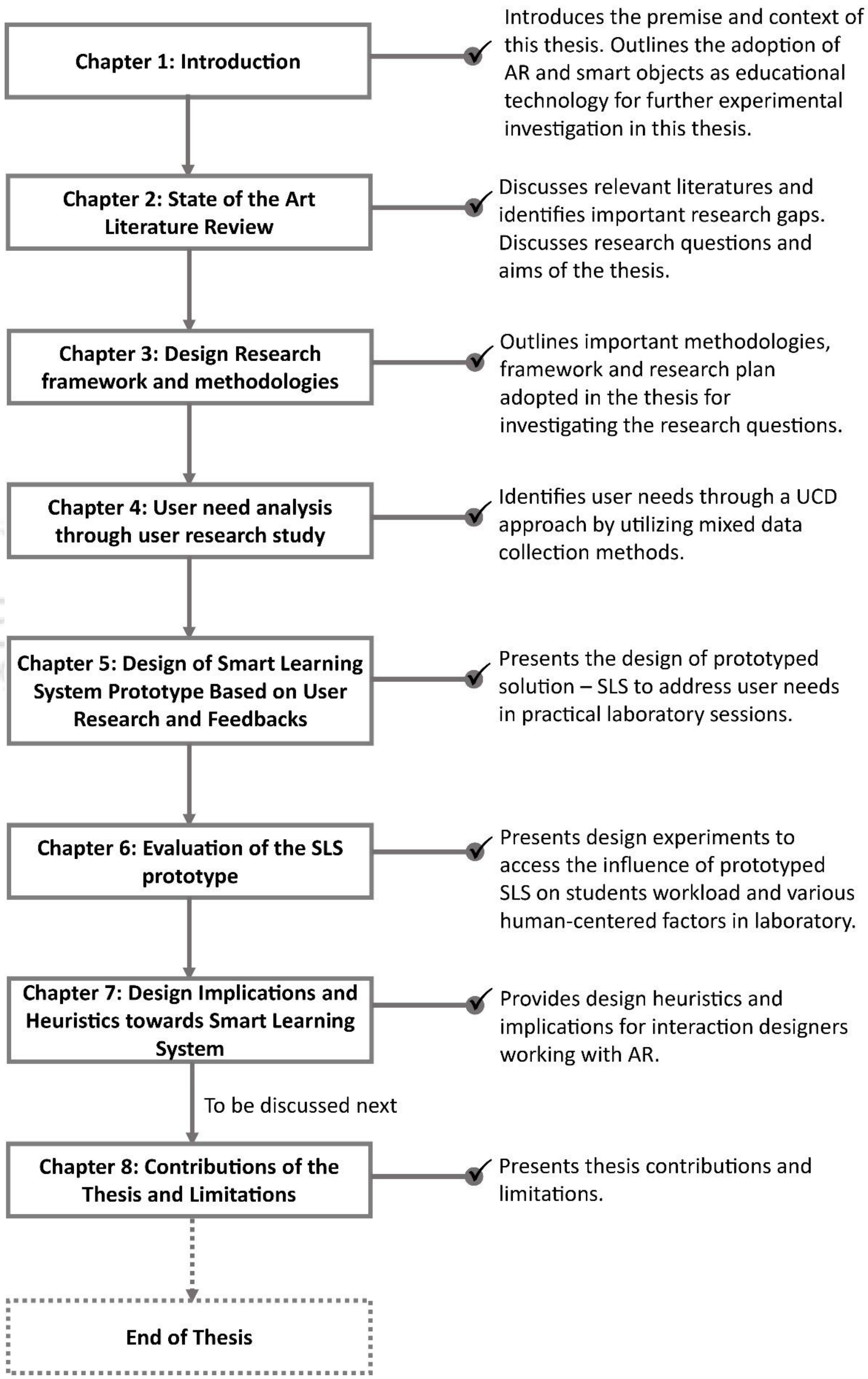
Another implication of SLS will be regarding improving the quality of learning and teaching if implemented in national and state-level community institutes with a paucity of human resources and infrastructure. This aspect of SLS can be explored as future work.

7.4 Chapter Summary

This chapter presents design implications and heuristics derived from experimental investigations reported in this thesis. These heuristics hold practical use for interaction designers and HCI researchers working towards improving education through AR with a specific focus on educational laboratories.

A quick recap of previous chapters:

A visual summary of the chapters covered so far is provided as follows:



Chapter 8: Contributions of the Thesis and Limitations

Chapter Abstract: This chapter presents the contributions of the thesis, its limitations and directions for future work in this area.

8.1 Contributions

As seen from the state of the art-literature review, discussed in Chapter 2, major research gaps were identified that indicate lack of insights in research works on practical electronics laboratory sessions. These gaps suggest that there are not many novel technologies designed to address the human-centered needs of users in practical electronics laboratory context. This thesis attempts to bridge these gaps by developing a system of devices knit together by new hardware, new software, and inputs from human ware (user). The device is in the form of a system that was developed in the context of education – electronics engineering practical laboratory.

A novel Smart Learning System, consisting of mobile AR that utilizes a smartphone or digital tablet, intelligent breadboard, User Interface, and learning content – all knit together by software that is specifically written to do so – is the major outcome. The main features of the system designed and developed have been highlighted in Chapter 5.

This thesis contributes in terms of formulating a possible 'design methodology' for developing 'learning products' based on emerging technologies such as Augmented Reality, Smart object, Artificial Intelligence. The human-centered emphasis and the user-centered design approach as adopted in this thesis suggests a viable method (as validated by user testing) for designing functionally useful products to ease human work in complex learning environments and assist better learning systems that emerging technology can afford.

Finally, this thesis attempted to develop design heuristics for designers of products planning to use AR, MR, IoT as well as AI based new products. Figure 8.1 depicts the major contributions of the thesis.

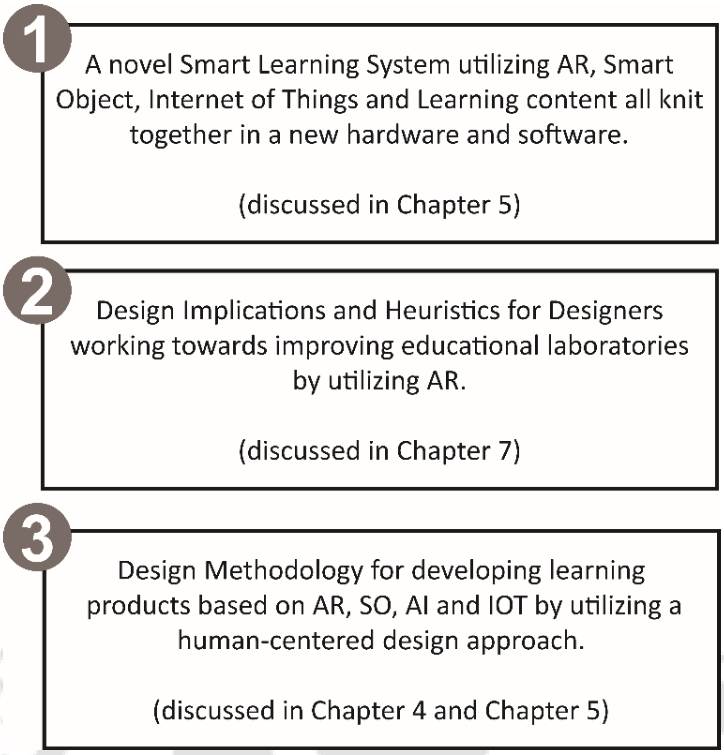


Figure 8.1 Major thesis contributions

8.1.1 The application potential of SLS in Indian Context

In India, every year, around 1.2 lacs students enroll in Electronics related branches across all levels of courses viz., diploma to post-graduation (AICTE, n.d.-a). This figure takes into account all the courses like a diploma, undergraduates, postgraduates, and PhDs. For nurturing their fundamentals in electronics and developing quality hands-on learning skills, India needs at least 1.5 lacs (approximate) working instructional laboratories all across the country. However, as many technical institutes face a severe shortage of funds, teachers, and infrastructure, the number, and quality of these working labs are reduced significantly (AICTE, 2010, MHRD, 2017).

Given India's current rate of education expansion and its colossal size, it is going to become increasingly difficult in future to close the gaps between (a) demand and supply, (b) cost and resources, and, (c) quality and quantity. Thus, India needs to move towards digitization through mass e-Learning deployments and seek innovative ways to fill these gaps. The work presented in thesis presents a way to incorporate digital technologies that can be used specifically in Indian context in the areas lacking in quality in learning abilities due to the dearth of knowledge transfer capabilities and equipment issues and problems.

8.2 Limitations of this research

A major limitation during the research reported in this thesis was resources to come up with a fully functional prototype for large-scale user study. Therefore, lightweight working prototypes were developed to demonstrate the utility of novel aspects of the design solution to the research problems. Due to this limitation, the work reported in the thesis does not verify the effect of proposed Smart Learning System on overall academic performance and learning of user. It is validated within the limited context of a practical laboratory session.

There is a scope for summative evaluation of our system if designed and built more robustly, for large-scale nationwide field study. Further assessment can be carried out regarding understanding how SLS can improve the efficiency in laboratory sessions, reduce instructor's workload and the social implications. For such user testing studies, large sample size and at least ten robustly built prototypes will be required. This requirement for robustly designed prototypes was a limitation of the thesis.

Annexure A

Design of Tangible Interactive Learning Aids for Pre-primary School Teaching Environment

Aim: This experiment presents a way to embed intelligence into objects which in turn can be used in classrooms to enhance learning experience. Two tangible interactive objects were adapted and prototyped as well as tried out in three local schools. We show how these devices can constitute as a sound educational pedagogy by demonstrating how they embody Multiple Intelligence theory of Howard Gardner. The experiment opens up possibilities for working further in embedding intelligence into the object itself leading towards cognitive development in children in learning environment.

Prototypes

These prototypes were consciously developed to be inexpensive – and with the intention to be sustainable given Indian school scenario. They were made for underprivileged schools. They also involved group interaction among children. Since such devices are not available in the market, we had to conceive and prototype them. In this section we present two models of the prototypes embedded with intelligence, which can be used to teach the children of pre-primary schools. These prototypes were constructed from the readily available everyday materials such as aluminium foil, cardboard, tires, and bicycle wheel. The first prototype is called an Interactive Board and the second one is called Round piano. In the following section we describe the steps involved in developing these prototypes. These prototypes had to be developed with embedded activity to enable experimentation with school children.

a. Interactive Board

This was constructed using easily accessible materials such as cardboard, aluminium foil and a microcontroller (Arduino Uno). By using capacitive sensing library of Arduino (Paul Badger, n.d) and several aluminium foils, we were able to make capacitive touch sensors.

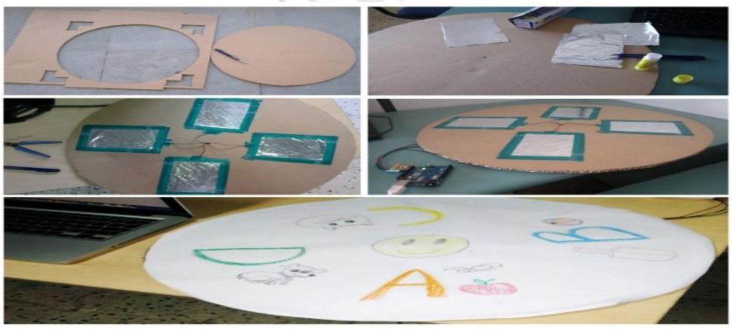


Figure 1. Interactive board prototype, made from readily available materials, connected to computer through Arduino board.

Four such sensors, made from aluminum foil were placed at equal distance on a round card-board of diameter 53cms. The sensors were then connected to the Arduino board, which serially sent the data to the computer whenever a touch was detected on either four sensors. These data values were then read by the software, which made using Processing 2.0, to play the required sound depending on the sensor being touched. The main goal of this prototype was to teach the sound of alphabets to the children of nursery schools. Since it was prototype, it only consisted of four alphabets (i.e. A, B, C & D). Figure 1 illustrates the steps involved in making the first prototype and its final version.

b. Round Piano

This prototype was constructed using a bicycle wheel. Eight sensors, made from aluminium foil were placed at equal distance around the circumference of the wheel. These sensors were then connected to the microcontroller. On pressing or touching the sensors, musical notes were produced from the speakers mounted on the device. The main goal of this prototype was to teach various musical notes to the children of upper kindergarten class. The applications for both of these prototypes were developed on Processing 2.0 and Arduino IDE. Figure 2 shows the construction of this prototype.

Figure 2. Round Piano prototype showing Arduino board mounted at the center to allow rotation of the wheel with touch-sensitive aluminum foils on the sides.

Study Description

Our main focus was to find the interplay between Bloom's taxonomy and Multiple Intelligence theory when children interact with tangible devices. In order to understand how students interact with these devices and how they would derive the learning content by themselves from them, a study was conducted in three schools of Guwahati, India over a time period of three full days. The observations were made by recording the behaviours of 30 children (10 from each school) between the age group of 3 – 4 years, i.e. nursery class and 30 children (10 from first school, 20 from second) between the age group of 4 – 6 years from upper kindergarten (UKG) class. We also interviewed 10 teachers and qualitatively analyzed the data.

Methodology

Each group of children from nursery consisted of ten students of same class who were guided by their class teacher. The nursery class students were given the Interactive Board prototype. The second prototype was given to a group of 8 students of same class from upper kindergarten under the supervision of their class teacher. Video recording and photographs were taken for each session of the study to capture the physical behaviour and the learning activity of the students. After performing the activity, the class teachers were interviewed. The interview was recorded for the purpose of content analysis.

The activity allotted for the interactive board, to the nursery class was to touch a particular alphabet, one at a time, and repeat the song that played through the computer. The song taught the students the sound of alphabets and various objects and animals related to them. We also instructed the kids to perform the action and make sounds of animals and objects being mentioned in the song. When the song was about to get over, the children were asked to turn around while standing at one place and then sit down and stand-up quickly while clapping along. We then asked the children to reproduce what they had learned and perform it by action, e.g. balloon is round, and so they moved their hands forming a big circle in the air. Figure 3 below shows the activity being performed by the children while using Interactive board.

Figure 3. Children performing the assigned activity with Interactive board.

The second prototype, round piano, was allotted to the UKG children. In our first survey, we left the device alone amongst the children after explaining its working. We then observed their behaviours and video recorded the event. In the second survey with this prototype, three groups of eight children were called to interact with the device and asked to stand near a particular key. We then allotted a particular musical note, “Sa”, “Re”, “Ga”, “Ma”…, to each child and asked them to sing the note as they pressed the keys. Figure 4 shows this activity. The first group of children was asked to create the music on their own. The second group was to sing the notes whenever they pressed the keys.

Figure 4. Children interacting with Round piano by touching the sides having touch-sensitive aluminum foil.

Analysis and Findings

a. Analysis

The analysis was done by qualitatively studying audio and video data, which was obtained by recording the interviews of the teachers and children's activity. Several observations were also noted down for the overall behaviour of the class and children who had completed their activity. The video data was collected to identify vital aspects of the classroom dynamics and gain an insight into how children coordinated amongst each other and interacted with the devices.

The video was recorded for a series of activity sessions conducted during the period of study. They were viewed iteratively and interpreted as discussed in the literature of interaction analysis by Jordan et al (1995). Different levels of thinking as described by Bloom's Taxonomy, which are involved in learning, were observed from the data collected. Similarly, the different types of intelligences being displayed by children while using the prototypes were observed through this process. Also, using the technique of content analysis described by Bruce (2001), the audio data recorded while conducting the interviews were transcribed and keywords highlighting intelligences and types of learning from sentences were identified upon repeated listening. The steps involved in this process have been described in the consecutive section.

b. Findings

Figure 5 shows important actions along with a description of the scene and the type of intelligence as observed by the authors, being displayed by the children while operating the prototype. Dashed white circles on the photographs have been used to highlight these actions in the clips shown below.

Pictures/Clips	Description	Intelligence Type
	Children exploring the device and its functions by pressing different keys. (Still Photo)	Logical, Musical, Body-kinesthetic, Naturalistic
	All the children started knocking the tire together. (12:03)	Body-kinesthetic, Musical, Interpersonal
	The girl presses the tire hard while making a face. This indicates the exploration of materiality of the device. (12:17)	Musical, Body-Kinesthetic, Naturalistic, Intrapersonal
	After sometime all children left but two remained and explored the device. (13:27)	Intrapersonal, Musical
	The child was inquisitive about the device and tried to look under the hood. He also explored the materiality of the tire. (15:39)	Naturalist, Musical, Intrapersonal
	After 20 minutes, all children left except this boy, who kept on going around the device in circular motion and pressing each key to make sound. (20:05)	Body-Kinesthetic, Musical

Figure 5. Interaction process analysis of Round Piano

For the two boys shown in the last three rows of Figure 5, we enquired from their class teachers about their nature in class. It was found that these boys were usually silent and did not socialize much as they were new to class. However, they were quite observant as compared to other students. This observation about their observant nature has been mentioned in the fifth row of Figure 5 as ‘naturalist’. The teachers also informed that these boys didn’t show much inclination towards musical activities, which were conducted in school. This gives an indication that they got interested in operating the device, which was presented to them. The class teachers verified this inference too.

It was interesting to see that the children explored the elasticity of the tire by pressing it hard and knocking it. This gives a direction to also explore the materiality of the tangible interfaces. The children eventually lost interest in the prototype after 16 minutes, and went back to their places. This gave an insight that the device should be more engaging as children have a short attention span.

It was also observed that the group of children, who were taught the musical notes, sang them repeatedly after they went back to their places and some of them enacted as pianists. Figure 6 shows the expression and action of a girl, captured in one of our videos, after performing the activity.

Figure 6. A girl enacting as a pianist after operating the Round Piano.

Similarly, interaction process analysis for first prototype has been shown in Figure 7. The children took some time to understand what the device was. After we explained them what they had to do, they adapted quickly. We observed that the children were quite inquisitive to touch the board. Whenever the song was played on touching the board, they felt extremely happy. Also, if one child touched the board, the other one would follow in his/her shoe and do the same thus interrupting the previous song, which was being played. Seeing this, we then instructed the children to press the alphabet only after the song ended. Upon completion of the song, we observed that many children were willing to press the alphabets and nearly all of them brought their hands forward. It was also noted that the involvement of the teacher/ researcher with the children was highly necessary to perform the activity.

After the activities, we interviewed the class teachers and principals of these schools to find the effectiveness of the devices for learning and how well they suit their current pedagogy/ practices. The response of each teacher was named as R1, R2,…, R8 and placed on the horizontal axis of the table and the vertical axis indicated type of intelligences as indicated by their statements. Similarly, all other responses were then quantified through the technique of content analysis.

Pictures/Clips	Description	Intelligence Type
	A child interacting with the device. (Still Photo)	Body-Kinesthetic, Spatial, Interpersonal
	Repeating the alphabets being played after the song (3:28)	Musical, Intrapersonal
	Children spinning around as instructed by the song(4:05)	Body-Kinesthetic, Musical, Linguistic
	All of them clapping after the song is over (09:55)	Body-Kinesthetic, Musical, Interpersonal

Figure 7. Interaction process analysis of Interactive Board.

Table 1 shows the number of intelligences as indicated by the responses of the teachers. Table 2 shows the quantified data obtained from this method. Figure 8 shows a radar-plot which was constructed based on the data obtained from content analysis performed on similar other responses of the interview. It can be inferred that the effectiveness of the prototypes is most probably based on the type of multiple intelligence embodied in the device.

During our sessions, we observed that as children's handling can be rough on technology, schools are sometimes reluctant to buy such products. This we suppose can be another reason why technology has not been used in Indian pre-primary schools. We however noticed that our prototypes were quite durable and were able to sustain the rough usage without causing any disruption in their working process.

One important suggestion that we received from a teacher, thereby increasing the chance of sustainable performance, was that the song that is being played should rather not just be in English. He suggested that the device should support different types of vernacular languages. Altogether, the teachers were satisfied with the effectiveness of devices and stated that they could readily accept such kind of equipment as a teaching aid.

Table 1. Response of teachers indicating different types of intelligences coming into picture while children interact with these prototypes. Here only two out of eight responses have been shown for the sake of brevity.

Intelligence/Response	R1	R6
Linguistics	"…matching of capital letters and small letters..."	"…children know alphabets; they can see and touch it. Plus sound comes…"
Spatial	"…draws attention as it is big in size and has big alphabets…"	"…children know alphabets; they can see and touch it. Plus sound comes…"
Body-Kinesthetic		"children will like it…game way of learning"
Musical		"…children love music… this utilizes it" "…children know alphabets; they can see and touch it. Plus sound comes…"
Interpersonal	"…children can stand in a circle…forward counting; backward counting…these games can be played."	
Intrapersonal		"…the fear will go away at the time of learning"
Logical-Mathematical	"…matching of capital letters and small letters..."	
Naturalist	"…they can learn different types of animal names and sounds…"	

Table 2 Word counts of intelligence types indicated by the teachers obtained from content analysis of interview data

Intelligence	Word Counts
Linguistics	9
Spatial	9
Body-Kinesthetic	6
Musical	8
Interpersonal	3
Intrapersonal	5
Logical-Mathematical	8
Naturalist	7

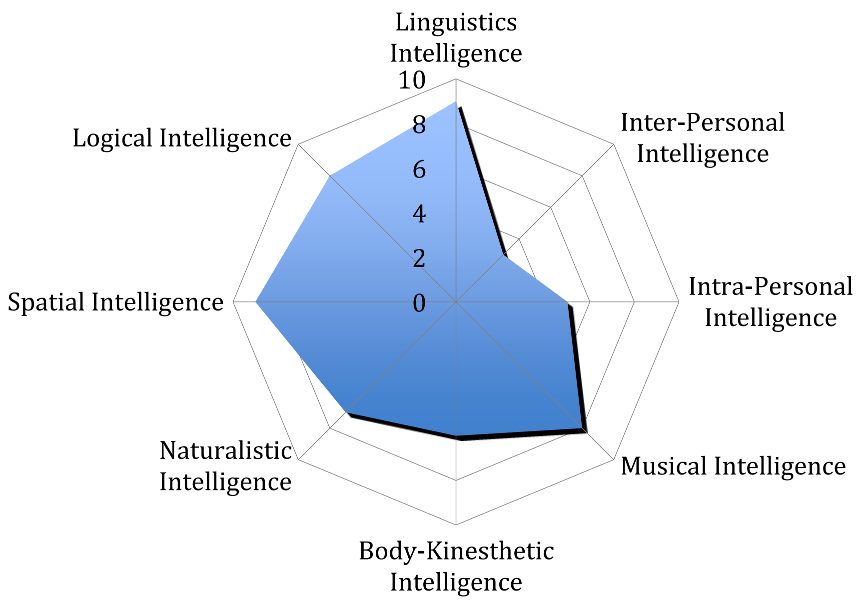


Figure 8. Radar-plot showing the type of intelligences embodied in the prototypes

Implications of the device on child development and classroom dynamics

Through this experimental investigation, we wanted to understand the implications of our devices on the children and overall classroom dynamics. By doing so we posited that heuristic of embedding intelligence in learning aids can be eventually developed. This is an important aspect from an educational psychologist and educators point of view. Studies have shown that the pre-school years are critical years in the brain development of children. It has been found that the children start developing areas key to executive functions when they reach the age of three. These are the critical cognitive processes, such as problem-solving, sustaining attention, monitoring performances, and planning and directing various activities, that shape how they will turn out in school (Forbes, 2014). If we recall the presentation on sensitive periods of childhood by Dr. Randa Grob-Zakhary, CEO of Lego foundation, the 'sensitivity of brain development' is maximum towards numbers, peer social skills, conceptualization, language, emotional control, habits, vision and hearing is between the periods of three-five years of age. These are marked as the pre-school years. After this period, this sensitivity starts decreasing as they move towards school years. By the age of seven, the sensitivity becomes limited to only a few things (Lego Foundation, 2014). It is evident from this study that it is during these initial years, specifically speaking between the ages of three-five years, that a significant amount of learning can take place in children, if nurtured properly. Devices with embedded intelligence can therefore be introduced at ages of 3 to 5 years.

We adopted the MI/RBT (Multiple Intelligence-Revised Bloom's Taxonomy) matrix as suggested by Nobel, 2004 to understand various activities and higher-order cognitive process that combines while the children use tangible learning aids. Figure 9_shows the result of analysis, obtained from interaction and content analysis, mapped onto the matrix grid. It depicts how children utilized various intelligences and derived learning contents while interacting with these devices.

MI/RBT	Bloom's Taxonomy: Six Thinking Levels					
	Remember	Understanding	Applying	Analysing	Evaluating	Creating
Verbal	Speak out different alphabets represented on the device.					
Logical-Mathematical		Comparing different musical notes		Tell the difference between the objects shown on the device.		Creating different tones
Visual/Spatial	Recognize the alphabets and objects shown on the device.		Be able to point out objects or animals starting with these alphabets as represented on the device.			
Kinaesthetic		Compare different notes by moving around the piano	Creating different tones			Create different actions through body for these nouns.
Musical	Recognize different musical notes	Create the sounds of these alphabets and the objects or animals shown on the device.	Creating different tones			Creating different tones
Interpersonal			Collaborating with other children to create tones	Collaborating with other children to create tones		Be able to synchronize with the actions of students and teachers.
Intrapersonal		Observing different sounds and trying to make a composition			Be able to differentiate between alphabets and be able to judge if the answer to the question being provided is right or not	
Naturalist	Operating the devices Exploring materiality of the tire				Compare different notes by moving around the piano	
■ ■	Interaction with Interactive Board Interaction with Round Piano					

Figure 9. Matrix showing the interplay of Multiple Intelligence and Bloom's Taxonomy when children interact with the prototypes. The vertical axis shows Multiple Intelligences and horizontal axis show six thinking levels of Bloom's Taxonomy.

The matrix being proposed in the paper provides an insight on how tangibles can be designed to achieve a greater depth towards achieving learning activities. It can be noticed from the matrix that by engaging children in various activities using tangibles invokes different levels of thinking as well as intellect. From above analysis, it becomes evident that children tend to explore new areas while they are interacting with such devices. It can also be noted that introducing such tangibles can also help nurture the quiet students of the class, (refer Figure 5).

Conclusion

From the above study, it is indicative that introducing tangibles learning aids with embedded intelligence at a pre-school level (3-to-5 years of age) can prove to be beneficial for the children. It is also suggests that introduction of these devices can help teachers plan better activities in class thereby helping them to impart better instructions to students.

Annexure B

Annexure B1

List of Objectives by ABET Inc.:

1. **Instrumentation:** Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.
2. **Models:** Identify the strengths and limitations of theoretical models as predictors of real-world behaviours. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.
3. **Experiment:** Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.
4. **Data Analysis:** Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.
5. **Design:** Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.
6. **Learn from Failure:** Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions.
7. **Creativity:** Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem-solving.
8. **Psychomotor:** Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.
9. **Safety:** Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.
10. **Communication:** Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.
11. **Teamwork:** Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.
12. **Ethics in the Lab:** Behave with highest ethical standards, including reporting information objectively and interacting with integrity.
13. **Sensory Awareness:** Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.

Annexure B2

Extracted from Model Scheme of Instruction and Syllabi for UG Engineering Degree Programmes (Electronics & Communication Engineering) – October 2012, Prepared by: All India Board for UG Studies in Engineering & Technology, Page 12 - 13

Expected Educational Outcomes:

Special attention was also paid to ensure that the Model Scheme of Instruction and Syllabi had built-in provision to enable the following ten educational outcomes from the E&T students passing out of the Universities/Institutions adopting them:

1. Ability to apply the knowledge acquired in subject areas like, Mathematics, Basic Sciences, Engineering Sciences, Professional Subjects and Environmental Issues;

2. Strong foundation in theoretical/experimental work for being able to analyze, synthesize and design engineering products, processes and systems as desired;

3. Expertise in collecting field data, designing and conducting experiments in the laboratory/elsewhere and analyzing/interpreting the results;

4. Capacity to function in multi/inter-disciplinary teams with a spirit of tolerance, patience and understanding so necessary for teamwork;

5. Competence to acquire knowledge on one's own through libraries/databases for contributing to knowledge assimilation, creation, dissemination & life-long learning;

6. Better understanding and acceptance of professional, social, moral and ethical responsibilities and good knowledge of contemporary issues;

7. Familiarity with ICT and seeking pollution-free and/or environment- and energy friendly solutions to day-to-day problems faced by the society at large, based on ICT;

8. Broad education necessary to get a perception of the impact of solutions provided for developmental issues in a global/societal context;

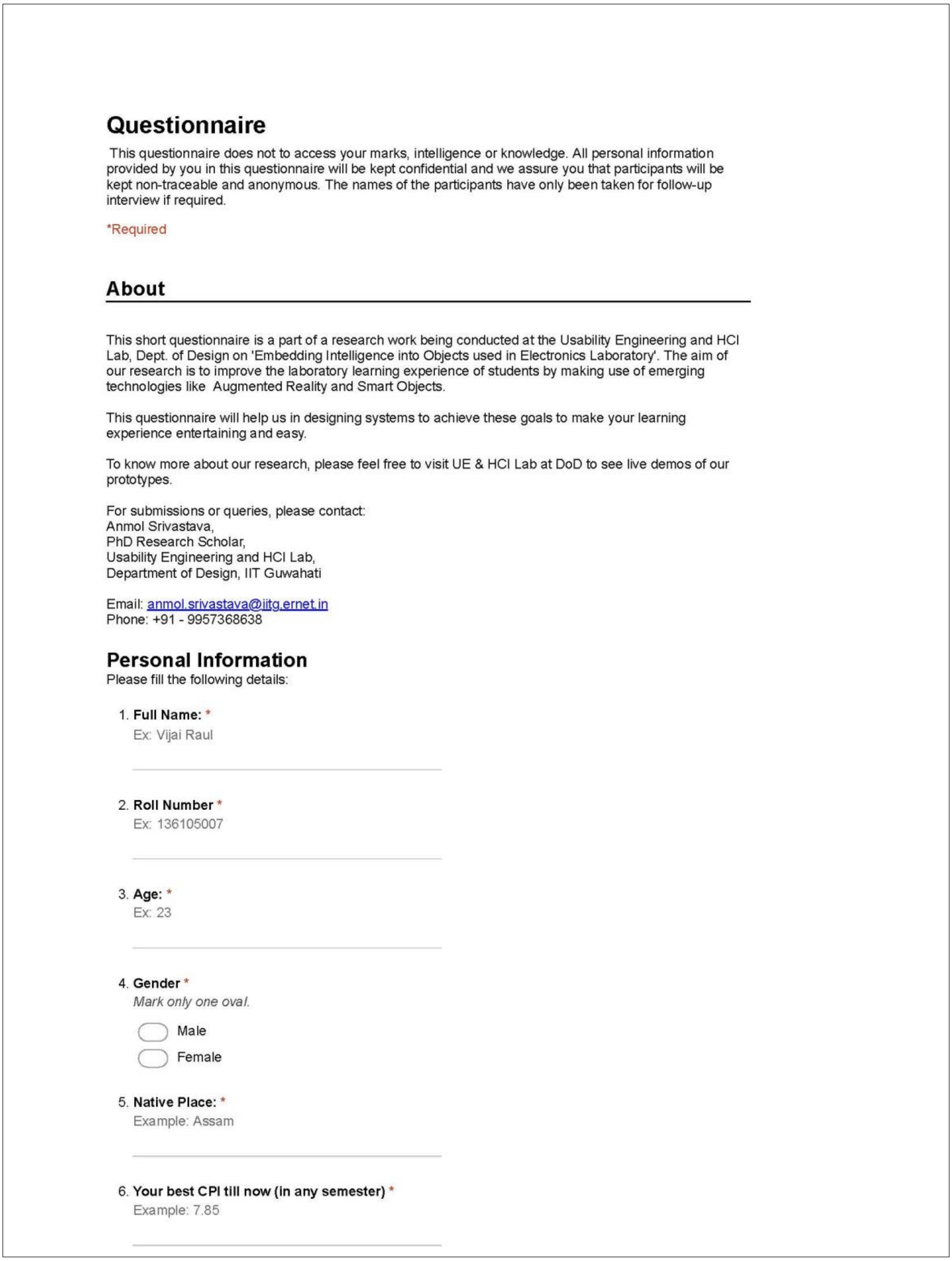
9. Capacity for rational, objective, orderly and logical thinking and ability to communicate with fellow professionals/society effectively in written/oral forms; and,

10. Good attitudes and skills in personnel management and maintenance of human relations, required in every ones working life.

Annexure C

Annexure C1

The following questionnaire was administered to the students via e-mail to access their confidence level regarding various laboratory-based activities and internet usage.



Questionnaire

This questionnaire does not to access your marks, intelligence or knowledge. All personal information provided by you in this questionnaire will be kept confidential and we assure you that participants will be kept non-traceable and anonymous. The names of the participants have only been taken for follow-up interview if required.

*Required

About

This short questionnaire is a part of a research work being conducted at the Usability Engineering and HCI Lab, Dept. of Design on 'Embedding Intelligence into Objects used in Electronics Laboratory'. The aim of our research is to improve the laboratory learning experience of students by making use of emerging technologies like Augmented Reality and Smart Objects.

This questionnaire will help us in designing systems to achieve these goals to make your learning experience entertaining and easy.

To know more about our research, please feel free to visit UE & HCI Lab at DoD to see live demos of our prototypes.

For submissions or queries, please contact:
Anmol Srivastava,
PhD Research Scholar,
Usability Engineering and HCI Lab,
Department of Design, IIT Guwahati

Email: anmol.srivastava@iitg.ernet.in
Phone: +91 - 9957368638

Personal Information

Please fill the following details:

1. **Full Name:** *
   Ex: Vijai Raul

2. **Roll Number** *
   Ex: 136105007

3. **Age:** *
   Ex: 23

4. **Gender** *
   Mark only one oval.
   - Male
   - Female

5. **Native Place:** *
   Example: Assam

6. **Your best CPI till now (in any semester)** *
   Example: 7.85

7. **In which semester did you score the above CPI?** *
Ex: Second semester

8. **IITG webmail id** *

Skip to question 13.

Confidence level with Test Instruments

The following set of questions are for knowing about your comfortability and confidence on operating tools and equipment in a lab single handedly without any assistance.

A. CRO and Function Generator

Please mark your confidence level on a scale of 1 to 10 with the following statements regarding single handedly operating the CRO in lab without any assistance.

9. **My ability to understand and operate the features on the CRO at first attempt is** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

10. **My ability to understand and operate the features on the CRO when it behaves unpredictably is** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

11. **My ability to display, measure and interpret the wave forms on the CRO is** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

12. **My ability to set correct amplitude and frequency of signals on function generator is** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

Skip to "Important Note."

Important Note

Please note that this questionnaire is only for gathering your confidence levels regarding exercises done in electronics laboratory. This questionnaire does not to access your marks, intelligence or knowledge. All information provided by you in this questionnaire will be kept confidential and we assure you that participants will be kept non-traceable and anonymous. The names of the participants have only been taken for follow-up interview if required.

Skip to question 9.

Confidence Level with components

The following set of questions are for knowing about your comfortability and confidence with various electronic components used in a lab single handedly without any assistance.

B. Components

Please mark your confidence level on a scale of 1 to 10 with the following statements regarding single handedly using various electronic components in lab without any assistance.

13. **My ability to understand resistor colour codes and determine its values is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

14. **My understanding of the codes of capacitors and determining its values is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

15. **My ability to understand inductor colour codes and determine its values is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

16. **My understanding of different types of diodes and their practical significance is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

17. **My ability to understand IC pins and layout is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

18. **My ability to understand IC numbers and refer to their data sheet for reference is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

19. **My ability to understand transistor pin layouts without referring to their data sheet is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

20. **My ability to understand numbers written on electronic component to find and refer to their data sheet is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

Skip to "Important Note."

Important Note

Please note that this questionnaire is only for gathering your confidence levels regarding exercises done in electronics laboratory. This questionnaire does not to access your marks, intelligence or knowledge. All information provided by you in this questionnaire will be kept confidential and we assure you that participants will be kept non-traceable and anonymous. The names of the participants have only been taken for follow-up interview if required.

Skip to question 21.

Confidence Level with circuit assembly

The following set of questions are for knowing about your comfortability and confidence with assembly of circuits in a lab single handedly without any assistance.

C. Use of Breadboard

Please mark your confidence level on a scale of 1 to 10 with the following statements regarding single handedly using breadboard for circuit assembly in lab without any assistance.

21. **My understanding of the matrix of rows and columns and their interconnections on breadboard is** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low											High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

22. **My ability to assemble components and construct complex circuits on breadboards is** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

23. **My ability to troubleshoot when circuits did not operate on breadboard is** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Low	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	High
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	

Skip to question 24.

Gathering information regarding experiments in laboratory

Select the most appropriate number of each statement which corresponds closely to your desired response.

24. **I always use internet to search for information regarding experiments in lab** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

25. **I sometimes get distracted while searching for information regarding experiments on the internet** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

26. **I am able to quickly find the required information regarding the experiment through internet** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

27. **Gathering information on the internet is time consuming in a laboratory class** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Annexure C2

Online open-ended questionnaire for practical laboratory Teaching Assistants.

Questionnaire

'Embedding Intelligence into Objects used in Electronics Laboratory'

This short questionnaire is a part of a research work being conducted at the Usability Engineering and HCI Lab, Dept. of Design on 'Embedding Intelligence into Objects used in Electronics Laboratory'. The aim of our research is to improve the laboratory learning experience of students and instructors by embedding intelligence into tools and equipment used in electronics laboratory and making use of emerging technologies like Augmented Reality and Internet of Things. This questionnaire will help us understand the type of intelligence that needs to be embedded into objects and designing them so that they can be used by the instructors to teach students better. Such systems, we believe, would be helpful in developing future learning aids that are able to assist students and instructors in augmenting their learning and tutoring capabilities.

For any queries, please contact:
Anmol Srivastava,
PhD Research Scholar,
Usability Engineering and HCI Lab,
Department of Design, IIT Guwahati

Email: anmol.srivastava@iitg.ernet.in
Phone: +91 - 9957368638

*Required

Disclosure

All personal information provided by respondents will be kept confidential. The names of the participants have only been taken for follow-up interview if required. The data collected will be used for the purpose of academic research.

Please fill the following information

1. **Full Name** *

....

2. **Have you conducted EE102 - Basic Electronics Lab before this semester?** *
Mark only one oval.
   - ◯ Yes
   - ◯ No

3. **Teaching Experience (in years, if any)**
Ex: 1.5 yrs

....

4. **E-mail Address** *

....

5. **Phone Number**

Please fill the following

Your response will help us gather knowledge required to make applications and systems that can assist both instructors and students in laboratory for tutoring and learning.

6. **Rate your judgement regarding the level of difficulty faced by students in circuit assembly for the following experiments** *

1= Easy; 5= Difficult

Mark only one oval per row.

	1 (Easy)	2	3	4	5 (Difficult)
Circuit Theorem	◯	◯	◯	◯	◯
RLC Circuit	◯	◯	◯	◯	◯
Diode Circuits	◯	◯	◯	◯	◯
Power Supply	◯	◯	◯	◯	◯
Study of Common-Emitter Amplifier	◯	◯	◯	◯	◯
OPAMPS	◯	◯	◯	◯	◯
Voltage to Frequency Converter	◯	◯	◯	◯	◯

Please fill the following

Your response will help us gather knowledge required to make applications and systems that can assist both instructors and students in laboratory.

7. **Rate your judgement regarding the level of difficulty faced by students in using test equipment for the following experiments. (Test equipment refers to - CRO, Function Generator, etc)** *

1= Easy; 5= Difficult

Mark only one oval per row.

	1 (Easy)	2	3	4	5 (Difficult)
Circuit Theorem	◯	◯	◯	◯	◯
RLC Circuit	◯	◯	◯	◯	◯
Diode Circuits	◯	◯	◯	◯	◯
Power Supply	◯	◯	◯	◯	◯
Study of Common-Emitter Amplifier	◯	◯	◯	◯	◯
OPAMPS	◯	◯	◯	◯	◯
Voltage to Frequency Converter	◯	◯	◯	◯	◯

Please fill the following

Your response will help us gather knowledge required to make applications and systems that can assist both instructors and students in laboratory.

8. **Do you face any problems in while conducting lab classes for students? If yes, please mention.** *

....

....

....

....

Please fill the following

Your response will help us gather knowledge required to make applications and systems that can assist both instructors and students in laboratory.

9. **Rate your judgement on a scale of 1 to 10 on the level of confidence of students to single handedly operate the following tool/ equipment in lab.** *

1= Easy; 10 = Difficult

Mark only one oval per row.

	1 (Low)	2	3	4	5	6	7	8	9	10 (High)
Breadboard	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
CRO	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Function Generator	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Digital Multimeter	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
DC Power Supply	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

In the following section, kindly fill in all possible mistakes (including conceptual) that students make (or can make) while conducting the following experiments.

Your response will help us gather knowledge required to make applications and systems that can assist both instructors and students in laboratory.

10. **Expt. 2 - Circuit Theorems** *

....

....

....

11. **Expt No. 3: RLC Circuits** *

....

....

....

12. **Expt No. 4: Diode Circuits** *

....

....

....

In the following section, kindly fill in all possible mistakes (including conceptual) that students make (or can make) while conducting the following experiments.

13. **Expt No. 5: Power Supply** *

....

....

....

....

14. **Expt No. 6: Study of Common – Emitter Amplifier** *

....

....

....

....

15. **Expt No. 7: OPAMPS** *

....

....

....

....

16. **Expt No. 8: Voltage to Frequency Converters** *

....

....

....

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Annexure C3

Open-ended questionnaire for practical laboratory Faculties.

Questionnaire

'Embedding Intelligence into Objects used in Electronics Laboratory – EE102'

Respected Sir/ Ma'am,

This short questionnaire is a part of a research work being conducted at the Usability Engineering and HCI Lab, Dept. of Design on 'Embedding Intelligence into Objects used in Electronics Laboratory'. The aim of our research is to improve the laboratory learning experience of students and instructors by embedding intelligence into tools and equipment used in electronics laboratory and making use of emerging technologies like Augmented Reality and Internet of Things. This questionnaire will help us understand the type of intelligence that needs to be embedded into objects and designing them so that they can be used by the instructors to teach students better. Such systems, we believe, would be helpful in developing future learning aids that are able to assist students and instructors in augmenting their learning and tutoring capabilities.

This questionnaire is for EE 102 - Basic Electronics Laboratory.

Alternatively you can also fill this questionnaire by going to the following link:
http://tiny.cc/ee102

Kindly fill this questionnaire by 7th February 2016.

Thank you

For any queries, please contact:
Anmol Srivastava,
PhD Research Scholar,
Usability Engineering and HCI Lab,
Department of Design, IIT Guwahati

Email: anmol.srivastava@iitg.ernet.in
Phone: +91 - 9957368638

Disclosure:

All information provided by the respondents will be kept confidential. The names of the participants have been taken for follow-up interview if required.

Please fill the following information:

Full Name: ____

Teaching Experience (in years): ____

Working Experience (in years, optional): ______________________________________

In which organization/ industry have you worked prior to teaching (optional) :

____

E-mail address: ____

When is a suitable time to contact you on weekdays? ___________________________

1. According to you, what are the common type of mistakes students make in the following experiments? Mention all that are possible, including conceptual.

a. Expt No. 2: Circuit Theorems

b. Expt No. 3: RLC Circuits

c. Expt No. 4: Diode Circuits

d. Expt No. 5: Power Supply

e. Expt No. 6: Study of Common – Emitter Amplifier

f. Expt No. 7: OPAMPS

g. Expt No. 8: Voltage to Frequency Converters

2. Do you face any problems in while conducting lab classes for students? If yes, please mention.

3. How do you handle students lagging behind in laboratory class due to lack preparation or understanding?

4. What type of problems do students face in laboratories while conducting experiments?

5. What type of mediums such as diagrams, videos, models, etc. do you use in laboratory to teach students?

6. Kindly provide any other information which might be important for helping students learn better in laboratory.

7. Any suggestions? (Please mention below)

Annexure C4

Open-ended questionnaire for students.

Free Comments

Tip: Is there anything you find particularly good or frustrating while performing experiments in lab?

List the features that you liked in the following application:

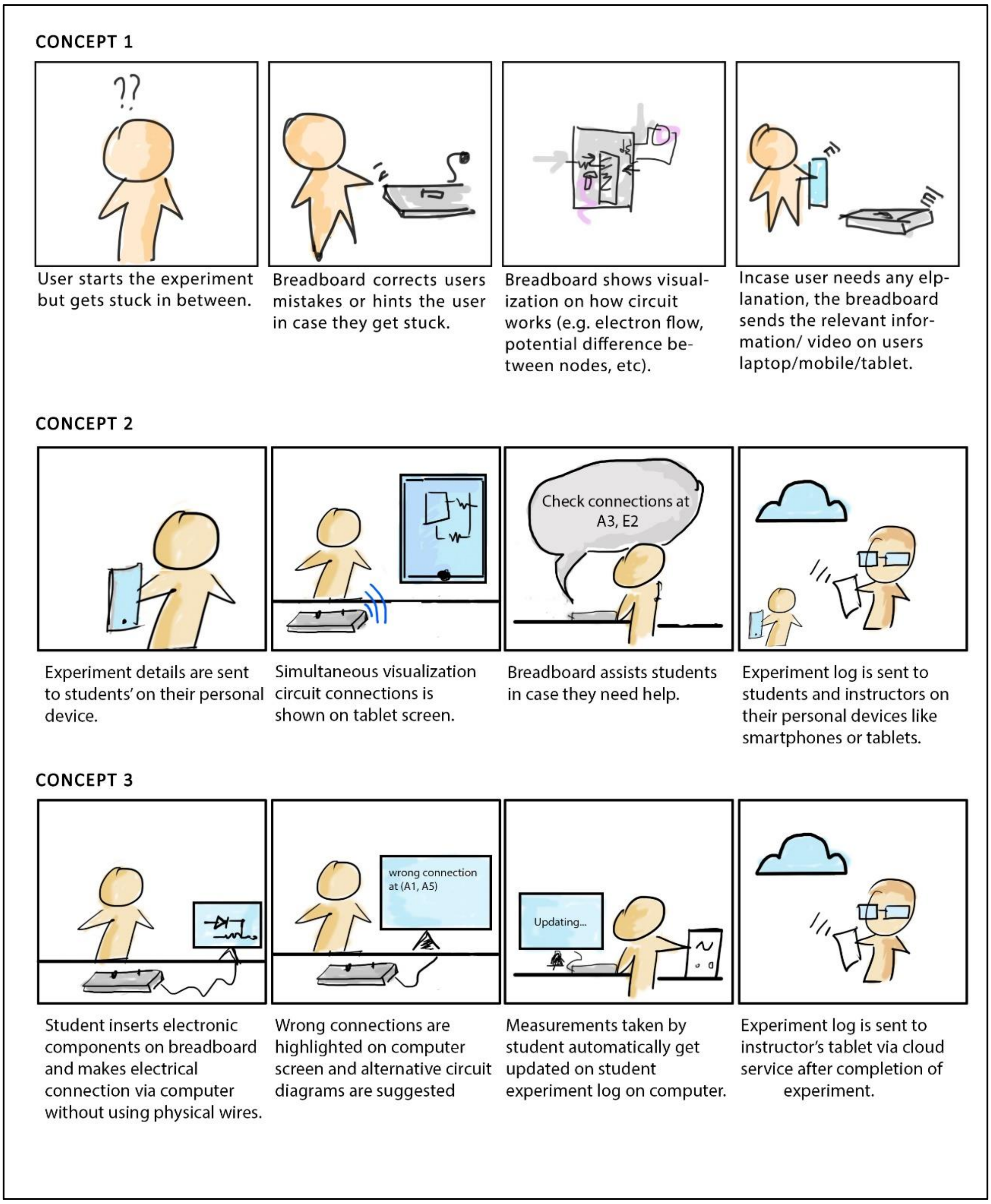
1. Application for Full wave rectifier:

2. Application for Response of RC, RL and RLC circuits:

Please give suggestions for improvements

Annexure C5

Conceptual scenarios presented to students during user studies.



Annexure C6

This annexure is a continuation of Table 4.6 in Chapter 4 and presents the descriptive statistics regarding confidence level and internet usage of students in practical laboratories.

Questionnaire items	Mean	Std. Dev
Regarding confidence level of students in laboratory (10-point Likert Scale)		
1=Low, 10 - High		
My ability to understand and operate the features on the CRO at first attempt is	7.88	1.97
My ability to understand and operate the features on the CRO when it behaves unpredictably is	6.80	2.23
My ability to display, measure and interpret the waveforms on the CRO is	8.37	1.63
My ability to set correct amplitude and frequency of signals on function generator is	8.74	1.80
My ability to understand resistor colour codes and determine its values is	8.68	1.60
My understanding of the codes of capacitors and determining its values is	7.12	2.69
My ability to understand inductor colour codes and determine its values is	6.22	3.26
My understanding of different types of diodes and their practical significance is	6.54	2.74
My ability to understand IC pins and layout is	3.94	2.95
My ability to understand IC numbers and refer to their data sheet for reference is	3.95	3.10
My ability to understand transistor pin layouts without referring to their data sheet is	4.37	3.17
My ability to understand numbers written on electronic component to find and refer to their data sheet is	5.98	3.02
My understanding of the matrix of rows and columns and their interconnections on breadboard is	8.98	1.65
My ability to assemble components and construct complex circuits on breadboards is	8.55	1.87
My ability to troubleshoot when circuits did not operate on breadboard is	7.80	2.05
Questions regarding use of the Inter in laboratory (5 point Likert Scale)		
1 = Strongly Disagree, 5 = Strongly Agree		
I always use internet to search for information regarding experiments in lab	3.43	1.26
I sometimes get distracted while searching for information regarding experiments experiment on net	2.95	1.40
I am quickly able to find the required information regarding experiment through net	3.35	1.27
Gathering information on internet is time-consuming in a lab class	3.55	1.30

Appendix C7

Semi-structure interview script

The interview started by introducing the participants to this research. The participants were then asked to share their experiences of practical laboratory sessions, how they felt about the laboratory course, what types of experiments they conduct.

1. Have you worked on electronics before? How do you find it? What about electronics laboratory session?
2. Tell me about your experiences in practical electronics laboratory sessions? How was the overall learning experience?
3. What are the first things you do when you enter the laboratory?
4. What is your favorite experiment? What did you like or dislike the most about it?
5. What about other experiments difficulties face in?
6. How do you overcome these difficulties? Any specific methods that you use?
7. What about laboratory instructors? Do you enquire difficulties with peers or instructors?
8. Which equipment gives the most trouble in laboratory session? Why? How do you overcome the difficulty, if any?
9. Is the laboratory session timing fine? Are you able to complete the experiment on time? What happens if you are not able to complete the circuit?
10. What happens if you are rigging a complicated circuit and the laboratory time gets over? Do you disassemble the complete circuit and reassemble it in the next session?
11. What happens if a simple circuit gives problems? Like you are not getting the desired result? Does it happen?
12. How do you like complicated circuits? Do they always give problems?
13. What about easy circuits? Has it ever happened that the circuit is simple to rig but you are not getting the output? What did you do in such cases?
14. What is the best way to troubleshoot any circuit?
15. Which laboratory equipment is most difficult to operate? Why so? How do you go around troubleshooting or working with such equipment?
16. How do you find working with breadboards? Any problems faced while using them?
17. If you have to find to any information about electronic components, pin configurations or experiment, what do you do?
18. How often do you rely on instructors? What type of help do you usually take from them?
19. Is there anything you would like to share about electronics as a subject or practical laboratory experience? Any suggestions on how it can be improved?

End of interview session.

Annexure D

Annexure D1

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
Department of Electronics & Electrical Engineering
EE102 : Basic Electronics Laboratory

EXPT. No. 5 : POWER SUPPLY

OBJECTIVES : Design and analysis of full-wave rectifier and zener regulator.

MATERIALS REQUIRED

- Breadboard
- Equipment : Oscilloscope
- Components :
  - Transformer : One: 230 V to 12–0–12 V
  - Diode : Two: Type 1N4007 (Forward voltage drop V_F = 0.7V)
  - Zener Diode : One: (Zener voltage V_Z = 6.2 V)
  - Resistance : Three: 220 Ω, 560 Ω, 1 kΩ
  - Capacitor : One: 100 μF.

GENERAL GUIDELINES

1. Switch on the mains supply to the transformer only after you have made all other connections (in order to avoid electric shock).
2. Also, while making any changes in the circuit, switch off the mains supply to the transformer.
3. Connect the capacitor with correct polarity. The capacitor being of electrolytic type, it is polarized, and will be damaged if connected with incorrect polarity. Similarly, confirm the polarity of the diodes before connecting.
4. Use "*line*" as the source of triggering in the oscilloscope. Put the oscilloscope in *CHOP* mode.
5. Never ever **ground** the probes of CRO while measuring the voltage cross transformer as it may get damaged due to shot-circuit. Adjust the dc level of CRO prior to connecting the probes to the circuit.

PART A : Unregulated Power Supply : Using center tapped Transformer and Full - Wave Rectifier (FWR)

i) Full-wave rectifier (FWR)

1. Set up the circuit as shown in Fig. 5.1 without the capacitor *C*. The transformer TX has rating of 230 V to 12-0-12 V,1 A. Take R_L = 1 kΩ. Connect transformer primary to the mains and switch on the mains. Display the secondary voltages V_{AG} and V_{BG} (V_{AG} to Ch-1, V_{BG} to Ch-2) on the oscilloscope. Make sure that both the "probe grounds" are connected to the circuit ground. Sketch the waveforms overlapping, with the same time and amplitude axes. They should be 180° out of phase.
2. Display and sketch the full-wave rectified output V_o across R_L. Measure the peak voltages in both halves.

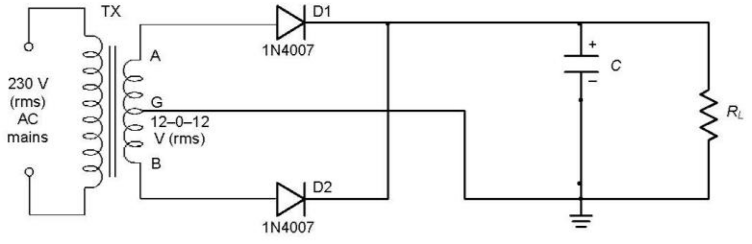


Fig. 5.1 Power supply using a centre tapped transformer and full-wave rectifier.

Q. 1 : If the peak amplitudes are not equal, what could be the reason?

3. Now connect *C* = 100 μF as shown in Fig. 5.1. Sketch V_o and measure V_r (peak-to- peak ripple voltage). Set the oscilloscope channel to *AC coupling* and increase vertical sensitivity (decrease V/div) while measuring V_r.

Annexure D2

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
Department of Electronics & Electrical Engineering
EE102: Basic Electronics Laboratory
EXPT. NO 3 : RLC Circuits

OBJECTIVE: To find the step response of RC and RL circuits and RLC series circuit resonance

MATERIALS REQUIRED

- Breadboard
- Equipment : Function Generator, Oscilloscope
- Components : Resistors: One 1 k Ω, One 4.7 kΩ; Inductor: 0.1 H; Capacitors: One 0.1 µF, One 1 µF

PRECAUTIONS AND GUIDELINES

1. Make sure the ground terminals of the oscilloscope probes and function generator are connected together.
2. While switching on the set-up, switch on the oscilloscope first, followed by the function generator.

Pre-experiment observation

Part A: Calculate the value of the time constant for RC circuit given in Fig. 3.1.
Part B: Calculate the value of the time constant for RL circuit given in Fig. 3.2.
Part C: Find the value of the resonant frequency for RLC circuit given in Fig. 3.3 using the formula

$$f_r = \frac{1}{2\pi\sqrt{(LC)}}$$

Part A: STEP RESPONSE OF RC CIRCUIT

When a step input V_S is applied to an RC circuit with no charge on capacitor, the capacitor starts charging towards V_S with time t. The instantaneous voltage across capacitor is given by $V_C(t) = V_S\,(1 - exp(-t/RC))$. The time required by the capacitor to charge up to 63% of full charge voltage is called the time-constant 'τ' of RC circuit and is given by $\tau = RC$.

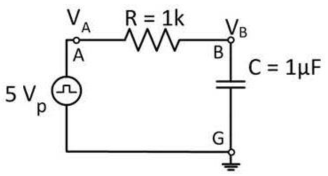


Fig.3.1

1. Assemble the circuit shown in Fig. 3.1. Connect Ch1 and Ch2 probes of CRO to node A and node B, respectively. Use the dc coupling mode of CRO for this part of the experiment.
2. Apply a **unipolar** square wave input (5 V; 0.1 kHz) from the function generator.
3. Observe the voltages at node A and node B in CRO and measure the time-constant 'τ' by noting the time taken by the capacitor to rise to 63% of its maximum charge voltage.
4. Now increase the frequency of the input signal and note the frequency 'f' for which the capacitor just gets charged up to maximum possible voltage. Find the ratio of $T\,/\,\tau$, where $T = 1/f$.

Part B: STEP RESPONSE OF RL CIRCUIT

When a step input V_S is applied to an RL circuit with inductor having no stored energy, initially the current through it is zero but increases towards the maximum value of V_S/R with time 't'. The instantaneous value of current through inductor is given by $I_L(t) = (V_S/R)\,(1 - exp(-Rt/L))$. The time required by the voltage across inductor to drop to 37% of maximum voltage or the voltage across resistor to rise up to 63% of maximum voltage is called the time-constant 'τ' of RL circuit and is given by $\tau = L\,/\,R$.

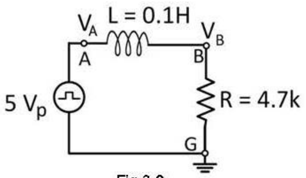


Fig.3.2

1. Assemble the circuit shown in Fig. 3.2. Connect Ch1 and Ch2 probes of CRO to node A and node B, respectively. Keep using the dc coupling mode of the CRO.
2. Apply a unipolar square wave input (5 V; 0.5 kHz).
3. Observe the voltages at node A and node B in CRO and measure the time-constant 'τ' by noting the time taken by the voltage drop across resistor to rise to 63% of its maximum value.

Part C: RESONANCE IN SERIES RLC CIRCUIT

The resonance in a series RLC circuit is a state where the current drawn from the source is in phase with the voltage applied. This occurs at a particular frequency which is called the resonant frequency. At resonance, the reactance of the inductor and that of the capacitor cancel each other so the RLC circuit offers minimum impedance and hence the current through the circuit is maximized.

1. Assemble the circuit as shown in Fig. 3.3. Apply a sinusoidal input (8 Vp-p) to the circuit.

2. Using CRO measure the applied input across terminals A-G in Ch1 and the current through RLC circuit through the voltage drop across terminals B-G in Ch2.

3. Vary the frequency of the function generator as suggested below and measure the peak-to-peak amplitude of voltage across terminals B-G (Ch2) which proportional to the current in the circuit.
Estimate the coarse resonant frequency of the RLC circuit from these measurements.

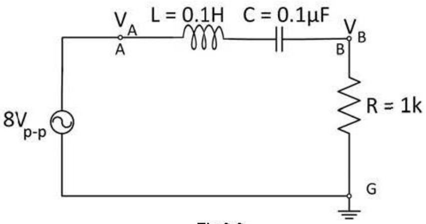


Fig.3.3

Frequency (in kHz)	Voltage across B-G
0.1	
0.5	
1.0	
1.5	
2.0	
4.0	
10.0	

4. To refine the estimate of resonant frequency, set the function generator again to the coarse estimate of the resonant frequency and now observe the phase difference between the applied input voltage (Ch1) and the circuit current (Ch2). Finely varying the frequency of the function generator till voltages in Ch1 and Ch2 get phase synchronized. The frequency at which synchronization is achieved is a precise estimate of the resonant frequency of the RLC circuit. Compare that with theoretically computed value.

5. In the same setup, reset input frequency to 0.1 kHz and observe the amount and the nature of the phase difference between Ch1 and Ch2.

6. Repeat step 5 for input frequency of 10 kHz instead of 0.1 kHz.

7. Comment on the cause of the observations made in step 5 and 6, if any. Also draw the phasor diagram of voltages across all three components at resonant frequency using given nominal value of components.

****

Appendix D3

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
Department of Electronics & Electrical Engineering
EE102: Basic Electronics Laboratory
EXPT. NO 2 : Circuit Theorems

OBJECTIVE: Verification of superposition theorem, Thevenin's theorem and maximum power transfer theorem

MATERIALS REQUIRED

- Breadboard
- Equipment : Multi-output DC Power Supply, Oscilloscope
- Components : Resistances: One 10 Ω, One 560 Ω, Three 1 kΩ, Three 2.2 kΩ, One 3.9 kΩ, One 4.7 kΩ

PRECAUTIONS AND GUIDELINES

1. Make sure the ground terminals of the oscilloscope probes and power supplies are connected together in the circuit.
2. While switching on the set-up, switch on the oscilloscope first, followed by the power supply.

Pre-experiment observation

Part A: For the circuit shown in Fig. 2.1, find the voltage V_C across resistance R for the cases listed in Table 2.1. Assume $V_1 = 5$ V, $V_2 = 3$ V and zero source resistances. Also repeat the same for $V_1 = 12$ V and $V_2 = 5$ V.

Part B: Calculate the Thevenin's voltage and resistance a seen into terminals A-B of the circuit given in Fig 2.2.

Part C: For the circuit in Fig 2.2, find the value of R_L for which maximum power transfer would take place and also find the value of maximum power transferred.

Part A: SUPERPOSITION THEOREM

The response of any circuit variable in a multi-source linear memory-less circuit containing 'n' independent sources can be obtained by adding the responses of the same circuit variable in 'n' single-source circuit with i^{th} independent source active and all the remaining independent sources deactivated.

1. Assemble the circuit shown in Fig. 2.1. Use 0-32V and 5V sources of the multi-output DC power supply for realizing voltage sources V_1 and V_2 in the circuit.
2. For the safety of resistors, do not apply more than 20 V from 0-32V source for the experiment purpose.
3. Verify the superposition theorem for the voltage V_C developed across the resistance R due to voltage sources V_1 and V_2.

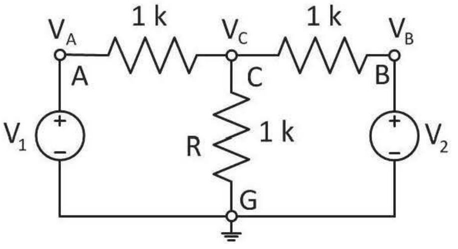


Fig. 2.1

Take the measurements listed in Table 2.1. Verify that voltage V_C for Case I is the sum of voltages obtained in Case II and III.

Case	Circuit modification required	V_1 (V)	V_2 (V)	V_A (V)	V_B (V)	V_C (V)
I	Both sources connected	5	3	5	3	2.67
II	V_2 removed from circuit and port B-G shorted	5	0	5	1.67	0
III	V_1 removed from circuit and port A-G shorted	0	3	0	1	3

Table. 2.1

Repeat the experiment for $V_1 = 12$ V while keeping $V_2 = 5$ V.

4. Comment on the possible cause if the superposition theorem is not verified exactly.

Annexure E

Annexure E1

This annexure is a continuation of discussion on prototype design from Chapter 5, Section 5.2. Complete technical details of the developed prototype has been presented.

Design of Augmented Reality module

In this section we describe the design, technical requirements, functionalities and features of our mobile AR instructional application prototype.

Development Environment for AR prototype

Figure E1 represents a simplified block diagram of the technical implementation of AR prototype which was developed for an Android mobile platform (Android Developers, 2014) using Unity3D and Vuforia AR SDK (Unity extension). Unity is a cross-platform game engine with a built-in Integrated Development Environment (IDE). It is used to develop video games for web plugins, desktop platforms, consoles and mobile devices. It provides a base platform to use 3D models generated in SketchUp with the Vuforia plugin. Additional functionalities and interactions such as GUI buttons, audio support and virtual buttons can be built on this IDE (Unity, n.d.).

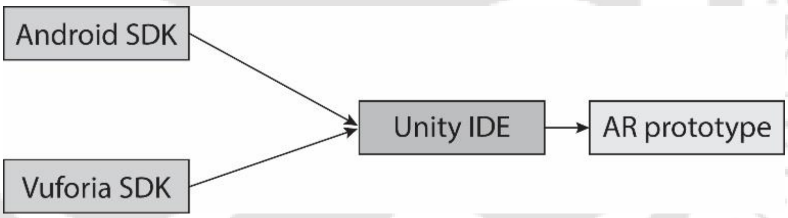


Figure E1. Simplified block diagram of the technical implementation of AR application prototype

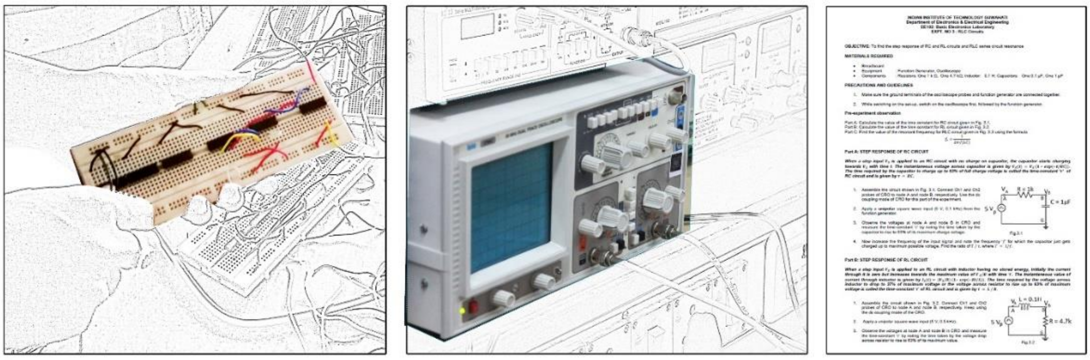
Vuforia is an Augmented Reality Software Development Kit (SDK) for mobile devices. It uses Computer Vision technology to recognize and track planar images (Image Targets) and simple 3D objects, such as boxes, in real-time (Vuforia, n.d.). This image registration capability enables developers to position and orient virtual objects, such as 3D models and other media, in relation to real-world images when these are viewed through the camera of a mobile device. The virtual object then tracks the position and orientation of the image in real-time so that the viewer's perspective on the object corresponds with their perspective on the Image Target, so that it appears that the virtual object is a part of the real world scene. Apart from providing Image tracking capabilities, Vuforia also gives developers the flexibility to add interactions through buttons, gestures, animation, sound etc. in the mobile application. "Image Targets represent images that the Vuforia SDK can detect and track. Unlike traditional fiducial markers, data matrix codes and

QR codes, Image Targets do not need special black and white regions or codes to be recognized. The SDK detects and tracks the features that are naturally found in the image itself by comparing these natural features against a known target resource database. Once the Image Target is detected, the SDK will track the image as long as it is at least partially in the camera's field of view." (Vuforia, n.d.)

AR tracking techniques for practical electronics laboratory session

Augmented reality utilizes various tracking methods to overlay virtual or digital data onto real-world scenarios. To align this virtual data onto real-world scenario or environment, a visual marker-based approach is used, e.g. a 2D barcode or a QR code detectable by various computer vision methods. Different types of visual markers affect the performance of AR application; therefore, suitable markers are adopted for a given application. There are certain methods in computer vision that can also use natural features of the physical objects or environment to align virtual data instead of using a visual marker. These methods are also referred to as marker-less tracking technique (Siltanen, 2012). Our prototype utilizes both these techniques, i.e. marker and marker-less, to overlay virtual data in a laboratory environment.

From user studies (described in Chapter 4), we identified three physical objects – breadboard, laboratory manual and CRO (see Figure E2), used in practical laboratory on which, if digital data was overlaid in form of contextualized instructions, could help students gain better understanding of the practical experiment and reduce the amount of effort to perform activity.



(a) (b) (c)

Figure E2. Physical objects used in laboratory selected for augmentation. (a) breadboard, (b) Cathode Ray Oscilloscope, and, (c) a screenshot of laboratory manual used by students. Photos were taken during field study.

We explored various possibilities to augment user interactions with these objects using by different tracking methods. In this thesis, we are referring to 'Markers' as elements that need to be attached to a physical object to enable AR tracking for overlaying virtual data, i.e., the user needs to attach a printed image or an image pattern over a physical object to achieve augmentation. A 'marker-less' tracking technique does not require user to attach any printer markers on physical objects to enable tracking. Our AR module utilized multiple image target tracking.

Marker design for breadboard

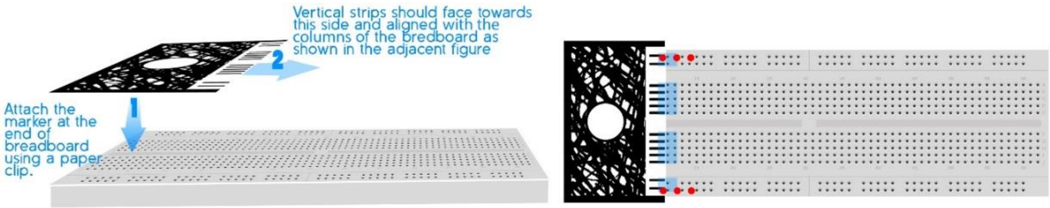


Figure E3. Using our designed marker with breadboard.

We found that attaching a marker worked best for overlaying virtual data on breadboard. We also tried to explore object tracking technique on breadboard but found that it was not a feasible method as the tracking was not efficient. Therefore, we designed and used markers for breadboard, as per guideline provided by Vuforia developers guide on creating effective image targets (Vuforia, n.d.-c). The markers could be printed on a normal paper and attached to the end of a breadboard. Figure E3 depicts this procedure. The marker was designed such that it could provide proper tracking while being used in a laboratory. In addition to the above marker, we also used an image based image target in the subsequent iterated version of our AR prototype – that were embedded with additional conceptualized functionalities. Altogether, two types of marker were designed and used with breadboard**.** Figure E4 depicts these markers attached on a breadboard and their tracking features.

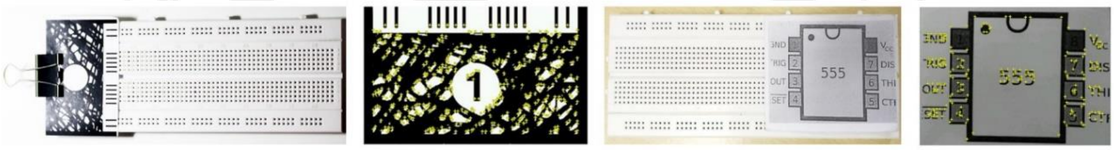


Figure E4. Different types of breadboard markers used with our AR prototype and their tracking features, shown in yellow, stored in image target database. These features are tracked as long as the image is at least partially in the camera's field of view.

When a smartphone or digital tablet's camera was hovered was over this setup, 3D circuit instructions could be viewed on the screen. The 3D instructions were primarily made for helping students with circuit assembly on a breadboard with which the marker was attached. Figure E5 shows a screenshot of our AR based circuit assembly instructions for one of the experiment. This functionality helped students visualize complicated circuit diagrams on a breadboard. The instructional prompts via AR were given to students in form of text and were supplemented by voice.

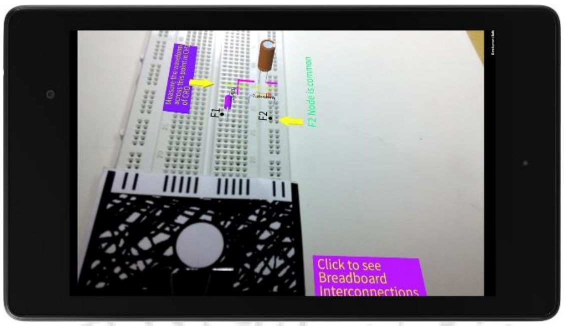
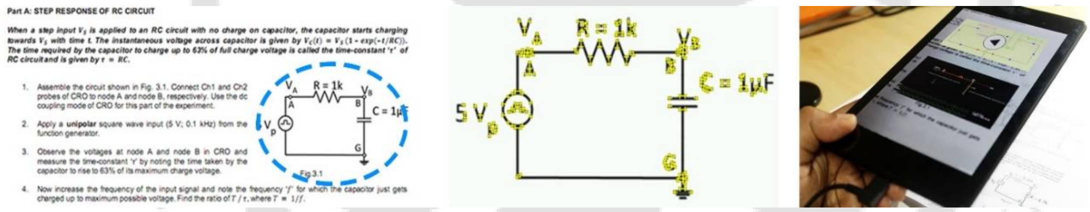


Figure E5. Circuit assembly instruction via AR. 3D graphics and circuit overlay on the breadboard as seen on AR view of the digital tablet.

Image target tracking for laboratory manual

We utilized already existing circuit diagrams on laboratory manual as image target to overlay virtual data. Whenever the user pointed device camera over these circuit diagrams, videos pertaining to the working of circuit was displayed. Figure 6 represents one such circuit diagram of RC experiment that was used as an image target as well as videos overlay.



(a) **(b)** **(c)**

Figure E6. Circuit diagrams were utilized as image targets. (a) A snapshot from laboratory manual depicting a RC circuit diagram adopted as image target. (b) Image target features, shown in yellow, that are tracked by the camera. (c) Video pertaining to the working of circuit diagram were overlaid on the laboratory manual.

Image target tracking for Cathode Ray Oscilloscope

We explored different methods of tracking for CRO. We initially tried to attach markers on it's control panel user interface on it to see if effective tracking could be achieved. However, we found it to be challenging as size of the marker to be attached on a CRO needs to be small so that it does not obstruct with other functionalities on its control panel. A small sized marker was not detectable by the camera; hence, no information could be overlaid over it. We then explored the possibility of utilizing natural features of CRO's control panel to be used as image tracker which was successful. Figure E7 represents the front side control panel of a CRO which was used as an image target and it's tracking features. Whenever the camera was pointed towards the CRO, it projected 2D AR buttons over CRO interface. When these 2D buttons were pressed, voice-based instructions were provided to the student regarding the functionalities on CRO

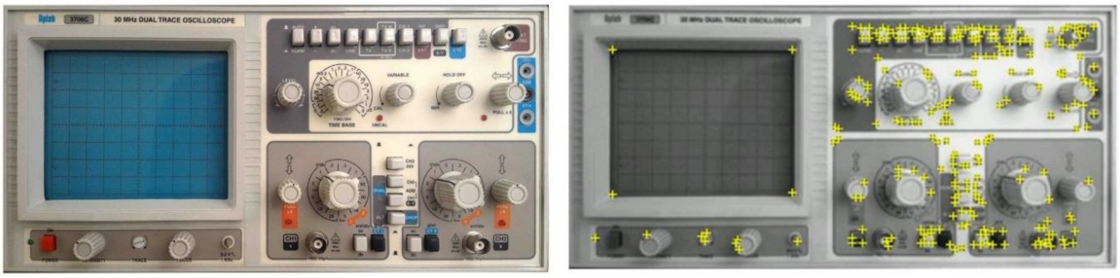


Figure E8. Right side of the image shows CRO interface as image target. Left side shows tracking features of CRO as in yellow crosses.

Design of Intelligent breadboard

This section presents the technical details on the development of our intelligent breadboard prototype.

Hardware and Software Platforms for Intelligent Breadboard

The hardware platform of our prototype consists of Arduino Uno microcontroller board, 1-Sheeld board that can be physically connected to Arduino Uno, HC-05 Wireless Bluetooth RF Transceiver module and voltage divider networks consisting of a number of resistors.

The Arduino Uno board is based on ATmega328P microcontroller. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs (pins A0 to A5), 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button and contains everything needed to support the microcontroller (adopted from Arduino, n.d.).

1Sheeld is an easily configurable shield (i.e. an auxiliary board) for Arduino. It connects to a mobile app that allow the usage of all of Android smartphones' capabilities such as LCD Screen, Gyroscope, Switches, LEDs, Accelerometer, Magnetometer, GSM, Wi-Fi, GPS …etc. into Arduino program code (or also referred to as sketch). It consists of two parts:

- The first part is a shield that is physically connected to Arduino Uno board and acts as a wireless intermediary, piping data between Arduino and any Android smartphone via Bluetooth.
- The second part is a software platform and application (app) on Android smartphones that manages the communication between 1Sheeld and smartphone and let users choose between different available functionalities. By doing that, 1Sheeld acts as input or output

from Arduino and make use of all of the sensors and peripherals already available on Android smartphone. (adopted from 1Sheeld, n.d.)

HC-05 is an easy to use Bluetooth SPP (Serial Port Protocol) Module designed for transparent wireless connection setup (adopted from eprolabs, n.d.). The module can easily be connected to Arduino Uno board to wirelessly transmit and receive data. Figure E8 depicts all these modules.

(a) (b) (c)

Figure E8. Hardware platforms used for the development of intelligent breadboard. (a) Arduino Uno. (b) 1-Sheeld board that can be physically connected on top of Arduino Uno. (c) HC-05 Bluetooth transceiver module. Images adopted from platform websites using the Internet(Arduino, n.d.; 1Sheeld, n.d.; eprolabs, n.d.)

A nodal voltage sensor was designed which could communicate with the microcontroller. This nodal sensor allowed sensing of various circuit parameters.

The software side consists of 1Sheeld mobile application to provide text-to-speech (TTS) and text display capabilities via smartphone. Unity IDE with Vuforia SDK is used for AR based instructional prompts utilizing marker-based tracking functionality. Figure E9 depicts a basic block diagram of how various hardware and software components of intelligent breadboard interact. The 1Sheeld board interacts with its application on an Android smartphone. HC-05 Bluetooth module interacts with Unity IDE running Vuforia plugin on a computer. The following section describes the mechanisms of intelligent breadboard in further details.

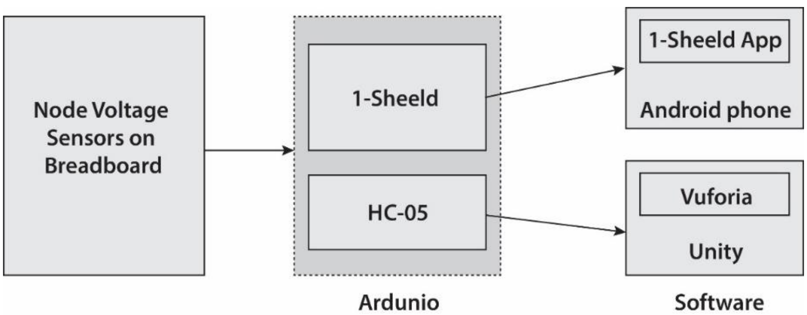


Figure E9. Block diagram-describing interactions between various hardware and software components of intelligent breadboard.

Appendix E2

Concepts and Wireframe diagram of AR application prototype.

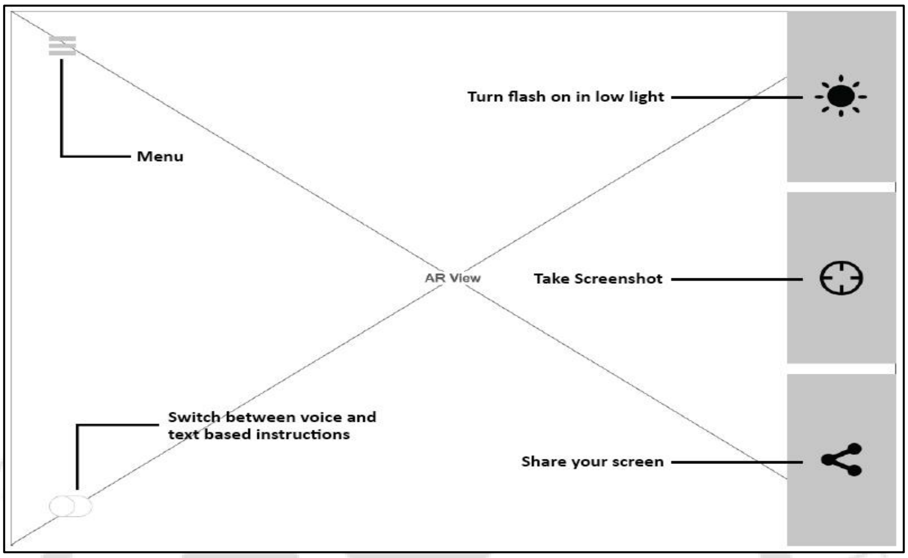
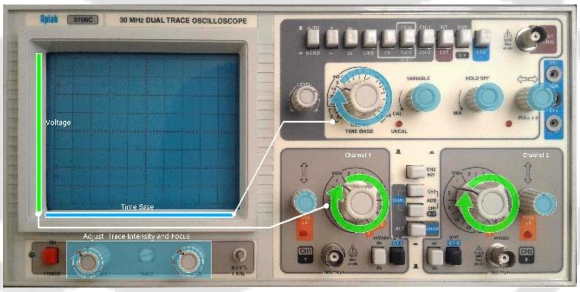
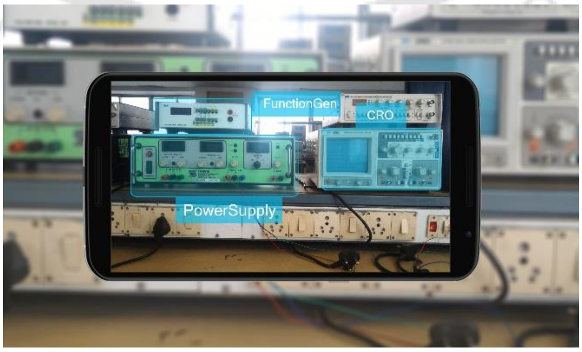


Figure 1. Wireframe of AR application



(a)



(b)

Figure 2. Concepts for AR. (a) Concept of AR for overlaying instructions on CRO, (b) Viewing equipment information via AR

Mock-up of SLS prototype utilized during design experiments.

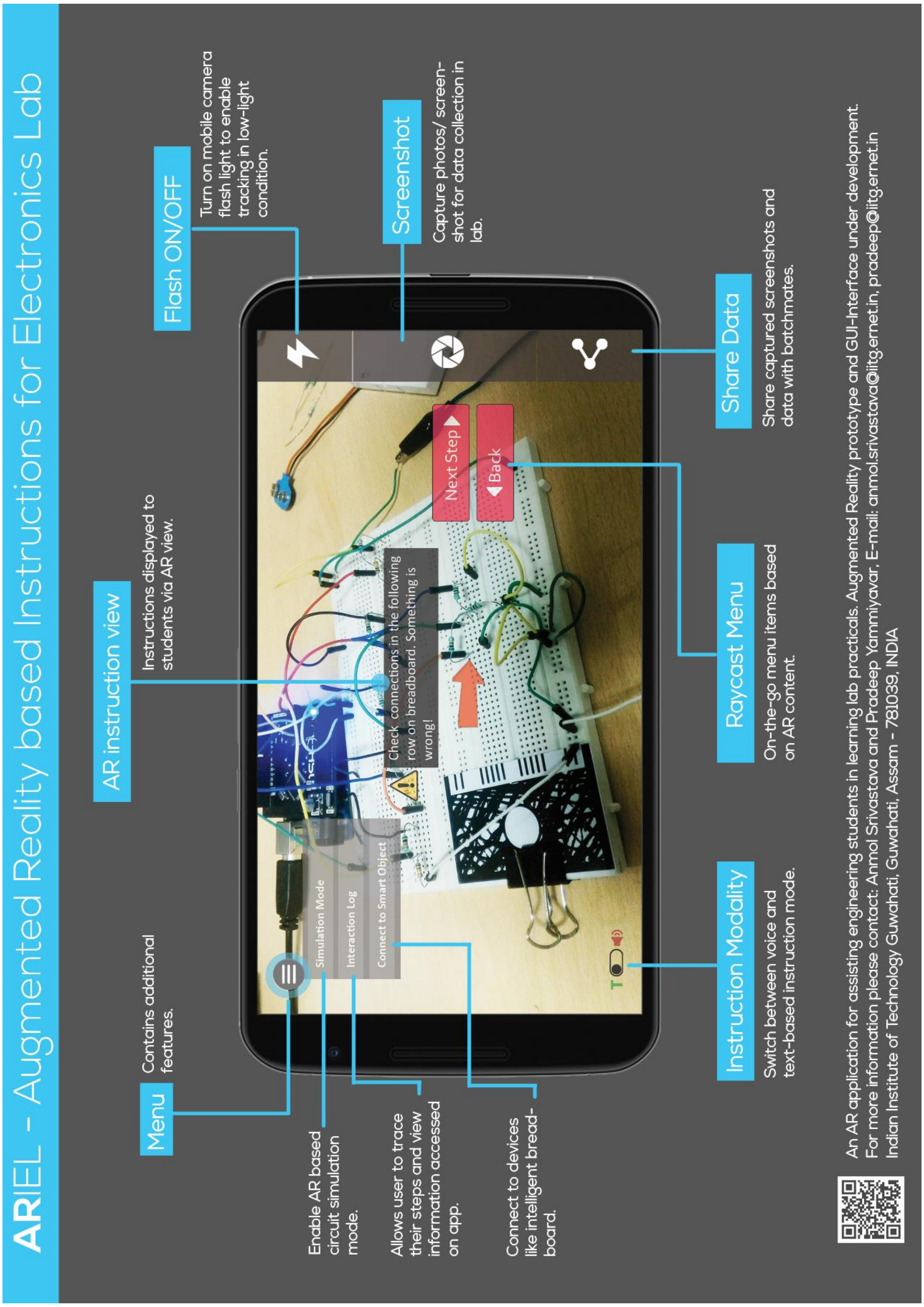


Figure 1. Complete conceptualized GUI of AR application that can interface with intelligent breadboard.

Interaction flow diagram of mock-up AR application presented to participants during design experiments. Figure 1 to Figure 5 depict the splash screens that inform user about how to use AR. Figure 6 and Figure 7 depict the AR view of the application that has been interfaced with the intelligent breadboard.

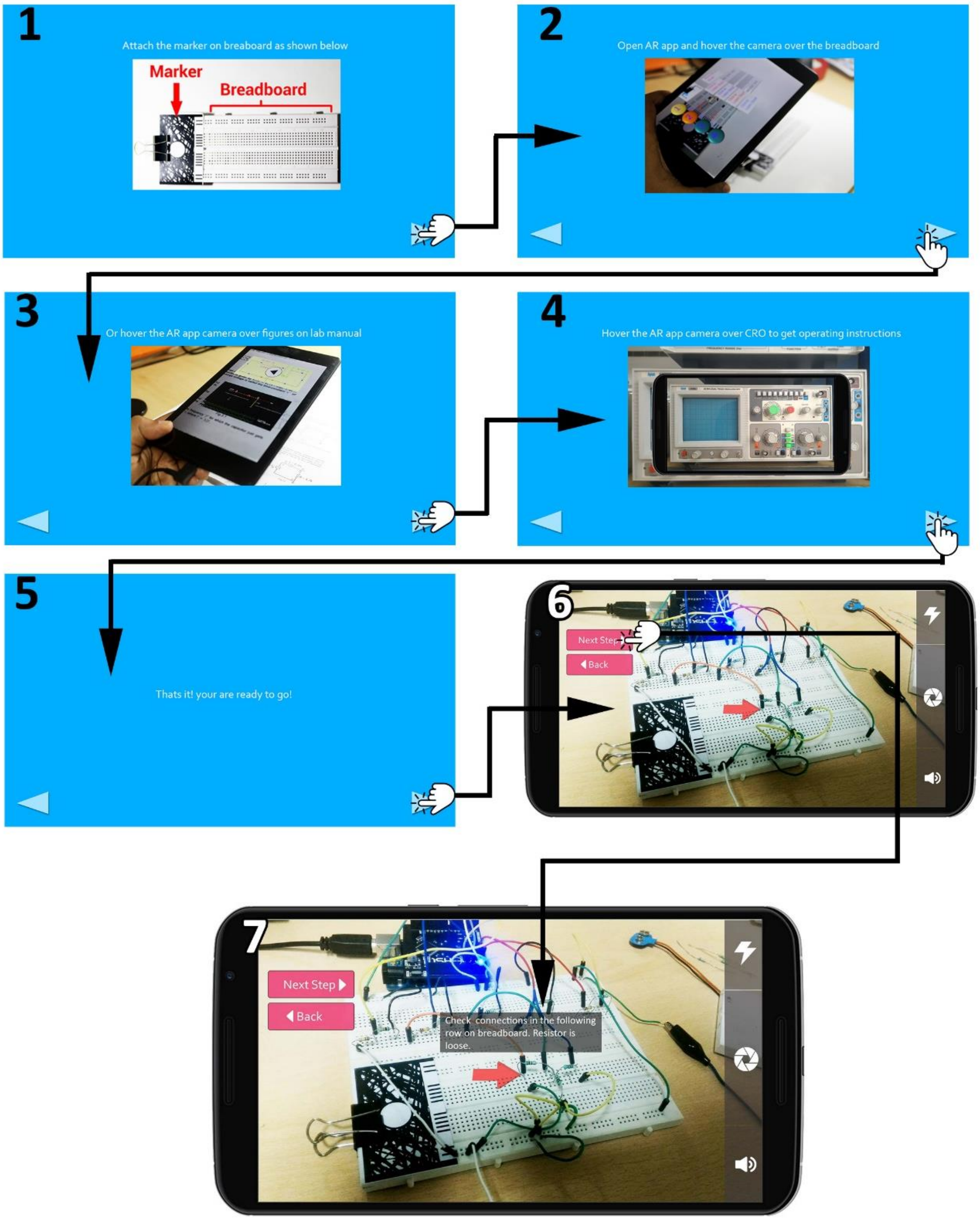
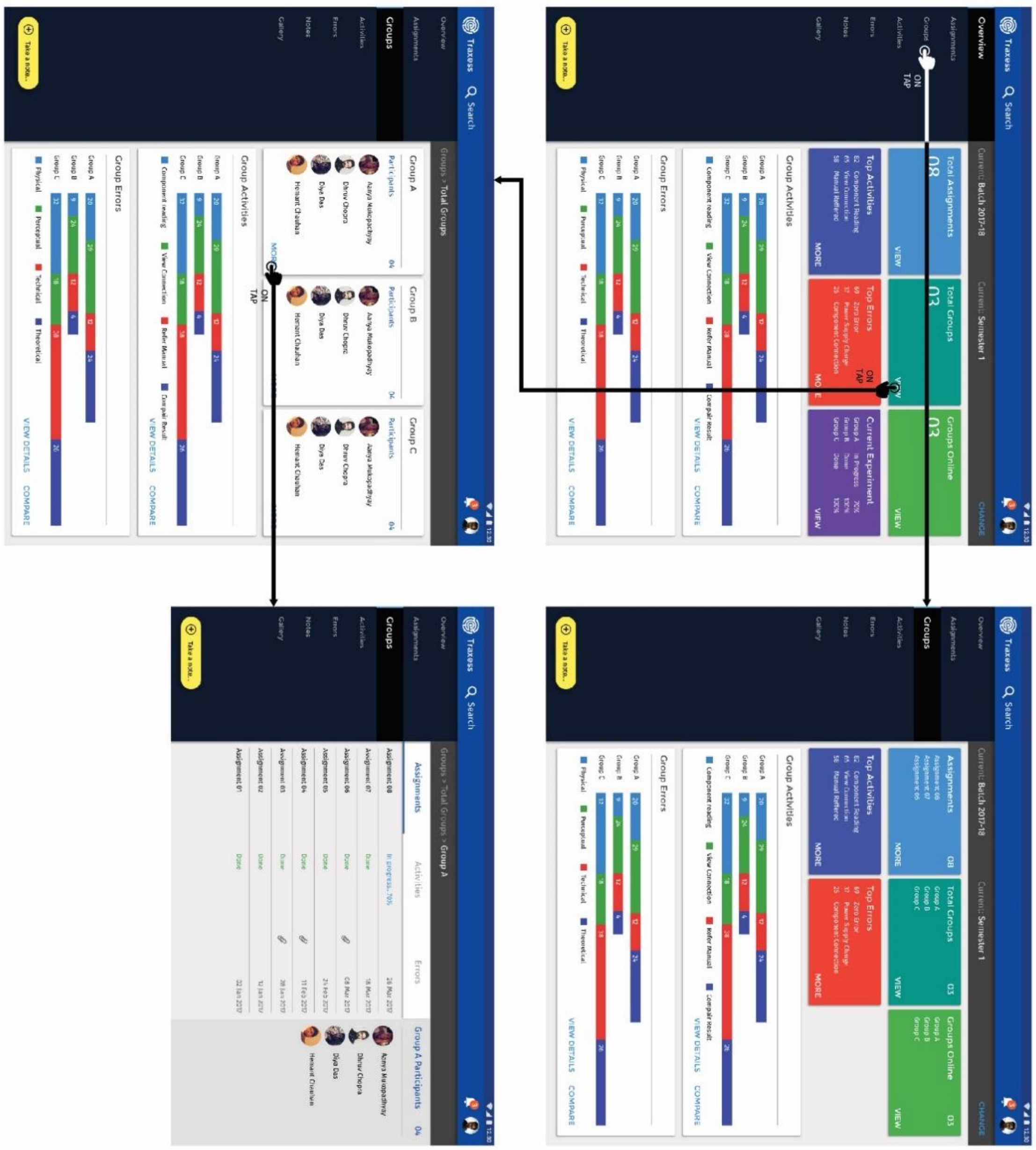


Figure 2. Interaction flow diagram of the conceptualized SLS system utilizing AR

Appendix E3

As discussed in Section 5.4.1, this annexure depicts the interaction flow diagram of the conceptualized instructor dashboard application. The dashboard presents information regarding real-time progress of student groups, information accessed by them through AR application and difficulties faced by them.



Annexure F

Annexure F1

The following set of questionnaires were utilized during Design Experiment - I:

Introduction to this Questionnaire

Thank you very much for agreeing to take part in this important research study to imporve students' learning experience in practical electronics lab sessions.

This short questionnaire is a part of a research work being conducted on 'Embedding Intelligence into Objects used in Electronics Laboratory' at Usability Engineering & Human Computer Interaction Lab at Department of Design, IIT Guwahati. The aim of our research is to improve the laboratory learning experience of students by making use of emerging technologies like Augmented Reality and Smart Objects.

This questionnaire will help us in designing systems to achieve these goals to make your learning experience entertaining and easy.

This survey should take only 10 – 15 minutes to complete. All personal information provided by you in this questionnaire will be kept confidential and we assure you that participants will be kept non-traceable and anonymous. The names of the participants have only been taken for follow-up interview if required.

This questionnaire does not to access your marks, intelligence or knowledge.

Once again, thank you for participating in this research study and giving us your precious time.

For submissions or queries, please contact:

Anmol Srivastava,
PhD Research Scholar,
Usability Engineering and HCI Lab,
Department of Design, IIT Guwahati

Email: anmol.srivastava@iitg.ernet.in
Phone: +91 – 9957368638

1

General Information – Please fill in the following details

1. **Full Name:**____

   (Example: Vijay Rai)

2. **Age:**____

   (Example: 21 years)

3. **Gender :** ☐ **Male** ☐ **Female**

4. **Name of the degree/ course and institution you are enrolled in**

   (Ex: M.Sc Electronics or Diploma – Electronics, DBS College, Dehradun)

   ____

5. **Your academic performance overall (marks/ division/ grade) in last semester/exam falls in category:**

   (Tick the appropriate box.)

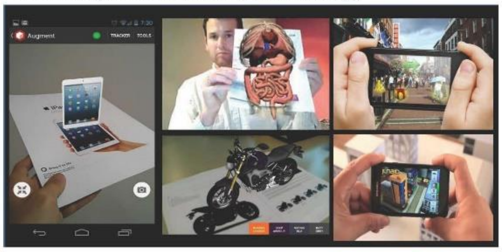
   ☐ **Upto 50%** ☐ **Upto 70%** ☐ **Above 70%**

6. **Have you heard/ read about terms such as Augmented Reality and related technology?**

   (Check the appropriate box. Mark only one box.)

   ☐ **Yes** ☐ **No**

About Augmented Reality Technology



The basic idea of augmented reality is to superimpose graphics, audio and other sensory enhancements over a real-world enviornment in real-time.

2

The following form, printed on A3 sheet, was utilized for cognitive walkthrough. Participants were asked to will in their responses in each column.

	State the difficulties experienced by you in doing this/these experiment(s).	How do you solve these issues?	What would you like to be told before the experiment so that learning becomes easy?	Rate your understanding on a scale of 1 to 10 of the principle behind this/these experiment(s) that resulted from: (1 = Low, 10 = Highest)
Referring to lab manual	(E.g. - understanding procedures)		(E.g. – The white stripe of capacitor is negative terminal)	(Ex: 7/10) 1. Reading the lab manual: ____________________ 2. Getting instructions from your instructor or lab teacher: ___________________ 3. Discussing and taking hints with your batch mates: __________________________ Any comments you want to share regarding your lab based learning experience, please share:
Rigging up Circuit on breadboard	(E.g. – use the series rail for power supply and ground connection)			
Operating Test Equipment (like CRO, Multi-meter)				
Reporting of experiment				
In terms of learning that is expected to happen after undergoing this experiment, do you have any comments?				3

The participants were asked to fill the following form after the demonstration of AR prototype and SLS mock-ups for qualitative assessment.

Assume this AR application is made available to you, mention the percentage of extra learning that would happen in-terms of:
(Ex: 40%)

1. Understanding the principle behind the experiment: ________________________
2. Time-saving in labs: ________________________
3. Readiness for the lab: ________________________
4. Saving of time during lab: ________________________
5. Concentrating on experiment rather than involving in debugging part of experiment: ____________

Any comments you want to share regarding this AR application?

4

Perceived Learners Satisfaction Scale

Put a tick-mark (✓) in the appropriate box. This questionnaire assesses the perceived learner satisfaction for using Augmented Reality application in practical lab sessions.

1. **The AR application provides content that exactly fits your needs in conducting specific lab practical at the right time.**
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

2. **The AR application is easy to use.**
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

3. **The AR application makes it easy for you to find the content you need in your own way of exploring.**
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

4. **The content provided by the AR application is easy to understand.**
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

5. **The AR application is user-friendly in term of its user-interface.**
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

6. **The AR application responds to your request fast enough.**
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

5

7. **The AR application makes it easy for you to evaluate your learning performance and become confident.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

8. **The testing methods provided by the AR application are easy to understand.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

9. **The AR application provides secure testing environments in which you are not afraid to make mistakes.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

10. **The AR application enables you to choose what you want to learn and when you want to learn.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

11. **The AR application provides the personalized learning support and tailored mode for you.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

12. **The AR application makes it easy for you to discuss questions with your teachers and batch mates.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

13. **The AR application makes it easy for you to share what you learn with the learning community.**
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

6

14. **The AR application makes it easy for you to share what you learn with the learning community.**

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

15. **As a whole, you are satisfied with the AR application.**

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

16. **As a whole, the AR application is successful and you would like to use them if made available.**

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

Perceived Ease of Use Scale

Put a tick-mark (✓) in the appropriate box.

1. **It was simple to use this AR application.**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

2. **I feel comfortable using this AR application.**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

3. **It was easy to learn to use this AR application.**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

4. **I believe I became productive quickly using this AR application.**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

Perceived Usefulness Scale

Put a tick-mark (✓) in the appropriate box.

5. **I can effectively complete my lab practical for a specific experiment using this AR application.**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

6. **I am able to complete my lab practical for a specific experiment using this AR application.**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

8

7. **I am able to efficiently complete my lab practical for a specific experiment using this AR application.**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

Relative Advantage Scale

Put a tick-mark (✓) in the appropriate box.

8. **Performing Lab practical, using this AR application is more effective than using traditional paper and simulation based format.**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

9. **This AR application is better that other lab instructional systems like online simulations, simulation software I have used so far.**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

Willingness to Continue Usage Scale

Put a tick-mark (✓) in the appropriate box.

10. **Please rate your willingness to continue working with the software in future Examinations**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Lowest	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Highest

Annexure F2

The following set of questionnaires were utilized during Design Experiment-II:

NASA Task Load Index (TLX)

Name	Experiment Name	Date

Mental Demand — How mentally demanding was this experiment?

Very Low — Very High

Physical Demand — How physically demanding was this experiment?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the experiment?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed were you while performing this experiment?

Very Low — Very High

1

NASA Task Load Index (TLX) - Using Smart Learning System

Please fill in the appropriate responses on the following scales regarding your perceived Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration while working on this experiement if this smart learning system is made availabe to you in labs

Name	Experiment Name	Date

Mental Demand — How mentally demanding will the experiment be after using this smart learning system?

Very Low — Very High

Physical Demand — How physically demanding will the experiment be after using this smart learning system?

Very Low — Very High

Temporal Demand — How hurried or rushed will the pace of the experiment be after using this smart learning system?

Very Low — Very High

Performance — How successfully will you accomplish what you are asked to do using this smart learning system?

Perfect — Failure

Effort — How hard will you have to work to accomplish your level of performance using this smart learning system?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed will you get while performing the experiment using this smart learning system?

Very Low — Very High

Anything you'd like to share regarding this smart learning system. Please Comment:

2

Smart Learning System Survey Questionnaires

General Information

*Required

1. **Email address** *

2. **Name** *

3. **Age** *

4. **Branch** *
   Ex: Mech, EEE, Civil, Biotech

5. **Phone Number**
   The phone number is being taken in case we want to contact you for a follow-up interview.

Perceived Learners Satisfaction Scale

Select the appropriate box.. This questionnaire assesses the perceived learner satisfaction for using smart learning system in electronics practical lab sessions which was demonstrated and used before you.

6. **The smart learning system provides content that exactly fits your needs in conducting specific lab practical at the right time.** *
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

7. **The smart learning system is easy to use.** *
   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

3

8. **The smart learning system makes it easy for you to find the content you need in your own way of exploring.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

9. **The content provided by the smart learning system is easy to understand.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

10. **The smart learning system is user-friendly in term of its user-interface.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

11. **The smart learning system responds to your request fast enough.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

12. **The smart learning system makes it easy for you to evaluate your progress and learning performance and become confident.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

13. **The testing methods provided by smart learning system in understanding the experiment are easy to follow and interact with.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

14. **The smart learning system provides secure testing environments in which you are not afraid to make mistakes involving circuits, blown devices and short-circuits.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

4

15. **The smart learning system enables you to choose what you want to learn and when you want to learn when you are deeply concentrating in the experiment. ***
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree								Strongly Agree

16. **The smart learning system provides a personalized learning support just as an instructor/tutor/lab assistant would do. ***
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree								Strongly Agree

17. **The smart learning system makes it easy for you to discuss questions and doubts with your teachers and batch mates during the experiment itself. ***
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree								Strongly Agree

18. **The smart learning system makes it easy for you to share what you learn with your peers and batch-mates. ***
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree								Strongly Agree

19. **As a whole, you are satisfied with the advantages provided by the smart learning system. ***
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree								Strongly Agree

20. **If made available in your institute, you will definitely this smart learning system. ***
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree								Strongly Agree

Perceived Ease of Use Scale

Select the appropriate box. This questionnaire assesses the perceived ease of use for using smart learning system in electronics practical lab sessions which was demonstrated and used before you.

21. **The smart learning system was simple and easy to use** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

22. **I feel comfortable using this smart learning system system.** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

23. **It was easy to learn to use this smart learning system.** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

24. **I believe I became more productive using this smart learning system during my experiment.** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Perceived Usefulness Scale

Select the appropriate box. This questionnaire assesses the perceived usefulness of smart learning system in electronics practical lab sessions which was demonstrated and used before you.

25. **I can effectively complete my lab practical on my own using this smart learning system.** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Relative Advantage Scale

Select the appropriate box. This questionnaire assesses the relative advantage of smart learning system in electronics practical lab sessions which was demonstrated and used before you over conventional lab sessions.

26. **Performing lab practical, using this smart learning system is more effective than using only traditional paper and simulation based formats.** *
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

6

27. **This smart learning system is better that other lab instructional systems like Internet and simulation software I have used so far.** *

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

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7

Annexure G

Annexure G1

This annexure is a continuation of Section 6.4 on hypotheses testing. Results of additional hypotheses tested have been presented that measure the impact of SLS on various factors that contribute to the overall extraneous cognitive load (or the workload) of students in practical laboratory. The effect of SLS for different task variations (RLC, Circuit theorem, RJ45 experiments) has been measured using paired t-test for various workload factors. The results are describable as below. Complete inferences from all hypotheses tested has been described in Section 6.5.

1. Hypotheses (H1): Task specific mean weighted workload

The hypothesis (H_1) which is tested is given below.

H1: The designed SLS will affect the mean weighted workload (MWWL) of students on the NASA-TLX scale.

Table 1 gives the descriptive statistics of MWWL for traditional laboratory without the use of SLS and with the use of SLS. Table 2 depicts the results of paired sample t-tests.

Table 1. Descriptive statistics of Weighted Workload for different tasks on NASA-TLX scale (0 = Low to 100 = High)

		Traditional Lab		Smart Learning System	
Task Name	N	Mean	SD	Mean	SD
RLC Circuit	63	11.54	2.77	5.79	2.64
Circuit Theorem	9	9.38	2.46	6.46	3.20
RJ45 Connection	18	10.05	2.43	8.66	2.58

Table 2. Results of paired t-test for different task variations.

Task name	Result from paired *t*-test	Null Hypotheses
RLC Circuit	$t(62) = 11.778,\ p < .001,\ d = 1.48$	Failed to Accept H_{01}
Circuit Theorem	$t(8) = 3.535,\ p = .008,\ d = 1.18$	Failed to Accept H_{01}
RJ45 Cable Connection	$t(17) = 2.030,\ p = .058,\ d = 0.48$	Failed to Reject H_{01}

The paired sample t-test conducted on the data sets (see Table 1) reveals that for RLC Circuit task, there was a statistical significance (t(62) = 11.778, p < .001, d = 1.48), between the existing laboratory mean weighted workload $MWWL_{TL}$ (Mean = 11.54, SD = 2.77) and $MWWL_{SLS}$ (Mean = 5.79, SD = 2.64) on NASA-TLX. The result indicates that SLS affects the mean weighted workload of students significantly in RLC experiment.

For Circuit theorem task, there was a statistical significance ($t(8) = 3.535$, $p = .008$, $d = 1.18$) between $MWWL_{TL}$ (Mean = 9.38, SD = 2.46) and $MWWL_{SLS}$ (Mean = 6.46, SD = 3.20) on NASA-TLX. The result indicates that SLS affects the mean weighted workload of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was no statistical significance ($t(17) = 2.030$, $p = .058$, $d = 0.48$) between $MWWL_{TL}$ (Mean = 10.05, SD = 2.43) and $MWWL_{SLS}$ (Mean = 8.66, SD = 2.58) on NASA-TLX. The result indicates that SLS does not affect the mean weighted workload of students significantly for RJ45 cable connection experiment.

Figure G1 depicts the graph of overall workload of various NASA-TLX sub-scales and the MWWL for all experiments with 95% confidence interval.

2. Hypotheses (H_3): Mental demand

The working hypothesis (H_3) which is tested is given below.

H_3: The designed SLS will affect the mental demand of students on the NASA-TLX scale.

Table 3 gives the descriptive statistics of MD dimension for traditional laboratory without the use of SLS and with the use of SLS. Table 4 depicts the results of paired sample t-tests.

Table 3. Descriptive statistics of Mental Demand for different tasks on NASA-TLX scale (0 = Low to 100 = High)

		Traditional Lab		**Smart Learning System**	
Task Name	**N**	**Mean**	**SD**	**Mean**	**SD**
RLC Circuit	63	43.43	16.78	22.03	17.17
Circuit Theorem	9	32.89	16.59	24.44	25.33
RJ45 Connection	18	5.83	2.46	7.78	4.74

Table 4. Hypothesis H3 test results for different task variations.

Task name	Result from paired t-test	Null Hypotheses (H_{01})
RLC Circuit	$t(62) = 8.175$, $p < .001$, d = 1.03	Failed to Accept H_{03}
Circuit Theorem	$t(8) = 1.566$, $p = .156$, d = 0.52	Failed to Reject H_{03}
RJ45 Cable Connection	$t(17) = -1.694$, $p = .108$, d = -0.40	Failed to Reject H_{03}

The paired sample t-test conducted on the data sets (see Table 3) reveals that for RLC task, there was a statistical significance ($t(62) = 8.175$, $p < .001$, d = 1.03), between the existing laboratory mental demand MD_{TL} (Mean = 43.43, SD = 16.78) and MD_{SLS} (Mean = 22.03, SD = 17.17) on NASA-TLX. The result indicates that SLS affects the mental demand of students in RLC experiment.

For Circuit theorem task, there was no statistical significance ($t(8) = 1.566$, $p = .156$, d = 0.52) between MD_{TL} (Mean = 32.89, SD = 16.59) and MD_{SLS} (Mean = 24.44, SD = 25.33) on NASA-TLX. The result indicates that SLS does not affect the mental demand of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was no statistical significance ($t(17) = -1.694$, $p = .108$, d = -0.40) between MD_{TL} (Mean = 5.83, SD = 2.46) and MD_{SLS} (Mean = 7.78, SD = 4.74) on NASA-TLX. The result indicates that SLS does not affect the mental demand of students significantly for RJ45 cable connection experiment.

3. Hypotheses (H_4): Physical demand

The working hypothesis (H_4) which is tested is given below.

H_4: The designed SLS will affect the physical demand of students on the NASA-TLX scale.

Table 5 gives the descriptive statistics of MD dimension for traditional laboratory without the use of SLS and with the use of SLS. Table 6 depicts the results of paired sample t-tests.

Table 5. Descriptive statistics of Physical Demand for different tasks on NASA-TLX scale (0 = Low to 100 = High)

Task Name	N	Traditional Lab		Smart Learning System	
		Mean	SD	Mean	SD
RLC Circuit	63	6.37	3.83	5.03	3.92
Circuit Theorem	9	5.00	4.33	5.44	5.27
RJ45 Connection	18	31.83	15.06	22.33	15.68

Table 6 Hypothesis H4 test results for different task variations.

Task name	Result from paired t-test	Null Hypotheses (H_{04})
RLC Circuit	$t(62) = 2.537$, $p = .014$, $d = 0.32$	Failed to Accept H_{04}
Circuit Theorem	$t(8) = -0.314$, $p = .762$, $d = -0.10$	Failed to Reject H_{04}
RJ45 Cable Connection	$t(17) = 2.307$, $p = .034$, $d = 0.54$	Failed to Accept H_{04}

The paired sample t-test conducted on the data sets (see Table 5) reveals that for RLC task, there was a statistical significance ($t(62) = 2.537$, $p = .014$, $d = 0.32$), between the existing laboratory physical demand PD_{TL} (Mean = 6.37, SD = 3.83) and PD_{SLS} (Mean = 5.03, SD = 3.92) on NASA-TLX. The result indicates that SLS affects the physical demand of students significantly in RLC experiment.

For Circuit theorem task, there was no statistical significance ($t(8) = -0.314$, $p = .762$, $d = -0.10$) between PD_{TL} (Mean = 5, SD = 4.33) and PD_{SLS} (Mean = 5.44, SD = 5.27) on NASA-TLX. The result indicates that SLS does not affects the physical demand of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was a statistical significance ($t(17) = 2.307$, $p = .034$, $d = 0.54$) between PD_{TL} (Mean = 31.83, SD = 15.06) and PD_{SLS} (Mean = 22.33, SD = 15.68) on NASA-TLX. The result indicates that SLS reduces the physical demand of students significantly for RJ45 cable connection experiment.

4. Hypotheses (H_5): Temporal demand

The working hypothesis (H_5) which is tested is given below.

H_5: The designed SLS will affect the temporal demand of students on the NASA-TLX scale.

Table 7 gives the descriptive statistics of TD dimension for traditional laboratory without the use of SLS and with the use of SLS. Table 8 depicts the results of paired sample t-tests.

Table 7. Descriptive statistics of Temporal Demand for different tasks on NASA-TLX scale (0 = Low to 100 = High)

Task Name	N	Traditional Lab		Smart Learning System	
		Mean	SD	Mean	SD
RLC Circuit	63	21.02	9.24	11.84	9.36
Circuit Theorem	9	21.11	11.49	16.67	11.27
RJ45 Connection	18	14.89	6.83	14.11	8.85

Table 8. Hypothesis H5 test results for different task variations.

Task name	Result from paired t-test	Null Hypotheses (H_{05})
RLC Circuit	$t(62) = 6.242$, $p < .001$, d = 0.79	Failed to Accept H_{05}
Circuit Theorem	$t(8) = 1.153$, $p = .282$, d = 0.38	Failed to Reject H_{05}
RJ45 Cable Connection	$t(17) = .312$, $p = .759$, d = 0.07	Failed to Reject H_{05}

The paired sample t-test conducted on the data sets (see Table 7) reveals that for RLC Circuit task, there was a statistical significance ($t(62) = 6.242$, $p < .001$, d = 0.79), between the existing laboratory temporal demand TD_{TL} (Mean = 21.02, SD = 9.24) and TD_{SLS} (Mean = 11.84, SD = 9.36) on NASA-TLX. The result indicates that SLS affects the temporal demand of students significantly in RLC experiment.

For Circuit theorem task, there was no statistical significance ($t(8) = 1.153$, $p = .282$, d = 0.30) between TD_{TL} (Mean = 21.11, SD = 11.49) and TD_{SLS} (Mean = 16.67, SD = 11.27) on NASA-TLX. The result indicates that SLS does not affects the temporal demand of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was no statistical significance ($t(17) = .312$, $p = .759$, d = 0.07) between TD_{TL} (Mean = 14.89, SD = 6.83) and TD_{SLS} (Mean = 14.11, SD = 8.85) on NASA-TLX. The result indicates that SLS does not affects the temporal demand of students significantly for RJ45 cable connection experiment.

5. Hypotheses (H_6): Performance

The working hypothesis (H_6) which is tested is given below.

H_6: The designed SLS will affect the performance of students on the NASA-TLX scale.

Table 9 gives the descriptive statistics of P dimension for traditional laboratory without the use of SLS and with the use of SLS.

10 depicts the results of paired sample t-tests.

Table 9. Descriptive statistics of Performance for different tasks on NASA-TLX scale (0 = Low to 100 = High).

		Traditional Lab		Smart Learning System	
Task Name	N	Mean	SD	Mean	SD
RLC Circuit	63	12.24	4.95	15.10	5.68
Circuit Theorem	9	10.11	6.57	15.22	5.38
RJ45 Connection	18	48.33	9.08	44.67	13.72

Table 10. Hypothesis H6 test results for different task variations.

Task name	Result from paired t-test	Null Hypotheses (H_{04})
RLC Circuit	$t(62) = -3.682$, $p < .001$, d = -0.46	Failed to Accept H_{06}
Circuit Theorem	$t(8) = -2.240$, $p = .055$, d = -0.75	Failed to Reject H_{06}
RJ45 Cable Connection	$t(17) = 1.249$, $p = .229$, d = 0.07	Failed to Reject H_{06}

The paired sample t-test conducted on the data sets (see Table 9) reveals that for RLC Circuit task, there was a statistical significance (t(62) = -3.682, p < .001, d = -0.46), between the existing laboratory performance P_{TL} (Mean = 12.24, SD = 4.95) and P_{SLS} (Mean = 15.10, SD = 5.68) on NASA-TLX. The result indicates that SLS affects the performance of students significantly in RLC experiment.

For Circuit theorem task, there was no statistical significance (t(8) = -2.240, p = .055, d = -0.75) between P_{TL} (Mean = 10.11, SD = 6.57) and P_{SLS} (Mean = 15.22, SD = 5.38) on NASA-TLX. The result indicates that SLS does not affects the performance of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was no statistical significance (t(17) = 1.249, p = .229, d = 0.07) between P_{TL} (Mean = 48.33, SD = 9.08) and P_{SLS} (Mean = 44.67, SD = 13.72) on NASA-TLX. The result indicates that SLS does not affects the temporal demand of students significantly for RJ45 cable connection experiment.

6. Hypotheses (H_7): Effort

The working hypothesis (H_7) which is tested is given below.

H_5: The designed SLS will affect the effort of students on the NASA-TLX scale.

Table 11 gives the descriptive statistics of E dimension for traditional laboratory without the use of SLS and with the use of SLS.

12 depicts the results of paired sample t-tests.

Table 11. Descriptive statistics of Effort for different tasks on NASA-TLX scale (0 = Low to 100 = High)

		Traditional Lab		Smart Learning System	
Task Name	**N**	**Mean**	**SD**	**Mean**	**SD**
RLC Circuit	63	51.36	18.19	21.52	14.70
Circuit Theorem	9	46.22	18.77	21.78	21.18
RJ45 Connection	18	44.44	18.22	35.83	19.87

Table 12. Hypothesis H7 test results for different task variations.

Task name	Result from paired t-test	Null Hypotheses (H_{07})
RLC Circuit	$t(62) = 9.582$, $p < .001$, d = 1.21	Failed to Accept H_{07}
Circuit Theorem	$t(8) = 3.773$, $p = .005$, d = 1.26	Failed to Accept H_{07}
RJ45 Cable Connection	$t(17) = 1.576$, $p = .134$, d = 0.37	Failed to Reject H_{07}

The paired sample t-test conducted on the data sets (see Table 11) reveals that for RLC Circuit task, there was a statistical significance (t(62) = 9.582, p < .001, d = 1.21), between the existing laboratory performance E_{TL} (Mean = 51.36, SD = 18.19) and E_{SLS} (Mean = 21.52, SD = 14.70) on NASA-TLX. The result indicates that SLS affects the effort of students significantly in RLC experiment.

For Circuit theorem task, there was a statistical significance (t(8) = 3.773, p = .005, d = 1.26) between E_{TL} (Mean = 46.22, SD = 18.77) and E_{SLS} (Mean = 21.78, SD = 21.18) on NASA-TLX. The result indicates that SLS affects the effort of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was no statistical significance (t(17) = 1.576, p = .134, d = 0.37) between E_{TL} (Mean = 44.44, SD = 18.22) and P_{SLS} (Mean = 35.83, SD = 19.87) on NASA-TLX. The result indicates that SLS does not affects the effort of students significantly for RJ45 cable connection experiment.

7. Hypotheses (H_8): Frustration

The working hypothesis (H_8) which is tested is given below.

H_8: The designed SLS will affect the frustration of students on the NASA-TLX scale.Table 13 gives the descriptive statistics of F dimension for traditional laboratory without the use of SLS and with the use of SLS. Table 14 depicts the results of paired sample t-tests.

Table 13. Descriptive statistics of Frustration for different tasks on NASA-TLX scale (0 = Low to 100 = High)

		Traditional Lab		Smart Learning System	
Task Name	N	Mean	SD	Mean	SD
RLC Circuit	63	38.71	16.86	11.38	8.92
Circuit Theorem	9	25.33	19.15	13.33	7.36
RJ45 Connection	18	5.44	4.29	5.11	2.27

Table 14. Hypothesis H8 test results for different task variations.

Task name	Result from paired t-test	Null Hypotheses (H_{08})
RLC Circuit	$t(62) = 10.761$, $p < .001$, d = 1.36	Failed to Accept H_{08}
Circuit Theorem	$t(8) = 2.130$, $p = .066$, d = 0.71	Failed to Reject H_{08}
RJ45 Cable Connection	$t(17) = 0.336$, $p = .741$, d = 0.08	Failed to Reject H_{08}

The paired sample t-test conducted on the data sets (see Table 13) reveals that for RLC Circuit task, there was a statistical significance (t(62) = 10.761, p < .001, d = 1.36), between the existing laboratory frustration level F_{TL} (Mean = 38.71, SD = 16.86) and F_{SLS} (Mean = 11.38, SD = 8.92) on NASA-TLX. The result indicates that SLS affects the frustration level of students significantly in RLC experiment.

For Circuit theorem task, there was a no statistical significance (t(8) = 2.130, p = .066, d = 0.71) between F_{TL} (Mean = 25.33, SD = 19.15) and F_{SLS} (Mean = 13.33, SD = 7.36) on NASA-TLX. The result indicates that SLS does not affect the frustration level of students significantly for circuit theorem experiment.

For RJ45 Cable connection task, there was no statistical significance (t (17) = 0.336, p = .741, d = 0.08) between F_{TL} (Mean = 5.44, SD = 4.29) and F_{SLS} (Mean = 5.11, SD = 2.27) on NASA-TLX. The result indicates that SLS does not affects the frustration level of students significantly for RJ45 cable connection experiment.

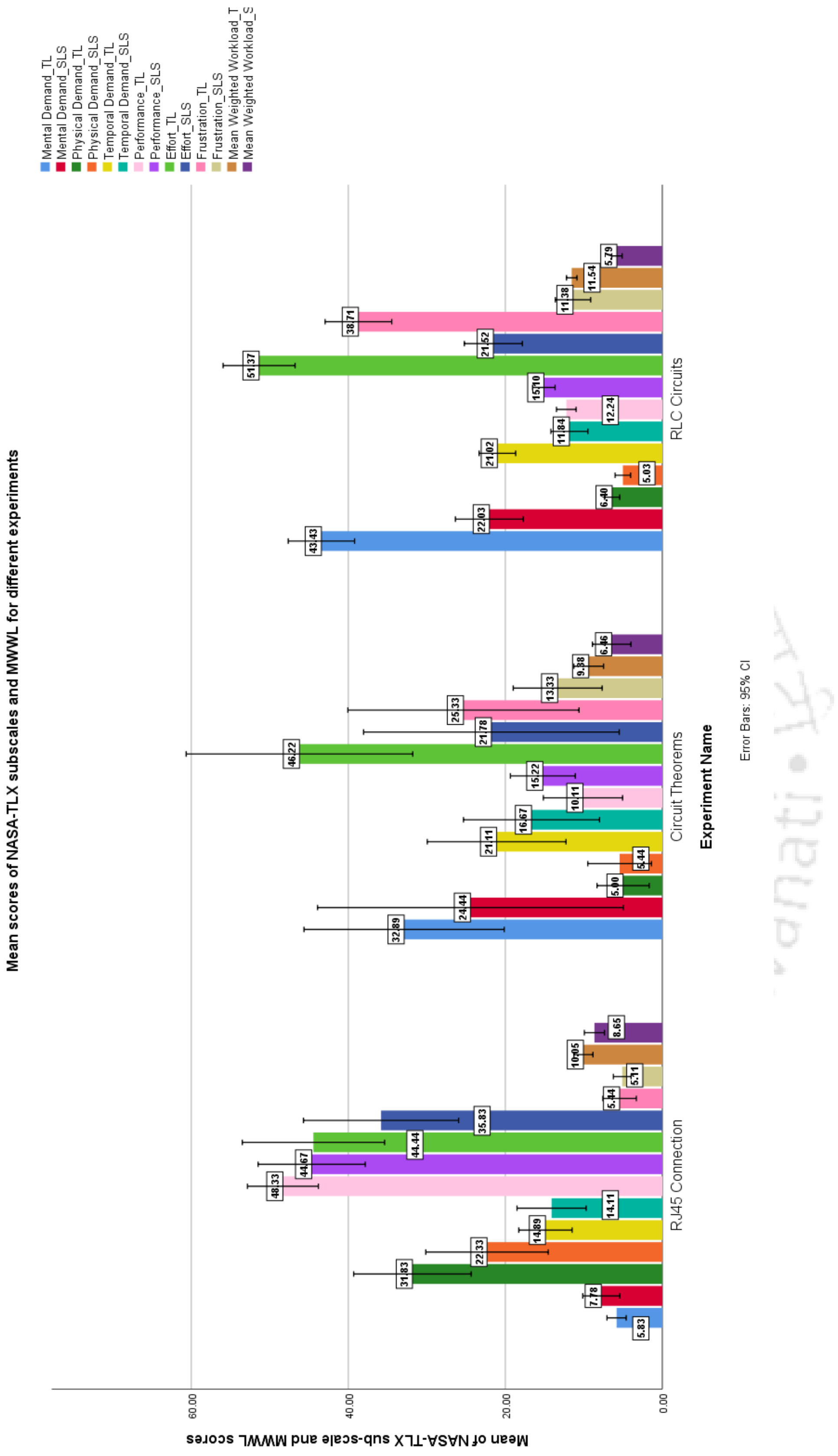

Figure G1. Overall workload of various NASA-TLX sub-scales and the MWWL for all experiments with 95% confidence interval

Publications and Awards associated with the research output of this thesis

List of publications associated with research output of this thesis work

1. **Srivastava A.,** Yammiyavar P. (2018). Automating Engineering Educational Practical Electronics Laboratories for Designing Engaging Learning Experiences. In proceedings of Human Work Interaction Design 2018 (HWID 2018), IFIP working conference in Espoo, Finland.
2. **Srivastava A.,** Yammiyavar P. (2018) Exploring Embedded Intelligence as a Means of Minimizing Cognitive Load of Students in Electronics Engineering Instructional Laboratory Sessions. In: Ray G., Iqbal R., Ganguli A., Khanzode V. (eds) Ergonomics in Caring for People. Springer, Singapore, 261–266. DOI: https://doi.org/10.1007/978-981-10-4980-4_32
3. **Srivastava A.**, Yammiyavar P. (2017) Students' Feedback into Enriching Learning Experiences for Design of Smart Devices and Applications. In Research into Design for Communities, Volume 2. ICoRD 2017. Smart Innovation, Systems and Technologies, vol 66, 1051 – 1060, Springer, Singapore. DOI: https://doi.org/10.1007/978-981-10-3521-0_89
4. **Srivastava, A.**, & Yammiyavar, P. (2016). Design of Multimodal Instructional Tutoring Agents Using Augmented Reality and Smart Learning Objects. In Proceedings of the 18th ACM International Conference on Multimodal Interaction (ICMI 2016). ACM, New York, NY, USA, 421-422. DOI: https://doi.org/10.1145/2993148.2998531
5. **Srivastava, A.**, (Supervisor: Yammiyavar, P). (2016). Enriching Student Learning Experience Using Augmented Reality and Smart Learning Objects. In Proceedings of the 18th ACM International Conference on Multimodal Interaction (ICMI 2016). ACM, New York, NY, USA, 572-576. DOI: https://doi.org/10.1145/2993148.2997623
6. **Srivastava, A.**, & Yammiyavar, P. (2016). Minimizing Cognitive Load of Students in Practical Engineering Laboratories through Augmented Reality Applications. Poster presented at 3rd Annual Conference on Cognitive Science, IIT Gandhinagar.
7. **Srivastava, A**., & Yammiyavar, P. (2016). Augmenting Tutoring of Students using Tangible Smart Learning Objects: An IOT based approach to assist student learning in laboratories. In Internet of Things and Applications (IOTA), International Conference on (pp. 424-426). IEEE. DOI: https://doi.org/10.1109/IOTA.2016.7562765
8. **Srivastava, A**., & Yammiyavar, P. (2015). Effectiveness of Tangible and Tablet Devices as Learning Mediums for Primary School Children in India. In ICoRD'15 – Research into Design across Boundaries Volume 2 (pp. 353-363). Springer India. DOI: https://dx.doi.org/10.1007/978-81-322-2229-3_30
9. **Srivastava, A**., & Yammiyavar, P. (2014). Tablets and Tangible Devices as a Learning Medium for Children: A Cognitive Ergonomics Approach. In Humanizing Work and Work Environment 2014, (pp. 776-779). McGraw Hill Education.

10. Yammiyavar, P., **Srivastava, A.**, & Shashidhara, S., (2014), Designing Tangible Interactive Learning Aids for Pre-primary School Teaching Environment: A Sustainable Approach. In the proceedings of Design for Sustainable Wellbeing and Empowerment 2014, DfWnE2014, Volume 1 (pp 393-406). IISc Press.

Poster / Invited Presentation

1. Srivastava, A., (Supervisor: Yammiyavar, P). Augmented Reality and Smart Object Based Laboratory Training System. Invited Presentation at PhD SRC, 24th IFIP WCC 2018, Poznan, Poland
2. Srivastava, A., Yammiyavar, P. & Reddy, V.K. (2017). Exploring the use of Augmented Reality and Physical Smart Objects to Improve Learning Experience of Students' in Practical Lab Sessions. Poster presented at Research Conclave 2017, IIT Guwahati
3. Srivastava, A., & Yammiyavar, P. (2016). Minimizing Cognitive Load of Students in Practical Engineering Laboratories through Augmented Reality Applications. Poster presented at 3rd Annual Conference on Cognitive Science, IIT Gandhinagar.
4. Srivastava, A., & Yammiyavar, P. (2016). Embedding intelligence into learning objects in engineering laboratories. Poster presented at Research Conclave 2016, IIT Guwahati.

Awards conferred to the research output of this thesis

1. Finalist, NASSCOM Design4India Award 2018 (Immersive Category), Bangalore, India
2. PhD Student Research Competition Grant, 24th IFIP World Computer Congress 2018, Poland
3. ACM SIGCHI Student Ambassador from India at the 50th Turing Awards Ceremony 2017, San Francisco, USA
4. Best Demonstration Award, ACM International Conference on Multimodal Interaction 2016, Tokyo, Japan
5. ACM SIGCHI Student Travel Grant 2016

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