

Design and Development of a Pipe Climbing Robot with a Compliant Bistable Gripping Mechanism

*A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of*

Doctor of Philosophy

by

Saurav Kumar Dutta

Roll No-156103012



**Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati-781039, India
August, 2021**



Dedicated to

*My beloved and revered teachers of
GIMT Guwahati*



**Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati-781039, India**

CERTIFICATE

It is certified that the work contained in this thesis entitled “**Design and Development of a Pipe Climbing Robot with a Compliant Bistable Gripping Mechanism**” submitted by **Mr. Saurav Kumar Dutta** (Roll No-156103012) to the Indian Institute of Technology Guwahati for the award of the degree of Doctor of Philosophy has been carried out under the supervision of **Dr. Annem Narayana Reddy** from July 2015 to June 2018 and under our joint supervision, after his sudden demise in June 2018, in the Department of Mechanical Engineering, Indian Institute of Technology Guwahati. This work has not been submitted elsewhere for the award of any other degree or diploma.

The thesis in our opinion, has reached the standard fulfilling the requirements for the award of Doctor of Philosophy in accordance with the regulations of the Institute.

August, 2021

B. Sandeep Reddy
17/01/2022

Dr. Basireddy Sandeep Reddy
Assistant Professor
Department of Mechanical Engineering
IIT Guwahati, India-781039

S. Dwivedy
17/01/2022

Dr. Santosha Kumar Dwivedy
Professor
Department of Mechanical Engineering
IIT Guwahati, India-781039

Acknowledgement

In my journey towards realisation of the PhD degree, I came across many people who helped me in different ways in their respective capacities. Now, when I write my PhD thesis, I feel that I should sincerely acknowledge the help I received from them.

First and foremost, I would like to acknowledge the help I received from my beloved deceased advisor, Dr. Annem Narayana Reddy. For me, he was more than a PhD advisor. Apart from supervising my PhD work, he played an influential role in changing my viewpoint towards science and my approach in tackling physical problems. This approach, which I imbibed from him, immensely helped me all throughout my PhD work. I consider myself to be privileged enough that I got a chance to work with him. His teachings on the basics of linear algebra, solid mechanics, analytical mechanics and finite element method greatly helped me in enhancing my understanding of these subjects.

Next, I would like to thank my present advisors, Dr. Santosha Kumar Dwivedy and Dr. Basireddy Sandeep Reddy, for agreeing to be my supervisors after the death of Dr. A.N.Reddy and for helping me in carrying ahead my research work. Under their supervision, I got the chance to explore into the fields of robotics, control and nonlinear dynamics. I would also like to appreciate and acknowledge their relentless suggestions in uplifting my standard of research. I would equally like to appreciate and acknowledge the suggestions, support and encouragement extended by the past and present members of my doctoral committee. The doctoral committee consisted of Dr. A.K. Singh, Dr. S.R. Deepak and Dr. S.K. Dwivedy initially. Later, Dr. D. Chakraborty replaced Dr. S.K. Dwivedy, who became supervisor and Dr. S.M. Hazarika replaced Dr. S.R. Deepak, who left IIT Guwahati.

I never shied away from asking doubts and seeking help from people on technical matters. This particular habit of mine led me to interact with a number of teachers across different faculty in different institutions, namely, Dr. A. Ravindranath, Dr. R.D. Kulkarni, Dr. A. Nandy, Dr. P. Biswas of IIT Guwahati, Dr. G.K. Ananthasuresh and Dr. S. Palathingal of IISc Bangalore, Dr. S. Rakshit of IIT Madras and Dr. A. Saxena of IIT Kanpur. In most cases, I didnt get direct help but the interaction itself helped me in getting insights into the subtleties of my problem. I would earnestly like to thank all of them. I am also grateful to Mr.

Siddhartha Devnath of Patent Information Centre-Assam for helping and guiding me in filing a patent.

I would also like to thank Mr. Arunjyoti Borgohain and Mr. Ayushman Gogoi of Yantrabot Technologies, TIC, IIT Guwahati for their help in fabrication of the pipe climbing robot. The fabrication process also required the expertise of technical superintendents of the Central Workshop of IIT Guwahati. In this regard, I would especially like to thank Mr. Mrinal Sarma, Mr. Dilip Chetri and Mr. Jiten Basumatary for their help in fabricating the different parts of the robot. I express my gratitude to Mr. Jyotirmoy Kakati, Mr. Sanjib Sarma and Mr. Monuranjan Dowarah of Mechanical Engineering Department for providing me the necessary equipment for carrying out experiments.

During the scary and woeful times of COVID-19, when I didn't have access to the computational facilities of the institute, I got a chance to remotely access one of the PCs in the CAD lab of the Mechanical Engineering Department for carrying out my research activities. In this regard, my sincere thanks to Dr. A. Nandy, Dr. D. Sharma and Mr. A. Kalita.

During my course of PhD, I developed friendship with many people across different departments. They all helped me in different capacities, ranging from technical help to non-technical help like installation of software or formatting my laptop. It might not be possible for me to include all of their names but I remember all their help, which they did by taking time out of their busy schedule and I gratefully acknowledge it. I would like to thank my seniors, Mr. Maharshi Kintada, Dr. Brajesh Rawat, Dr. Jitendra Kumar, Dr. Gaurav Kumar, who considerably helped me in debugging my finite element codes and electronic circuits during my initial days of PhD. I would also like to thank my dear friend and batch mate, Mr. Saibal Kanchan Barik, who selflessly helped me in almost every aspect of my PhD journey, starting from gathering materials for carrying out experiments to his expert opinion on various professional and personal matters. I would like to thank my other friends and seniors, especially, Avinish Tiwari, Vivek Gupta, Rajkumar Sarma, Dr. Soumya Ranjan Nanda, Sibananda Mohanty, Syed Nayab Rasool, Ranit Roy, with whom I liked to interact in many interesting topics.

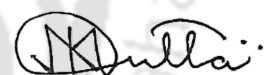
Apart from academics, the ambience of IIT Guwahati also gave me the opportunity to indulge in sports and music in the evening hours. It was through this indulgence that I could learn the basics of Hindustani Classical Violin under the tutelage of an exceptional teacher and a renowned artist, Dr. Devendra Pathak, then a visiting artist in residence at IIT Guwahati. It was during this period that I could complete a two-year certification course (provided by IIT Guwahati) on Hindustani Classical Violin in 2018. Playing music helped me remain calm during hours of distress and anxiety. My other source of recreation was table tennis, a sport which I had been playing from a very young age. But I had stopped pursuing table tennis for a long time. Again, the ambience of IIT Guwahati gave me the

opportunity to begin my pursuance of table tennis. In this pursuance of table tennis, I made friends with whom I practised. In this regard, I would like to thank my playing partners, Dr. Nidhi Kotoky, Avishek Tomar, Vishal Goyal, Kartik Kataria, Omkar Salvi, Dr. Tejas Namboodiri, Dr.B.Deepak Raj, Arooshi Bajaj, Surabhi Gupta and Dr. Namami Goswami. Lastly, I would like to thank my past and present lab mates, Dr. Firdausa Ahmed, Dr. Kamal Basumatary, Masruddin Shaik, Gargi Majumdar, Priyam Srivastava, Nishikant Mane, Sonu Singh, Rucha Pendse, Jithin Krishnan B, P Anirudh Reddy, Sanju Yadav, Gopinath Sengupta, Bipul Basumatary, Kanak Jindal, Santosh Kumar, Jyotindra Narayan, Mohamed Abbas, Rahul Bharti, Bhavik Patel, for making the lab environment conducive for intellectual activity and research and also helping me out with many difficulties in experiments, softwares etc.

I would also like to thank the teachers of my previous alma mater, GIMT Guwahati, for their excellent teaching and mentorship which enabled me to clear GATE 2015 exam in my first attempt and to enrol myself as a PhD student here at IIT Guwahati, right after completing my Bachelors. I would like to specially mention the teachers, Dr. Bhaskor Jyoti Bora, Ms. Manoshi Devi, Dr. Madhumita Mahanta, for inspiring and encouraging me to pursue a career in research.

I would also like to thank my parents, Ms. Mithu Dutta and Mr. Samir Kumar Dutta, for being a pillar of support through this turbulent yet rewarding journey of PhD.

August, 2021



Saurav Kumar Dutta

Abstract

Rigid pipes are used in almost every walks of life, starting from industries to domestic household for the transportation of fluids. All these pipes are subjected to wear and tear after a period of time. Any such wear and tear of the pipes leads to the disruption of supply lines in residential areas and may lead to a major accident in industries. Hence, the structural health of the pipes, especially in industries, is to be inspected on a periodic basis for any flaws or cracks. Apart from the dangers associated with the inspection of the toxic fluid carrying pipes, many a time some portion of the pipelines are situated at such remote locations or at heights where the human workers are unable to reach. Hence, there is a need to develop a pipe climbing robot to suit the industrial needs, with a payload to weight ratio greater than 0.5 and the overall load bearing capacity greater than 1 kg. Also, it should have a structure similar to a parallel manipulator so that industrial equipment can be kept or mounted on it.

The pipe climbing robot considered in this work has a motion similar to that of an inchworm as inchworm type pipe climbing robots have a better load carrying capacity as compared to their wheeled counterparts. The gripper in the proposed robot uses a bistable buckled beam, which is one of the types of bistable compliant mechanism. A bistable buckled beam is chosen as the gripping mechanism as it has two stable equilibrium states and no power or energy is required to maintain the stable states. The bistable buckled beam in the gripper of the proposed robot is alternately actuated between its two stable equilibrium states by a mechanical drive system involving cams and lever. The values of the design parameters of the bistable buckled beam are obtained both experimentally and numerically. Depending on the dimensions of the bistable buckled beam and the pre-stress it is subjected to, the cam profiles are also designed following the standard procedures. The proposed robot is modelled and the working and simulation of its different parts are checked in Solidworks.

After designing the gripper, two climbing mechanisms are proposed both of which are compatible to the designed grippers. One is based on a prismatic (or lead-screw based) joint for climbing straight vertical pipes and the other is based on a revolute-revolute-revolute-prismatic (RRRP) climbing mechanism having a three dimensional workspace, for climbing any bend pipe including ninety-degree bend pipes. The working of both the mechanisms is discussed. The end-effector po-

sitions of the RRRP climbing mechanism are generated by making use of its workspace. Then, a soft computing technique, namely, adaptive neuro-fuzzy inference system (ANFIS) is used to obtain the joint angles corresponding to the different end-effector positions of the climbing mechanism. The trajectory between the two points is planned in joint space using the method of modified linear function with parabolic blends. After that, the Euler-Lagrange equations of motion of the climbing mechanism are derived. These equations are evaluated to obtain the nominal torques acting at the joints.

After the dynamic analysis of the climbing mechanism, a proportional-integral-derivative (PID) control law is used in a RRRP serial pick and place robot for trajectory tracking of the joints of the robot. The feedback gains of the PID control law are tuned using Floquet theory. The advantage of using Floquet theory for RP class of serial manipulators is that no information is required on the bounds of the inertia matrix and the Jacobian of the gravity vector. The successful demonstration of Floquet theory for a RRRP pick and place robot shows that it can also be used for accurate trajectory tracking in the proposed RRRP climbing mechanism.

After designing the grippers and the climbing mechanism, the parts of the robot are fabricated and assembled. The pipe climbing robot for straight vertical climbing is only fabricated. The working of the pipe climbing robot is successfully demonstrated on a polyvinyl chloride (PVC) pipe of 110 mm diameter. The designed and developed pipe climbing robot has a payload to weight ratio of 0.52, overall load bearing capacity of 11.69 kg, a power consumption of 18.58 W and a speed of 0.2 m min^{-1} .

The thesis has five chapters. Chapter 1 gives a brief introduction on pipe climbing robots and the motivation behind the design and development of a pipe climbing robot. This chapter also carries out the scientific and comprehensive analysis of literature. Chapter 2 discusses the model and the design process of the gripping mechanism. The model of the climbing mechanism and its dynamic analysis are given in chapter 3. After the design of the mechanisms, chapter 4 discusses the development of the pipe climbing robot, which includes the fabrication, materials used and electronics. Lastly, chapter 5 concludes the thesis with a scope for future work.

Contents

List of Figures	xi
-----------------	----

List of Tables	xvi
----------------	-----

1 Introduction and Literature Review	1
1.1 Introduction	1
1.2 Pipe Climbing Robots	1
1.3 Literature Review	4
1.3.1 Locomotion in External Pipe Climbing Robots	5
1.3.1.1 Snake Robots	5
1.3.1.2 Inchworm Robots	6
1.3.1.3 Wheeled Robots	9
1.3.1.4 Legged Robots	12
1.3.1.5 Robots with Combination of Two Locomotions	13
1.3.1.5.1 Snake cum Wheeled Robots	14
1.3.1.5.2 Inchworm cum Wheeled Robots	16
1.3.2 Gripping in External Pipe Climbing Robots	16
1.3.2.1 Electrically Actuated Gripping	16
1.3.2.2 Pneumatically Actuated Gripping	17
1.3.2.3 Gripping with Magnets	18
1.3.2.4 Gripping with Springs (Strain Energy)	18
1.3.2.5 Gripping due to Self-Weight	20
1.3.3 Control in External Pipe Climbing Robots	20
1.3.4 Sensors in External Pipe Climbing Robots	22
1.3.5 Bistable Grippers	25
1.3.6 Bistable Compliant Mechanisms	29
1.3.7 Adaptive Neuro-Fuzzy Inference System (ANFIS) based In-verse Kinematics of Serial Robots	30
1.3.8 Trajectory tracking of joints of RP class of serial manipulators	30
1.3.9 Summary of Literature Review	31
1.4 Technical gaps	33
1.5 Objective	34
1.6 Thesis Organisation	34

2	Design of a Gripping Mechanism	35
2.1	Introduction	35
2.2	Mechanical Design of the Gripper	35
2.2.1	Working	36
2.2.2	Design Parameters	37
2.2.3	Experimental and Numerical Determination of Design Pa- rameters	38
2.3	Design of Mechanical Drive Systems to Automate the Gripping . .	48
2.3.1	Design of Scotch Yoke cum Beam Engine Inspired Mechanism	52
2.3.2	Design of Cams	53
2.4	Summary	56
3	Design of a Climbing Mechanism	57
3.1	Introduction	57
3.2	CAD Models of the Climbing Mechanisms	57
3.3	RRRP Climbing Mechanism	58
3.3.1	Direct Kinematics	59
3.3.2	Steps For Climbing 90° bend pipes	60
3.3.3	Adaptive Neuro-Fuzzy Inference System (ANFIS) based In- verse Kinematics	65
3.3.4	Determination of Joint Angles for the End-Effector Positions	69
3.3.5	Torque Estimation	70
3.4	Tuning of Feedback Gains of a RRRP serial chain manipulator . .	75
3.4.1	Model of the RRRP pick and place robot	75
3.4.2	Periodic Trajectory Planning	77
3.4.3	Application of Floquet theory to the RRRP robot	80
3.4.4	Numerical Simulation Results for Trajectory Tracking	81
3.4.5	Comments on Floquet theory	88
3.4.5.1	Advantages and Limitations of Floquet theory . . .	89
3.4.5.2	Future Possible applications of Floquet theory . . .	91
3.5	Summary	92
4	Development of a Pipe Climbing Robot	93
4.1	Introduction	93
4.2	Materials Used and Fabrication	93
4.3	Load Carrying Capacity of the Gripper	95
4.4	Prototype of the Pipe Climbing Robot	96
4.4.1	Working	97
4.4.2	Actuators and Sensors Used	98
4.4.3	Demonstration	98
4.5	Mode of Operation of the Robot	100
4.6	Summary	102

5 Conclusion and Scope for Future Research	103
5.1 Introduction	103
5.2 General Conclusions	103
5.3 Specific Conclusions	104
5.3.1 Design of the Gripping Mechanism	105
5.3.2 Design of the Mechanical Drive Systems	105
5.3.3 Dynamic Analysis of the Climbing Mechanism	105
5.3.4 Trajectory Tracking of the RRRP Pick and Place Robot	106
5.3.5 Development of the Pipe Climbing Robot	106
5.4 Scope for Future Research	106
References	108
Appendices	125
A Experimental Data Points between D_v and D_a, and L_s and D_a	125
A.1 Trial I	125
A.2 Trial II	126
A.3 Trial III	128
B Algorithm for Generating the Training Data Set for ANFIS	130
C Trajectory Planning Using Modified Linear Function with Parabolic Blends	132
D Coefficients of Mass matrix, Coriolis vector and Gravity vector	138
E Algorithm for carrying out numerical search to generate K_p versus K_v map	141
Publications	142
About the Author	144

List of Figures

1.1	Locomotion of an inchworm type pipe climbing robot	3
1.2	Snake robots	6
1.3	Inchworm robots	8
1.4	Wheeled robots	11
1.5	Legged robots	13
1.6	Snake cum wheeled robots	14
1.7	Inchworm cum wheeled robot	14
2.1	Isometric view of the 3-D CAD model of the gripper	36
2.2	Top view of the gripper in (a) ungripped and (b) gripped positions	36
2.3	(a) Bifurcation buckling process of a straight unstressed column, (b) Snap through buckling process of the buckled beam	37
2.4	Front view of the set up (a) before snapping, (b) after snapping and (c) top view of the set up before snapping	39
2.5	Mode shapes of bifurcation buckling problem	40
2.6	$w - F$ relation (a) for full range of force and (b) for force between -40 N and +40 N	43
2.7	Relation between w and weights a_1, a_2 (a) for full range of force and (b) for force between -40 N and +40 N	43
2.8	$w - F$ relation for a buckled beam of thickness 0.3 mm and width 5 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	43
2.9	$w - F$ relation for a buckled beam of thickness 0.3 mm and width 10 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	44
2.10	$w - F$ relation for a buckled beam of thickness 0.3 mm and width 15 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	44
2.11	$w - F$ relation for a buckled beam of thickness 0.3 mm and width 20 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	45

2.12	$w - F$ relation for a buckled beam of thickness 0.5 mm and width 5 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	45
2.13	$w - F$ relation for a buckled beam of thickness 0.5 mm and width 10 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	46
2.14	$w - F$ relation for a buckled beam of thickness 0.5 mm and width 15 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	46
2.15	$w - F$ relation for a buckled beam of thickness 0.5 mm and width 20 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm	47
2.16	Front view of the gripper with the actuation points	49
2.17	(a) Front view, (b) Top view, (c) Isometric view and (d) A different view (e) Close up view of the gripper with Scotch Yoke cum beam engine inspired actuating mechanism	50
2.18	(a) Front view, (b) Top view, (c) Isometric view and (d) A different view (e) Close up view of the gripper with cams	51
2.19	Displacement versus time plots of the slider of (a) Scotch Yoke mechanism and (b) beam engine inspired mechanism	52
2.20	Velocity versus time plots of the slider of (a) Scotch Yoke mechanism and (b) beam engine inspired mechanism	52
2.21	Acceleration versus time plots of the slider of (a) Scotch Yoke mechanism and (b) beam engine inspired mechanism	53
2.22	(a) 2-D schematic and (b) kinematic diagram of the proposed Scotch Yoke cum beam engine inspired mechanism	53
2.23	(a) Cam profile, (b) Displacement diagram and plots of (c) First order, (d) Second order, (e) Third order kinematic coefficient (K.C.) of cam I	54
2.24	(a) Cam profile, (b) Displacement diagram and plots of (c) First order, (d) Second order, (e) Third order kinematic coefficient (K.C.) of cam II	55
2.25	Isometric view of a 3-D CAD model of the lever	55
3.1	CAD model of the climbing mechanism with prismatic joints (a) front view, (b) isometric view	58
3.2	Trimetric view of the 3-D CAD model of the pipe climbing robot with (a) extensor contractor pneumatic artificial muscle and (b) stepper motor driven lead screw	59
3.3	Isometric view of the 3-D CAD model of the modified gripper . . .	59
3.4	(a) Front view and (b) Isometric view of RRRP climbing mechanism for straight vertical climbing	60

3.5	(a) Front view and (b) Isometric view of RRRP climbing mechanism for climbing ninety degree bend pipes	60
3.6	Schematic diagram of the climbing mechanism (a) with the lower gripper gripped and the upper gripper ungripped (RRRP serial configuration) and (b) with the upper gripper gripped and the lower gripper ungripped (PRRR serial configuration)	61
3.7	Orientation of the base frame of RRRP configuration for types (a) I, II, and III; (b) IV and, (c) V, and VI motions	63
3.8	Orientation of the base frame of PRRR configuration for types (a) i, and, (b) ii, iii, iv, and v motions	63
3.9	Workspaces of (a) RRRP and (b) PRRR configurations of the climbing mechanism	64
3.10	Error plots generated during the training of ANFIS models corresponding to outputs (a) θ_2 , (b) θ_3 , and (c) d_4	66
3.11	Error plots generated during the training of ANFIS models corresponding to outputs (a) D_1 , (b) Θ_2 , and (c) Θ_3	69
3.12	(a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-I	71
3.13	(a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-II	72
3.14	(a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-IV	72
3.15	(a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-V	73
3.16	(a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-VI	73
3.17	(a)Trajectories of the joint variables D_1 , Θ_2 and Θ_3 and, torque plots of the actuators in (b) joint 1, (c) joint 2 and (d) joint 3 for motion type-i	74
3.18	(a)Trajectories of the joint variables D_1 , Θ_2 and Θ_3 and, torque plots of the actuators in (b) joint 1, (c) joint 2 and (d) joint 3 for motion type-iv	74
3.19	(a)Trajectories of the joint variables D_1 , Θ_2 and Θ_3 and, torque plots of the actuators in (b) joint 1, (c) joint 2 and (d) joint 3 for motion type-v	75
3.20	RRRP pick and place robot manipulator with 3-D workspace	76

3.21	(a) The trajectory of the joint variable θ_1 from pick position to place position, (b) The periodic trajectories of the joint variables θ_1, θ_2 and θ_3 till 100 s and, (c) The periodic trajectory of the joint variable d_4 till 100 s	79
3.22	Flowchart depicting the steps for carrying out the numerical search to generate the K_p versus K_v map	83
3.23	Regions of stability for K_p versus K_v plots, corresponding to 1 st joint of the robot, for various values of K_i (a) $K_i = 0.05$, (b) $K_i = 0.1$, (c) $K_i = 0.25$, (d) $K_i = 0.5$, (e) $K_i = 0.75$, (f) $K_i = 0.8$, (g) $K_i = 1$, (h) $K_i = 5$ and (i) $K_i = 10$	84
3.24	Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=280$, $K_v=5$ and $K_i=0.5$	86
3.25	Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=280$, $K_v=5$ and $K_i=0.5$ for a greater time	87
3.26	Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=180$, $K_v=0.5$ and $K_i=0.5$	88
3.27	Nominal torque plots of the actuators in (a) joint 1, (b) joint 2, (c) joint 3 and (d) joint 4 of the RRRP robot	89
3.28	Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=350$, $K_v=4$ and $K_i=0.25$ for a different inertia of the robot as compared to the design inertia	90
4.1	(a) Cutting operation being carried out at the Wirecut EDM machine, (b) display panel of the Wirecut EDM machine, showing the completion of cutting, (c) fabricated beams for carrying out experiments to determine snapping load (discussed in chapter 2), and (d) fabricated beams to be fitted into the gripper	94
4.2	(a) Fabricated cams, and (b) cams welded to the camshaft	94
4.3	(a) A mild steel bar being heated using oxy-acetylene flame coming out of a weld torch, (b) the bar being hammered to the required shape of the lever, and (c) the fabricated lever	95
4.4	Prototype of the gripper with (a) 6 bolts, (b) 2 bolts, (c) mechanical drive system and (d) snapshot of the experiment for determining the load carrying capacity	96
4.5	Isometric view of the 3-D CAD model of the pipe climbing robot with two grippers and a climbing mechanism	97
4.6	Isometric view of the 3-D CAD model of the climbing mechanism	97

4.7	Snapshots of the movement of the robot on a vertical pipe	99
4.8	Top view of the gripper with labels	102
C.1	Trajectory of modified linear function with parabolic blends	132
C.2	Trajectory of modified linear function with parabolic blends when $q_s > q_g$	136



List of Tables

1.1	Classification of inchworm robots on the basis of degrees of freedom (d.o.f.), stiffness and structure of their climbing mechanisms	9
1.2	Classification of different pipe climbing robots on the basis of their manoeuvrability over obstacles and bends	15
1.3	Classification of gripping in different pipe climbing robots on the basis of their actuation	19
1.4	A summary of pipe climbing robots	24
2.1	Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness	47
2.2	Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness	48
2.3	Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness	48
2.4	Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness	48
3.1	RRRP serial configuration link coordinate parameters	60
3.2	PRRR serial configuration link coordinate parameters	60
3.3	Steps involved in climbing	62
3.4	Comparison of known data with predicted data for RRRP configuration	67
3.5	Comparison of known data with predicted data for PRRR configuration	67
3.6	Determination of joint angles for different motion types of RRRP configuration	69
3.7	Determination of joint angles for different motion types of PRRR configuration	70
3.8	Properties of the RRRP pick and place robot	76
3.9	The values of joint variables at the <i>pick</i> and <i>place</i> positions	78
3.10	Changed properties of the RRRP robot	88
3.11	Absolute percentage change of properties in Table 3.10 with respect to the properties in Table 3.8	89

4.1	Comparison with similar pipe climbing robots	100
A.1	Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness (Trial I)	125
A.2	Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness (Trial I)	125
A.3	Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness (Trial I)	126
A.4	Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness (Trial I)	126
A.5	Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness (Trial II)	126
A.6	Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness (Trial II)	127
A.7	Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness (Trial II)	127
A.8	Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness (Trial II)	127
A.9	Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness (Trial III)	128
A.10	Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness (Trial III)	128
A.11	Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness (Trial III)	128
A.12	Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness (Trial III)	129

Chapter 1

Introduction and Literature Review

1.1 Introduction

This chapter introduces and discusses the need for research on pipe climbing robots. It has six sections, out of which section 1.2 discusses about pipe climbing robots, their application, locomotion and challenges. A very comprehensive and scientific analysis of literature is carried out in section 1.3. After the review of the literature, the technical gaps are identified, which are given in section 1.4. The objective and organization of the thesis are given in sections 1.5 and 1.6, respectively.

1.2 Pipe Climbing Robots

A pipe or pole climbing robot is a robot that climbs rigid pipes which are at an angle of ninety degrees from the ground. The pipe climbing robots can be classified as internal or external depending on the surface of the traversal of the robot. The pipe climbing robot, in this thesis, refers to an external pipe climbing robot. Rigid pipes are widely used in chemical, petroleum, pharmaceutical, nuclear and shipbuilding industries for the transportation of fluids. Apart from industries, pipes are also used in residential areas for the transportation of water to homes and sewage to treatment plants. These pipes get damaged after prolonged use. In industries like nuclear and petrochemical, pipes are subjected to corrosion. While corrosion in nuclear pipes is due to fast-flowing water and wet steam (Wu, 1989), corrosion in pipes in refineries is mostly due to hydrogen sulphide (Tandy, 1954). This leads to wall thinning of the pipes. Also, the pipes may develop flaws and cracks. A pipe with a crack under operation may lead to a major accident in the plant leading to the death of workers and the entire unit or plant may remain shut for days together (Wu, 1989; Tandy, 1954). Also, corrosive fluids may leak into

the outside environment and contaminate the surroundings. Hence, the pipes in these industries are inspected on a periodic basis for cracks or any flaws.

The present practice involves human beings, by putting their life at risk, inspecting pipes with the help of non-destructive testing (NDT) equipment ([Han et al., 2016](#)). Many a time, the pipes are located at such locations which are inaccessible to humans ([Kim et al., 2018](#)). Hence, there is a need to develop pipe climbing robots that could inspect the pipes in addition to carrying the NDT equipments. A pipe climbing robot will not just save human lives but will also help the industries to avert any accident. Apart from inspecting pipes in industries, the pipe climbing robots can also be used for many other applications. They can be used for climbing palm, areca nut and coconut trees for harvesting, for cleaning and changing bulbs from electric poles, for inspecting cables in cable-stayed bridges and for surveillance and search operations.

The pipe climbing robots have different locomotion and gripping techniques. As it can be observed in the literature that most of the already existing pipe climbing robots have either a wheeled locomotion or a step-by-step locomotion. A pipe climbing robot with a step-by-step locomotion resembles the motion of an inchworm and hence can be called as an inchworm robot. Wheeled robots are generally preferred over inchworm robots when the robot needs to move at higher speeds with minimal payload whereas inchworm robots are preferred when the robot needs to move with higher payloads and lesser speeds ([Tavakoli et al., 2010](#)). In a wheeled robot, wheels are pushed against the walls of the pipe which provide the grip and these wheels rotate to drive the robot in upward or downward direction. In an inchworm robot, there are two grippers which are connected to each other by a linear translatable mechanism or a two, three, four or five degrees of freedom climbing mechanism. The translatable motion of a typical inchworm type pipe climbing robot is shown in Fig. 1.1. The robot in Fig. 1.1 has two grippers A and B. After assembling the robot around the pipe, the grippers A and B are in the clamped position at points 1 and 2 respectively. Gripper B is freed first and then a translational mechanism pulls it towards gripper A, up to point 3. Then, the gripper B is clamped at point 3 and gripper A is freed. The translational mechanism pushes gripper A away from gripper B up to point 4. Then, the gripper A is clamped at point 4 and the gripper B is again freed and pulled by the translational mechanism towards gripper A. This process repeats itself, thus resulting in climbing motion. In the literature, this translatable motion between the two grippers is generally actuated by using a stepper motor driven lead screw or by using a pneumatically actuated linear actuator. The two grippers in an inchworm type pipe climbing robot are also connected by four and five degrees of freedom climbing mechanism. In these kinds of climbing mechanisms, most of the joints are revolute.

The gripping mechanism of a pipe climbing robot depends on the locomotion of

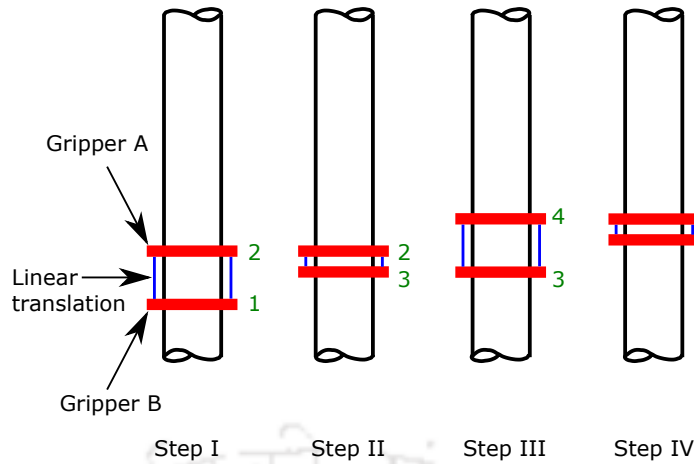


Figure 1.1: Locomotion of an inchworm type pipe climbing robot

the robot. In wheeled robot, wheels act as the grippers. Some wheeled pipe climbing robots also use magnetic wheels. Each gripper in inchworm type pipe climbing robots consists of a circular ring or a pair of V shaped gripping modules. These gripping modules are actuated either pneumatically or electrically. Most of the existing pipe climbing robots use motors and proportional-integral-derivative (PID) control law to control the overall motion and the force exerted by the grippers. The commonly used sensors include encoders, infra-red (IR) sensors, inertial measurement unit (IMU), accelerometers and force sensitive resistors (FSR).

One of the challenges of climbing robots is the availability of a proper gripping force, without which the robot begins to slip. The existing climbing robots increase the gripping force by using pneumatic cylinders or by using electrically driven actuators. A larger gripping force would result in larger pneumatic cylinders, which in turn would increase the weight of the robot. Also, both the pneumatically and electrically driven grippers consume energy throughout the working of the robot. To overcome these challenges, there is a need to develop a mechanism that provides a greater gripping force without increasing the weight of the robot. A large ratio of gripping force to the weight of the robot would increase the payload of the robot. Also, the gripping mechanism should consume less energy as compared to the existing grippers.

The other challenge of climbing robots is that there shouldn't be any unbalanced moment acting on the robot. The presence of any unbalanced moment would cause the robot to tip over and fall, as the gripping on the pipe won't be proper. To overcome this challenge, it is necessary that the center of gravity of the gripping mechanism and the climbing mechanism should be at their respective centres so that the net moment acting on the gripper and consequently, the robot is zero.

The climbing mechanism needs to be compatible with the grippers. The climbing mechanism needs to push and/or pull the grippers alternately. In the literature,

the inchworm type climbing robots have employed electrically driven lead screw, pneumatically driven Universal-Prismatic-Spherical (UPS) kinematic chains, electrically driven four degrees of freedom serial chain mechanisms, to name a few. There is a need to select a suitable climbing mechanism, based on its compatibility with the grippers, ease of control and economic feasibility. A pipe climbing robot with these primary characteristics can be put to large-scale production and used in industries and other domestic applications.

After the selection of a suitable clamping and climbing mechanisms, a suitable control strategy has to be devised for the control of the climbing robot. Without a proper control, the joints in the climbing mechanism of the robot would not be able to track the trajectories precisely. This is because the equation of motion of the climbing mechanism does not take into account the presence of friction, backlash in the gear mechanism of the motors, noise or disturbances, to name a few. Moreover, in the equation of motion of the climbing mechanism, it is very difficult to precisely compute the inertia matrix, Coriolis force vector and gravity loading force vector. A closed-loop control scheme can overcome the limitations of friction, backlash, disturbances and can track the trajectories of the joints of the climbing mechanism accurately in time. Thus, there is a need to select a suitable control law which can ensure accurate trajectory tracking of the joints of the climbing mechanism of the robot.

1.3 Literature Review

This section reviews and classifies the existing pipe or pole climbing robots on the basis of their locomotion, gripping, control and sensors. The pipe climbing robots have been further sub-classified into snake, inchworm, wheeled, legged, snake cum wheeled and inchworm cum wheeled robots, on the basis of their locomotion. The details of the locomotion are given in subsection 1.3.1. On the basis of gripping, the robots have been grouped into electrically actuated gripping, pneumatically actuated gripping, gripping due to magnets, springs and self-weight. The details of the gripping are given in subsection 1.3.2. These robots have also been arranged in tabular form on the basis of their structure, manoeuvrability, actuation, payload and energy consumption. Apart from the pipe climbing robots, some wall climbing and pipe crawling robots are also discussed as the grip and gait of these robots can be extended to pipe climbing robots. The control strategies and sensors used by the pipe climbing robots are given in subsections 1.3.3 and 1.3.4, respectively. After reviewing the external pipe climbing robots, this section also looks into the existing bistable grippers and bistable compliant mechanisms, the details of which are given in subsections 1.3.5 and 1.3.6, respectively. The literature relating to adaptive neuro-fuzzy inference system (ANFIS) is given in subsection 1.3.7. This section also reviews the different techniques used for designing the feedback gains

of a proportional-integral-derivative (PID) controller applied to revolute-prismatic (RP) class of mechanisms, the details of which are given in subsection 1.3.8. This section ends by summarising the findings in subsection 1.3.9.

1.3.1 Locomotion in External Pipe Climbing Robots

The locomotion of pipe climbing robots is important as it decides the gripping mechanism of the robots. Each class of robots has a different gripping mechanism based on its locomotion. This subsection classifies the pipe climbing robots into five groups on the basis of their locomotion. They are :- Snake robots, inch-worm robots, wheeled robots, legged robots and robots with combination of two locomotions.

1.3.1.1 Snake Robots

Real snakes exhibit four main types of locomotion, namely, lateral undulation, sidewinding, concertina and linear progression (Gray, 1946). However, snake robots exhibit both biological and non-biological gaits (Lipkin et al., 2007). The advantage of snake robots is that they are hyper-redundant and hence robust. The failure of one joint does not affect the overall working of the robot (Wright et al., 2007). In most of the snake robots, many configurations of the snake robot are sampled along different curves. Then, that curve is chosen or approximated by the robot's joint motions which has the effect of propelling the robot forward.

The snake robot of Lipkin et al. (2007) has 16 modules which are connected by revolute joints. The single degree of freedom joints of the robot exhibit yaw-pitch-yaw-pitch-yaw-... motion. For climbing outside of the pipes, the robot makes use of rolling, a differentiable non-biological gait. The robot forms a helix around the pipe and then rolls about its own axis to climb up. The same locomotion is also exhibited by HyDRAS, the snake robot of Goldman and Hong (2008) with the exception that in place of revolute joints, the modules in HyDRAS are connected by universal joints. The snake robot of Rollinson and Choset (2013) can climb pipes of variable diameters. They have proposed a gait based control technique that equips the robot to climb a pipe with changing diameter autonomously. The robot of Takemori et al. (2016) can climb pipes with flanges. The authors provide a bridge in the middle of the helical rolling gait, to overcome obstacles, like flanges in pipes. A combination of shift control strategy along with the rolling of the robot ensures that the robot smoothly climbs the pipe with flanges and with no collisions. Zhou et al. (2017) have proposed a spring like gait for a snake robot that can climb discontinuous pipes, that is, pipes with same diameter but kept one over the other with some distance in longitudinal direction. The proposed gait can also climb a pipe with varying diameter. The robot of Yaqub et al. (2019) can also climb a pipe with varying diameter. They have proposed a spiral gait



(a) [Lipkin et al. \(2007\)](#) (b) [Goldman and Hong \(2008\)](#) (c) [Rollinson and Choset \(2013\)](#)

Figure 1.2: Snake robots

curve along with rolling motion, in place of a helical rolling motion, that enables the robot to climb pipes with variable diameters.

The joints of the snake robots are electrically actuated and generally use servo motors or motors with some servo mechanism.

1.3.1.2 Inchworm Robots

The robots discussed in this subsection have a motion similar to that of an inchworm or a leech. This locomotion can also be called as a “grasp-push-grasp” motion ([Ripin et al., 2000](#)) or “clamp and push” motion ([Singh and Ananthasuresh, 2012](#)) or “step-by-step” motion ([Tavakoli et al., 2011](#)). In this kind of motion, there are two clamps or grippers which may be connected through a single or more degrees of freedom climbing mechanism.

One of the earliest external pipe climbing robots of this kind would be of [Ripin et al. \(2000\)](#). This robot uses two grippers for gripping the pipe and two arms, connecting the two grippers at the two ends, for climbing up and down. The two arms are arranged as a planar two link revolute-revolute-revolute (RRR) mechanism. Almost during the same time, [Saltarén et al. \(1999, 2005\)](#), [Aracil et al. \(2000, 2003\)](#) and [Almonacid et al. \(2003\)](#) came up with a robot based on Gough-Stewart parallel platform. The Gough-Stewart platform based robot has six prismatic joints (P), each of which is joined to the two grippers through a universal joint (U) on one end and a spherical joint (S) on the other end. Hence, the climbing mechanism is a 6-UPS parallel mechanism. This robot has two prototypes. The first prototype of the robot can climb straight pipes and pipes with less curvature or bend. The second prototype of the robot is capable of climbing pipes with high curvature or pipes with 90° bend. The second prototype of the robot has the same structure as the first prototype with the only difference that in the second prototype, the pipe lies outside the robot whereas in the first prototype, the pipe lies inside the robot. As opposed to a parallel robot, [Vossoughi et al. \(2004\)](#) and [Tavakoli et al. \(2005\)](#) came up with a hybrid robot. The climbing mechanism of this robot uses a combination of both serial chain and parallel mechanisms. In

place of a Gough-Stewart platform, they use a 3-RPR parallel mechanism. The base of the 3-RPR parallel mechanism can be rotated. This robot can climb bent pipes. There are also robots which have a single degree of freedom climbing mechanism such as the robots of [Lau et al. \(2013\)](#), [Khalid et al. \(2015\)](#) and [Das et al. \(2016\)](#). [Lau et al. \(2013\)](#) use a slider crank chain mechanism, [Khalid et al. \(2015\)](#) use a single linear actuator and [Das et al. \(2016\)](#) use a pair of linear actuators as the climbing mechanism.

The structure of Raupi robot by [Maempel et al. \(2009\)](#) and [Mampel et al. \(2009\)](#) is similar to the robot of [Ripin et al. \(2000\)](#). Both the robots have a kind of serial chain climbing mechanism. Raupi can climb 90° bent pipes and also pipes in skewed configuration. 3DCLIMBER robot developed by [Tavakoli et al. \(2008, 2010, 2011\)](#) has a RRR serial chain climbing mechanism and the base of the RRR mechanism can be rotated about the longitudinal axis of the pipe. This robot can climb over 90° bent pipes and T-junctions. Climbot robot by [Guan et al. \(2009, 2011, 2016\)](#) has five degrees of freedom serial chain climbing mechanism. All the joints are revolute in the climbing mechanism. The first and the fifth joints have the same axes of rotation and are perpendicular to the axes of rotation of the second, third and fourth joints, which have the same axes of rotation. Apart from the inchworm gait, the robot also has a swinging-around gait and flipping-over gait which are much faster than the inchworm gait. Climbot is capable of moving pipe bends, T-junctions and has enough manipulability to unscrew a light bulb. PiROB robot by [Kim et al. \(2012, 2016, 2018\)](#) has also the same structure as Climbot with a five degrees of freedom climbing mechanism. This robot is used for spray pipe inspection in nuclear plants. The robot of [Faizal et al. \(2015\)](#) is also very similar in structure to the robot of [Ripin et al. \(2000\)](#). Both the robots use a planar two link RRR mechanism. The robot of [Yao et al. \(2015\)](#) has four degrees of freedom serial chain climbing mechanism, all of which are revolute joints. The first, third and fourth joints have the same axes of rotation and are perpendicular to the second joint's axis of rotation. The second joint enables the robot to change its direction while moving upwards. [Qiaoling et al. \(2019, 2020\)](#) present a micro pole-climbing robot. The climbing mechanism of the robot consists of a five bar serial chain mechanism. The five bar mechanism has four joints in it. Just like Climbot by [Guan et al. \(2009, 2011, 2016\)](#) and PiRob by [Kim et al. \(2012, 2016, 2018\)](#), this robot can also exhibit flip-over gait in addition to inchworm gait. iCrawl robot by [Khan et al. \(2020\)](#) is a five degrees of freedom robot. The robot has two gaits - a step gait and a sliding gait. This robot can move over flanges and T-junctions.

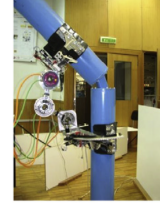
There are also robots which are made of pneumatic artificial muscles ([Singh et al., 2019; Jiang et al., 2020; Xie et al., 2020](#)). The robot of [Singh et al. \(2019\)](#) is made of pneumatic artificial muscles called FREE (Fiber Reinforced Elastomeric Enclosure). This robot uses two types of FREEs, namely, extending FREEs and bending FREEs. This robot can climb curved pipes. [Jiang et al. \(2020\)](#) propose a



(a) Tavakoli et al. (2005)



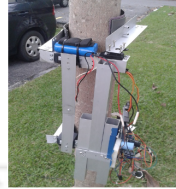
(b) Khalid et al. (2015)



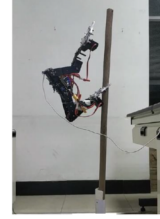
(c) Tavakoli et al. (2011)



(d) Guan et al. (2011)



(e) Faizal et al. (2015)



(f) Qiaoling et al. (2019)



(g) Xie et al. (2020)



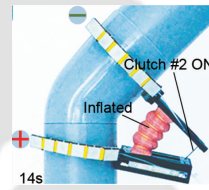
(h) Khan et al. (2020)



(i) Maempel et al. (2009)



(j) Singh et al. (2019)



(k) Jiang et al. (2020)

Figure 1.3: Inchworm robots

multimodal pipe climbing soft robot with origami clutches and soft modular legs. The climbing mechanism consists of a soft linear actuator. The origami clutches are selectively inflated depending on the curvature of the pipe and hence steer the robot on a curved pipe. The robot can move on curved pipes with a maximum bend of 45° with respect to horizontal axis. The robot of Xie et al. (2020) is a one piece 3D printed modular pipe climbing robot. The robot has two grippers and a middle section. The entire robot is made of membrane like cylinder unit (MLCU). MLCUs are connected end to end to form the gripper and the middle section. The locomotion and the actuation of this robot is similar to the robots of Singh et al. (2019) and Jiang et al. (2020). However, unlike the robots of Singh et al. (2019) and Jiang et al. (2020), this robot can move on vertical pipes with 90° bends.

Table 1.1: Classification of inchworm robots on the basis of degrees of freedom (d.o.f.), stiffness and structure of their climbing mechanisms

d.o.f.	Rigid			Soft
	Serial chain	Parallel	Hybrid	
1	Ripin et al. (2000) , Faizal et al. (2015)	Lau et al. (2013) , Khalid et al. (2015) , Das et al. (2016)	—	—
4	Tavakoli et al. (2008, 2010, 2011) , Yao et al. (2015) , Qiaoling et al. (2019, 2020)	—	Vossoughi et al. (2004) , Tavakoli et al. (2005)	—
5	Maempel et al. (2009) , Mampel et al. (2009) , Guan et al. (2009, 2011, 2016) , Kim et al. (2012, 2016, 2018) , Khan et al. (2020)	—	—	—
6	—	Saltarén et al. (1999, 2005) , Aracil et al. (2000, 2003) , Almonacid et al. (2003)	—	—
Infinite	—	—	—	Singh et al. (2019) , Jiang et al. (2020) , Xie et al. (2020)

1.3.1.3 Wheeled Robots

Wheeled robots are robots that are fitted with wheels and have a continuous motion. They are unlike inchworm robots, that have a step-by-step motion, and snake robots, that move like sledges. Wheeled robots have faster locomotion as compared to inchworm and snake robots. However, their load carrying capacity is less as compared to inchworm or step-by-step robots ([Tavakoli et al., 2008, 2010, 2011](#)).

The structure of wheeled robots is generally of two types. In the first type, a casing surrounds the pipe from all sides and wheels attached to the casing are pressed against the walls of the pipe, like the ones in the works of [Baghani et al. \(2005\)](#), [Mahdavi et al. \(2007\)](#), [Noohi et al. \(2010\)](#), [Lee \(2013\)](#), [Sebastian et al. \(2015\)](#), [Mishra et al. \(2018\)](#), [Khan and Prabhu \(2018\)](#), [Mustapa et al. \(2018\)](#), [Gao \(2020\)](#) and [Carabin et al. \(2020\)](#). In the second type, the robot is like a car and it climbs the pipe. Robots of the second type, due to their structure, may also climb walls in addition to climbing pipes. The car like pipe climbing robots can be found in the works of [Suzuki et al. \(2006\)](#), [Yukawa et al. \(2006b,a\)](#), [Sadeqi et al. \(2008\)](#); [Sadeghi et al. \(2008, 2012\)](#), [Fauroux and Morillon \(2010a,b\)](#), [Tavakoli et al. \(2013\)](#), [Tavakoli and Viegas \(2014\)](#), [Imajo et al. \(2015\)](#), [Fengyu et al. \(2015\)](#), [Wang et al. \(2016\)](#), [Fan et al. \(2018\)](#), [Takeda and Shimoyama \(2019\)](#), [Huang et al. \(2020\)](#) and [Jayasundara et al. \(2020\)](#). These car like climbing robots are also used in space applications ([Estier et al., 2000](#)).

The pole climbing robot of [Baghani et al. \(2005\)](#), [Mahdavi et al. \(2007\)](#) and [Noohi et al. \(2010\)](#) has six limbs attached to a triangular frame. The three limbs are on

the top side and the other three limbs are on the bottom side of the triangular frame. Each limb is connected to a wheel at its tip. The bottom three wheels are active and the top three wheels are passive. The robot is capable of moving on straight vertical pipes and vertical pipes with steps. The robot of [Lee \(2013\)](#) has a circumferential ring like structure that supports three wheels or driving modules. The driving modules are placed at an angle of 120° from each other. Each driving module has two degrees of freedom, one being the rotation of the wheels and the other being, the linear movement of the wheels along the radial direction. The pipe climbing robot of [Sebastian et al. \(2015\)](#) has four wheels. The robot has a base that has two arms on both the sides. The robot has two modes of operation, namely, differential drive and climbing. The robot approaches the pole by using the differential drive mode. After the robot encircles the pole by maintaining a proper grip, the robot uses the climbing mode. In the robot of [Mishra et al. \(2018\)](#), an encapsulated compliant cage houses eight wheels in two levels. Each level has four wheels surrounding the pipe circumferentially. Out of eight, only four wheels are active. The robot of [Khan and Prabhu \(2018\)](#) consists of a triangular aluminium casing, inside of which there are three wheels, one on each side of the triangle. The robot of [Mustapa et al. \(2018\)](#) consists of a circular mild steel casing, inside of which there are two wheels. In the robot of [Carabin et al. \(2020\)](#), three wheels are attached to a circular frame through three arms. The three arms are attached to the circular frame through revolute joints. The other end of the three arms are attached to the wheels.

In car like climbing robots, the robot of [Suzuki et al. \(2006\)](#) and [Yukawa et al. \(2006b,a\)](#) has three units, a front unit, a central unit and a rear unit. Each of these three units again have two units each, right and left units. The six units are connected to magnetic wheels at the contact points with the pipe. Each unit has a driving part and a lifting part. There are twelve motors in the robot, six for driving part and another six for lifting part. The robot has been specifically designed and developed to overcome obstacles such as flanges on pipes. The robot of [Sadeghi et al. \(2008, 2012\)](#) and [Sadeghi et al. \(2008\)](#) is inspired from a human pole climber. The robot has three wheels, two of which are free and the third one is active. Just like a human pole climber uses a strap to grip himself to the pole or tree, the robot also uses a strap arm. One of the free wheels is attached on one end of the strap arm and the active wheel is attached to the other end of the strap arm. To provide further stability to the robot, a spring leg is attached to the strap arm. The spring leg enables the robot to climb pipes of variable diameters. The latest prototype of [Sadeghi et al. \(2012\)](#) is much more improvised compared to its previous prototypes ([Sadeghi et al., 2008](#); [Sadeghi et al., 2008](#)) as the latest prototype has a washing mechanism attached to it that helps it in washing street lamps. Similar to the Pobot V2 robot of [Fauroux and Morillon \(2010a,b\)](#), the robot of [Sadeghi et al. \(2012\)](#) is also inherently stable wherein the robot gets more stable if more weight is carried. In the robot of [Fauroux and Morillon \(2010a,b\)](#),

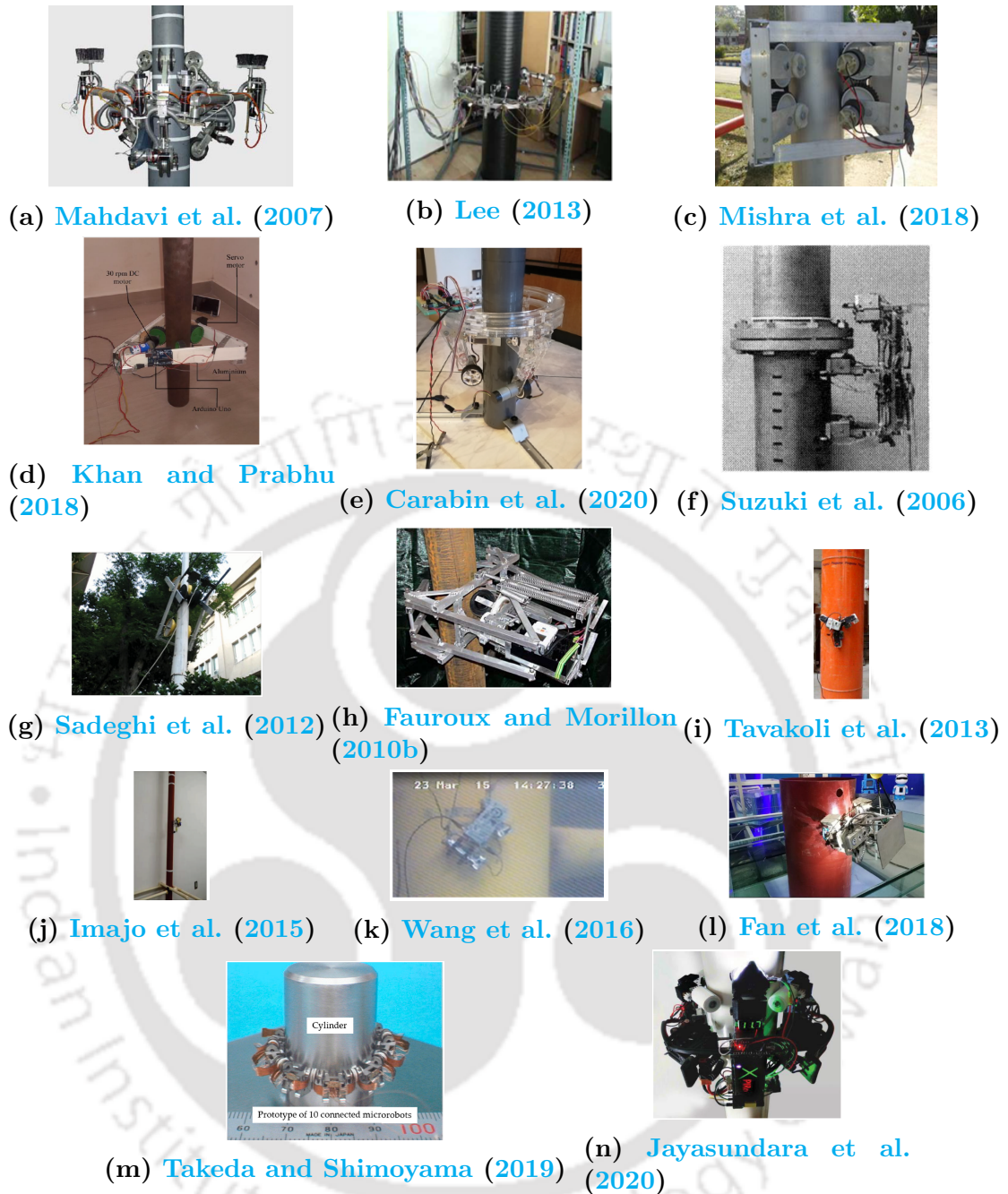


Figure 1.4: Wheeled robots

two rollers are attached to the frame encircling the pipe. The rollers help in climbing the pipe up or down. This robot can perform rotation about its axis, can cross obstacles and can climb conical poles. OmniClimbers robot by Tavakoli et al. (2013) is basically a wall climbing robot but it can climb pipes with diameters as low as 300 mm. An advanced prototype of the OmniClimbers robot, developed by Tavakoli and Viegas (2014) can climb pipes with diameters as low as 200 mm. The robot has three omni-directional wheels, each placed at an angle of 120° from each other. The use of omni-directional wheels gives the robot a superior manoeuvrability. The wheels are attached on a flexible chassis which gives better

adaptability to the robot to move on pipes with different curvatures. The robot of [Imajo et al. \(2015\)](#) has two rimless wheels with spokes, on one end and two guide wheels, at the other end. The tip of the spokes is attached with a neodymium permanent magnet. The robot can climb on walls and only on pipes with a large diameter. The robot of [Wang et al. \(2016\)](#) has a four-wheel configuration and has a steering mechanism. It is an underwater robot and is used for the removing of coatings from the pipe surfaces of offshore oil platform. Similar to the robot of [Wang et al. \(2016\)](#), the robot of [Fan et al. \(2018\)](#) also has a four-wheel configuration. However, they have incorporated the four wheel configuration with a self-adaption mechanism. The self-adaption mechanism comprises of a passive roll joint and the combined magnet adhesion unit. The passive roll joint is attached in the middle of the body of the robot. Its axis is parallel to the front and the rear axle of the robot. The self-adaption mechanism provides a better mobility to the robot. This robot is also an underwater robot and is used for cleaning the jackets of offshore oil platforms. The robot of [Takeda and Shimoyama \(2019\)](#) consists of multiple-connected microrobots with magnetic wheels. This robot consists of ten such microrobots connected to each other to form a closed circular chain. Each microrobot has six wheels. The wheels are arranged in a way that there are four wheels on the horizontal plane and there are four wheels on the vertical plane. This robot has its application in small spaces such as inspection of smaller pipes in power plants. ExPiRo robot by [Jayasundara et al. \(2020\)](#) consists of eight rollers which move the robot along the axial direction of the pipe. The eight rollers are arranged in two roller sets, each roller set consisting of four rollers. The rollers are pushed against the pipe surface by a clutching mechanism based on parallelogram four bar linkage. This robot can move on vertical pipes with varying diameter.

1.3.1.4 Legged Robots

The locomotion of most of the legged robots is similar to that of two-legged or four-legged terrestrial creatures, like human beings and dogs, respectively. RiSE V3 robot by [Haynes et al. \(2009\)](#) is a quadrupedal robot. Each leg in this robot has two active degrees of freedom and the four legs are attached to the body. There is an additional degree of freedom at the centre of the body to change posture. This robot can climb wooden poles. Similar to RiSE V3 ([Haynes et al., 2009](#)), the robot of [Shin et al. \(2010\)](#) also has four arms. Winspecbot robot by [Kamagaluh et al. \(2012\)](#) also has four legs, though its structure is different as compared to RiSE V3 ([Haynes et al., 2009](#)). The four legs are attached to the body and each leg has four degrees of freedom. This robot has a trotting gait. At a time, two legs remain attached to the surface and two legs, which are free, move. AnyClimb robot by [Liu et al. \(2015, 2016a\)](#), has eight legs. It can climb on pipes externally and also on vertical walls, walls with different curvatures. The robot comprises of two rectangular frames, each frame with four legs. The two frames are connected

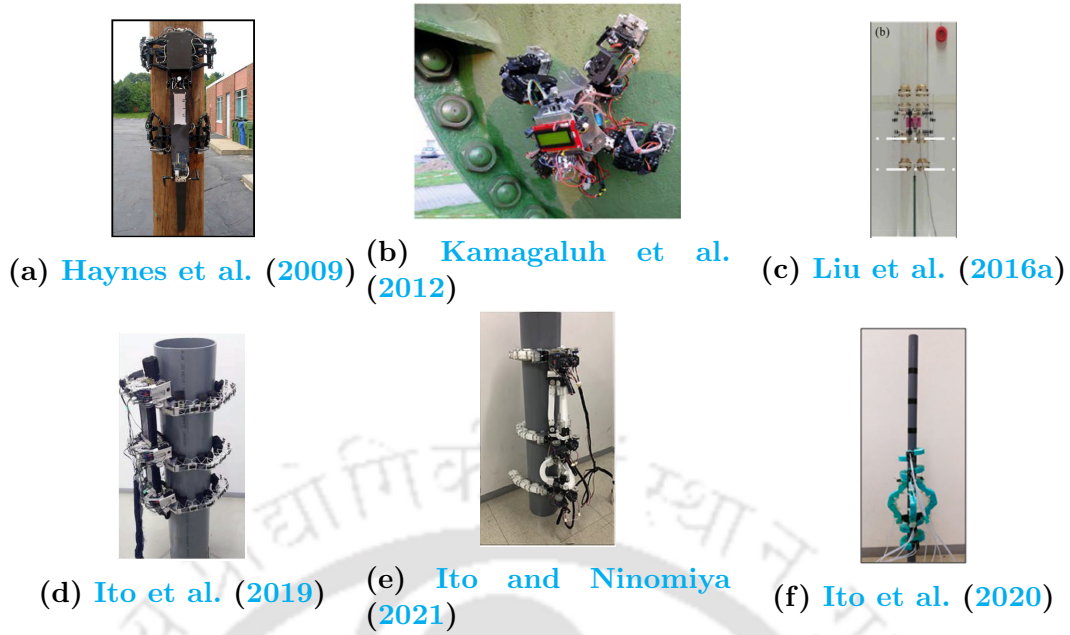
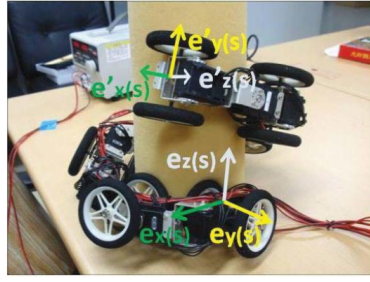


Figure 1.5: Legged robots

by a parallel four bar mechanism. The two frames move relative to each other to generate the walking locomotion, used for climbing. To move on vertical curved surfaces or on pipes, a compliant mechanism based asymmetric four bar mechanism is used. The robot by Sano et al. (2017) is basically a wall climbing robot, which can also be used in pipes and uneven surfaces. The robot has four legs. The four legs are attached to the body and the body has a translational degree of freedom. Each leg also has two translational degrees of freedom. TAOYAKA-III robot by Aoyagi et al. (2017) and Ito et al. (2019) is a six-legged flexible robot. There are three legs on each side of a flexible trunk. Each leg has five links and all the joints in it are passive. Rubber belts are attached between the links. A wire is attached on the other side of each leg. The wire is pulled to close in the flexible leg around the pipe. The wire is pulled by a servomotor. Another servo motor makes the leg move in up and down direction. TAOYAKA-V robot by Ito and Ninomiya (2021) is same as TAOYAKA-III robot (Aoyagi et al., 2017; Ito et al., 2019) except that TAOYAKA-V employs a clutching mechanism that enables TAOYAKA-V to walk on horizontal surfaces, in addition to climbing pipes. Also, in TAOYAKA-V, the flexible trunk consisting of one bellow in TAOYAKA-III is replaced by three flexible bellows. TAOYAKA-S II robot by Ito et al. (2020) is a soft robot. TAOYAKA-S II has eight flexible legs and the flexible trunk in it consists of three flexible links. The soft robot is made of silicone.

1.3.1.5 Robots with Combination of Two Locomotions

There are some pipe climbing robots, the locomotion of which cannot be classified as snake, inchworm, wheeled or legged. This is because the locomotion of these



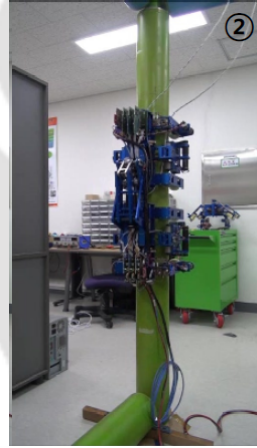
(a) Kamegawa et al. (2009)



(b) Polchankajorn and Maneewarn (2011a)

Figure 1.6: Snake cum wheeled robots

robots is a combination of two locomotions. The robots in this subsection can be further classified into two more subsections. They are :- Snake cum wheeled robots and Inchworm cum wheeled robots.



(a) Han et al. (2016)

Figure 1.7: Inchworm cum wheeled robot

1.3.1.5.1 Snake cum Wheeled Robots The robot of Kamegawa et al. (2009) is similar to the robot of Lipkin et al. (2007) with the difference that each module in this robot has two passive wheels. This robot has five modules and ten degrees of freedom. Cylinder or pipe climbing is achieved by using a simple cylinder climbing gait and a helical cylinder climbing gait. For simple cylinder climbing gait, the length of the robot should be shorter than the circumference of the cylinder. The robot after encircling the pipe, rolls about its axis to climb up or down. The helical cylinder climbing gait is used when the robot's length is greater than the circumference of the pipe. For helical cylinder climbing, the robot forms a helix and then rolls about its own axis.

Table 1.2: Classification of different pipe climbing robots on the basis of their manoeuvrability over obstacles and bends

Pipe climbing robots	Vertical pipes or poles		
	straight or bends with low curvature	with flanges or with variable diameters	with 90° bends with T-junction
Snake Robots	Lipkin et al. (2007), Wright et al. (2007), Goldman and Hong (2008)	Rollinson and Choset (2013), Takemori et al. (2016), Zhou et al. (2017), Yaqub et al. (2019)	—
Inchworm Robots	Ripin et al. (2000), First prototype of the robot by Saltarén et al. (1999, 2005), Aracil et al. (2000, 2003) and Almonacid et al. (2003); Vossoughi et al. (2004), Tavakoli et al. (2005), Qiaoling et al. (2019), Lau et al. (2013), Khalid et al. (2015), Faizal et al. (2015), Das et al. (2016), Singh et al. (2019), Jiang et al. (2020), Khan et al. (2020)	Yao et al. (2015), Qiaoling et al. (2020)	Second prototype of the robot by Saltarén et al. (1999, 2005), Aracil et al. (2000, 2003) and Almonacid et al. (2003); Xie et al. (2020) Maempel et al. (2009), Mampel et al. (2009), Tavakoli et al. (2008, 2010, 2011), Guan et al. (2009, 2011, 2016), Kim et al. (2012, 2016, 2018)
Wheeled Robots	Sebastian et al. (2015), Mishra et al. (2018), Khan and Prabhu (2018), Mustapa et al. (2018), Sadeqi et al. (2008), Sadeghi et al. (2008, 2012), Fauroux and Morillon (2010a, b), Tavakoli et al. (2013), Imajo et al. (2015), Wang et al. (2016), Takeda and Shimoyama (2019), Carabin et al. (2020)	Baghani et al. (2005), Mahdavi et al. (2007), Noohi et al. (2010), Yukawa et al. (2006b,a), Suzuki et al. (2006), Lee (2013), Fan et al. (2018), Jayasundara et al. (2020)	—
Legged Robots	Haynes et al. (2009), Kamagahih et al. (2012), Liu et al. (2015, 2016a), Sano et al. (2017), Aoyagi et al. (2017), Ito et al. (2019), Ito and Ninomiya (2021), Ito et al. (2020)	—	—
Snake cun wheeled Robots	Kanegawa et al. (2009), Polchankajorn and Maneewarn (2011a,b)	—	—
Inchworm cun wheeled Robots	—	—	Han et al. (2013, 2016)

The robot of [Polchankajorn and Maneewarn \(2011a,b\)](#) is a modular snake robot, with each module having two active wheels. The modules are connected to one another by a three degrees of freedom joint, the three degrees of freedom being the roll-pitch-yaw motion. The robot climbs the pole by forming a helix grasping the pipe and then the wheels are actuated to move the robot up the pipe.

1.3.1.5.2 Inchworm cum Wheeled Robots The robot of [Han et al. \(2013, 2016\)](#) has two driving modules which are connected by an actuated connecting arm. The two driving modules can be considered as grippers, as is found in typical inchworm climbing robots. Each driving module has two arms, a climbing arm and a rotation arm. Wheels are attached to both climbing arm and rotation arm. The climbing arm enables the robot to move along the pipe whereas the rotation arm enables the robot to rotate about the pipe axis. This robot is able to overcome flanges, valves, bends and T-junctions.

1.3.2 Gripping in External Pipe Climbing Robots

As stated previously, gripping or adhesion in any climbing robot is of utmost importance as without a proper grip, the robot begins to slip. For getting the desired gripping force, the grippers in the pipe climbing robots are actuated and pushed against the walls of the pipe, by various means. Some grippers are electrically actuated, some others are pneumatically actuated, some have springs (strain energy), some use magnetic grippers and some also use adhesives.

1.3.2.1 Electrically Actuated Gripping

In electrically actuated gripping, the gripper or the gripping device or the gripping mechanism is actuated using electric power. The commonly used electric actuators are DC motors and servo motors.

The gripping mechanism of most snake robots involves forming a helix around the pipe and wounding it, ([Lipkin et al., 2007](#); [Wright et al., 2007](#); [Rollinson and Choset, 2013](#); [Takemori et al., 2016](#); [Zhou et al., 2017](#); [Yaquib et al., 2019](#); [Kamegawa et al., 2009](#); [Polchankajorn and Maneewarn, 2011a,b](#)). After wounding the pipe, these robots squeeze against the walls of the pipe which gives the necessary gripping force, sufficient enough to avoid slip or fall. The joints of these hyper-redundant robots are powered by electric motors.

The gripping mechanism of almost all inchworm robots involves two grippers. In the robot of [Vossoughi et al. \(2004\)](#) and [Tavakoli et al. \(2005\)](#), there are two grippers and each gripper consists of a pair of v-shaped multi-fingered bodies, a pair of right and left handed screws, a pair of linear guides and a double shaft motor. This gripper can grip pipes of different dimensions. In Raupi robot by [Maempel et al. \(2009\)](#) and [Mampel et al. \(2009\)](#), the gripping module is driven by

a servomotor. The grippers used in 3DCLIMBER by [Tavakoli et al. \(2008, 2010, 2011\)](#) are the same as in their previous robot ([Vossoughi et al., 2004](#); [Tavakoli et al., 2005](#)) though the climbing mechanism in 3DCLIMBER varies greatly as compared to the previous robot. Also, in 3DCLIMBER, each gripper in each climbing step acts as a manipulator. In the robot of [Lau et al. \(2013\)](#), four servo motors are used for actuating the two grippers, a pair for each gripper. The robot of [Khalid et al. \(2015\)](#) uses two U-shaped bodies as grippers, both of which are actuated using two servo motor based linear actuators. In the robot of [Faizal et al. \(2015\)](#), two RC servo motors with metal gears are used to actuate the two grippers. Each gripper in Climbot by [Guan et al. \(2009, 2011, 2016\)](#) has two fingers. The two fingers are actuated by a single brushless DC motor. The fingers open and close linearly and simultaneously through a harmonic drive, a worm gear and two four bar linkage mechanisms. The grippers in Climbot are designed both for gripping and manipulation. The opening and closing of the gripper in PiROB by [Kim et al. \(2012, 2016, 2018\)](#) is done by using a small DC motor. In the robot of [Yao et al. \(2015\)](#), each gripper is made of four paws and its opening and closing is actuated by an electric linear motor. In the robot of [Qiaoling et al. \(2019, 2020\)](#), each gripper is associated with a support structure that helps the robot to clamp the pipe. The gripper is actuated by a motor.

Wheels act as grippers in wheeled robots. In the robot of [Lee \(2013\)](#), the linear movement of the wheels along radial direction is actuated by a linear actuator. Three linear actuators are used for the three wheels, each of which is placed at an angle of 120° from each other. The linear actuators provide the required gripping force to the wheels on the pipes. In the robot of [Sebastian et al. \(2015\)](#), the arm joints are actuated by servo motors. The arms on rotating push the wheels against the pipe surface. The robot of [Khan and Prabhu \(2018\)](#) uses DC motors with high torque for gripping the pipe. ExPiRo by [Jayasundara et al. \(2020\)](#) uses eight DC motors to actuate the eight rollers. Three DC motors are used for the three wheels. The robot of [Han et al. \(2016, 2013\)](#) uses two DC motors for grasping the wheels against the pipe at the opposite ends of the robot. In the legged robot of [Haynes et al. \(2009\)](#), RiSE V3, each leg is actuated by using brushless DC motor. Each leg has a claw fitted with surgical needles for gripping on a wooden pole. The gripping and actuation of all the TAOYAKA robots ([Aoyagi et al., 2017](#); [Ito et al., 2019](#); [Ito and Ninomiya, 2021](#); [Ito et al., 2020](#)) are the same. In the other side of each leg (the side away from the torso) of these robots, a wire is attached to a servo motor. When a wire is pulled, the flexible leg corresponding to that wire closes in around the pipe and grips.

1.3.2.2 Pneumatically Actuated Gripping

In the inchworm robot of [Ripin et al. \(2000\)](#), the two grippers are pneumatically actuated. A parallel four bar linkage is used to ensure that the gripper surface is

parallel to the pipe surface. In the robot of [Saltarén et al. \(1999\)](#), [Aracil et al. \(2000, 2003\)](#) and [Almonacid et al. \(2003\)](#), each of the two rings has three radial grip devices which are pushed against the pipe surface by three pneumatically actuated linear actuators. The robot of [Das et al. \(2016\)](#) has two C shaped grippers, each of which is actuated using a pair of pneumatic cylinders. In soft robots, the gripping mechanism comprising artificial muscles or other soft materials are actuated pneumatically, ([Singh et al., 2019](#); [Jiang et al., 2020](#); [Xie et al., 2020](#)). In the legged robot of [Sano et al. \(2017\)](#), vacuum pads are used to grip on the pipe surface.

1.3.2.3 Gripping with Magnets

Gripping with magnets on pipes is mostly found in wheeled robots. These robots with magnetic adhesion can only climb pipes which are made of ferromagnetic materials. In the wheeled robot of [Suzuki et al. \(2006\)](#) and [Yukawa et al. \(2006b,a\)](#), the wheels are made of neodymium magnet. In OmniClimbers by [Tavakoli et al. \(2013\)](#), magnets are placed at three places on the robot. A central magnet is placed at the center of the robot or the chassis. This magnet is the strongest as compared to the other two magnets and it enables the robot to grip the pipe surface. Then, there are side magnets which enable the robot to adapt to the curvature of the surface. Lastly, there are traction magnets which are placed near to or on the omni directional wheels. These magnets increase the traction of the wheels on the pipe surface and make sure that the robot climbs without any slip. All the magnets used in OmniClimbers are permanent magnets. The robot of [Imajo et al. \(2015\)](#) has two rimless wheels with spokes, the tips of which are attached to a neodymium permanent magnet. The chamber angle between the left and the right wheels can be adjusted that enables the robot to grip pipes with different diameters. The robot of [Fan et al. \(2018\)](#) also uses wheels made of neodymium magnets. The robots of [Wang et al. \(2016\)](#) and [Takeda and Shimoyama \(2019\)](#) also use magnetic wheels for gripping. [Khan et al. \(2020\)](#) in their inchworm inspired robot, use two legs with electromagnetic foots to grip on metallic flat surfaces and pipes. In Winspecbot by [Kamagahuh et al. \(2012\)](#), a magnetic pad is attached to the end of each leg. The magnets used in the robot are nickel-plated neodymium.

1.3.2.4 Gripping with Springs (Strain Energy)

In the robot of [Baghani et al. \(2005\)](#), [Mahdavi et al. \(2007\)](#) and [Noohi et al. \(2010\)](#), six springs are connected from the body to the wheels of the robot. The

Table 1.3: Classification of gripping in different pipe climbing robots on the basis of their actuation

Pipe climbing robots	Gripping			
	Pneumatically actuated	Electrically actuated	With magnets	With springs (strain energy)
Snake Robots	—	Wright et al. (2007), Lipkin et al. (2007), Goldman and Hong (2008), Takemori et al. (2016)	—	—
Inchworm Robots	Ripin et al. (2000), Saltarén et al. (1999), Aracil et al. (2000, 2003), Almonacid et al. (2003), Das et al. (2016), Singh et al. (2019), Jiang et al. (2020), Xie et al. (2020)	Vossonghi et al. (2004), Tavakoli et al. (2005), Maempel et al. (2009), Maempel et al. (2009), Tavakoli et al. (2008, 2010, 2011), Lau et al. (2013), Khalid et al. (2015), Faizal et al. (2015), Guan et al. (2009, 2011, 2016), Kim et al. (2012, 2016, 2018), Yao et al. (2015), Qiaoling et al. (2019, 2020)	Khan et al. (2020)	—
Wheeled Robots	—	Lee (2013), Sebastian et al. (2015), Khan and Prabhu (2018), Jayasundara et al. (2020)	Yukawa et al. (2006b,a), Suzuki et al. (2006), Tavakoli et al. (2013), Imajo et al. (2015), Wang et al. (2016), Fan et al. (2018), Takeda and Shimoyama (2019)	Baghani et al. (2005), Mahdavi et al. (2007), Noochi et al. (2010), Mishra et al. (2018), Mustapa et al. (2018), Carabin et al. (2020)
Legged Robots	Sano et al. (2017)	Haynes et al. (2009), Aoyagi et al. (2017), Ito et al. (2019), Ito and Ninomiya (2021), Ito et al. (2020)	Kamagalah et al. (2012)	Shin et al. (2010), Liu et al. (2015, 2016a)
Snake cum wheeled Robots	—	Kamegawa et al. (2009), Polchanka-jorn and Maneewarn (2011a,b)	—	—
Inchworm cum wheeled Robots	—	Han et al. (2013, 2016)	—	—

springs push the wheels against the pipe and also enable the robot to climb on a stepped pole. Similarly, in the robot of [Mustapa et al. \(2018\)](#), springs are put between the frame of the robot and the wheel to push the wheels against the tree. [Mishra et al. \(2018\)](#) use a compliant encapsulated cage along with a gripping adhesion mechanism to provide the necessary gripping force in their robot. In the robot of [Carabin et al. \(2020\)](#), springs are attached in the three arms. The three arms connect the frame and the wheels on their two ends. The springs provide the necessary gripping force to the wheels against the pipe. In the legged robot of [Shin et al. \(2010\)](#), the gripper consists of shape memory alloy wires and springs. When electricity is provided, the shape memory alloy wires contract and cause the gripper to ungrasp the pipe. When electricity is disconnected, the shape memory alloy wires return to their normal shape and the gripper grips the pipe with the help of springs. In AnyClimb by [Liu et al. \(2015, 2016a\)](#), the eight footpads are made of a dry adhesive. The preloads on the footpads are generated by torsional springs. The grip is due to the preloads and the dry adhesives. A single motor is used to detach a footpad from the surface.

1.3.2.5 Gripping due to Self-Weight

The robot of [Sadeqi et al. \(2008\)](#) and [Sadeghi et al. \(2012, 2008\)](#) is a naturally stable wheeled robot as the entire mechanism of the robot is inspired from a human pole climber. In this robot, more is the weight of the robot, the higher is the gripping force. Pobot V2 robot by [Fauroux and Morillon \(2010a,b\)](#) uses a rolling self-locking mechanism which is similar to the gripping of the robot by [Sadeqi et al. \(2008\)](#) and [Sadeghi et al. \(2012, 2008\)](#). The self locking mechanism involves a mechanism which grips the robot to the pole without consuming any energy. The gripping force depends on the weight of the robot and hence it is a self locking mechanism.

1.3.3 Control in External Pipe Climbing Robots

The use of servomotors is the simplest form of control technique that can be used in pipe climbing robots as a position feedback mechanism is attached to the motor.

The snake robot of [Wright et al. \(2007\)](#) uses a servo in each module. Each servo controls a single degree of freedom in each module. Each servo consists of an electric motor, a gear train and electronics to control the motor. A proportional-integral-derivative (PID) control law is used to control the position of each module in the robot. Similarly, in the robot of [Lipkin et al. \(2007\)](#), the motors are driven by using a PID control law. [Rollinson and Choset \(2013\)](#) use a compliant gait based control in their robot. They use curvature compliance to control the curvature of the robot and position compliance to temporarily control the position of the gait of the robot. In the robot of [Takemori et al. \(2016\)](#), the joints are controlled by

proportional control law. [Zhou et al. \(2017\)](#) uses a PD control law to control the angular displacements of the joints.

[Tavakoli et al. \(2005\)](#) use current feedback to control the torque exerted by the grippers in their inchworm robot. 500 pulse encoders are attached on the shaft of the DC motor inside the electrical cylinders to control the linear movements exerted by the cylinders. This robot uses a PID control law. Raupi by [Maempel et al. \(2009\)](#) and [Mampel et al. \(2009\)](#) uses servomotors and an integrated position controller to control its motion. The controllers used in 3DCLIMBER by [Tavakoli et al. \(2008, 2010, 2011\)](#) can control the motors in position, velocity or torque. Also, in this robot, position control is used when the gripper opens and force control is used when the gripper closes on the pole. The robots of [Lau et al. \(2013\)](#) and [Faizal et al. \(2015\)](#) use Arduino Uno micro controller to control the servo motors. The robot of [Khalid et al. \(2015\)](#) uses Arduino Mega micro controller to control the servo motors. The control unit of Climbot by [Guan et al. \(2009, 2011, 2016\)](#) has a three layered architecture. The top layer has a PC for motion planning and other tasks like task management and man-machine interface. The motion controller and the driver are present in the middle layer. The servo motors are at the bottom. PiROB by [Kim et al. \(2012, 2016, 2018\)](#) is controlled remotely on the ground with no cables between the robot and the remote control station. The robot uses five servomotors to control the five joints of the robot. In the robot of [Yao et al. \(2015\)](#), the joints of the robot are controlled using servo motors. [Qiaoling et al. \(2019, 2020\)](#) use a PID control law to control the robot. The feedback gains of the PID controller, used in the robot, are tuned using Ziegler Nichols method. In the wheeled robot of [Lee \(2013\)](#), each of the wheels is controlled independently using a motion controller. For linear actuation, the feedback signals are provided by the linear potentiometer and the rotary encoder. [Khan and Prabhu \(2018\)](#) use an Arduino Uno to control the three DC motors in their robot. RiSE V3 by [Haynes et al. \(2009\)](#) uses a PD control law. The robot of [Han et al. \(2013, 2016\)](#) is controlled remotely by an external PC through a tethered CAN communication. In the robot of [Polchankajorn and Maneewarn \(2011a,b\)](#), the servo motors are subjected to position control and speed control.

The inchworm robot of [Ripin et al. \(2000\)](#) uses a programmable logic circuit (PLC) to control the motion of the robot. They use solenoid control valves for controlling the direction of airflow. The robot of [Saltarén et al. \(1999\)](#), [Aracil et al. \(2000, 2003\)](#) and [Almonacid et al. \(2003\)](#) uses a motion control algorithm and a multi-axis controller board to control the robot's motion. This robot uses a PD control law. The airflow in each pneumatic cylinder in the robot of [Das et al. \(2016\)](#) is controlled using a single solenoid 5/2 way valves. An Arduino Uno is used to implement the control strategy. In the robot of [Singh et al. \(2019\)](#), air flow at an input pressure to the artificial muscles is regulated using a pressure regulator and solenoid valves. This robot uses an open loop control law and an Arduino Mega

microcontroller board.

In the wheeled robot of [Suzuki et al. \(2006\)](#) and [Yukawa et al. \(2006b,a\)](#), a micro-computer controls the motors through motor drivers. In OmniClimbers robot by [Tavakoli et al. \(2013\)](#), a controller puts all the actuators under velocity control. In one of the latest prototypes of OmniClimbers robot, [Tavakoli et al. \(2015\)](#) use dead reckoning method to control the motion of the robot. The robot of [Imajo et al. \(2015\)](#) uses a field-programmable gate array to issue signals to the motor drivers, which then cause the motors to rotate. The robot of [Wang et al. \(2016\)](#) uses speed control model to regulate the driving motors. [Fan et al. \(2018\)](#) use servo motors to control the robot. [Takeda and Shimoyama \(2019\)](#) have manufactured a microrobot controller that has both manual and automatic modes. The control is performed using computer in automatic mode. ExPiRo robot by [Jayasundara et al. \(2020\)](#) uses a custom printed circuit board having two H-bridges and an ATMELE microcontroller to control the DC motors. The robot of [Carabin et al. \(2020\)](#) uses three speed loop PI controllers to assure proper climbing of the robot. This robot uses a PID control law to control the robot position. iCrawl robot by [Khan et al. \(2020\)](#) uses servo motors for the five joints of the robot and Arduino Nano as the controller board. The robot of [Kamagaluh et al. \(2012\)](#) uses twenty servo motors in its legs and all these servos are controlled using a micro controller board. All the TAOYAKA robots use servo motors to control the robot's motion ([Aoyagi et al., 2017](#); [Ito et al., 2019](#); [Ito and Ninomiya, 2021](#); [Ito et al., 2020](#)).

In the wheeled robot of [Baghani et al. \(2005\)](#), [Mahdavi et al. \(2007\)](#) and [Noohi et al. \(2010\)](#), PID controllers are used for the DC motors. Their robots are modelled as an underactuated driftless nonlinear control system. The three control objectives, taken by the authors ([Baghani et al., 2005](#); [Mahdavi et al., 2007](#); [Noohi et al., 2010](#)) are position tracking, vertical alignment and rotation around the pole. [Mishra et al. \(2018\)](#) use a frequency based remote control to control the movement of the robot. [Mustapa et al. \(2018\)](#) use Arduino Mega microcontroller to control the four DC motors. [Fauroux and Morillon \(2010a,b\)](#) use a programmable controller with Bluetooth remote control to control the Pobot V2 robot.

1.3.4 Sensors in External Pipe Climbing Robots

A closed loop control of any robot requires sensors for detecting the set-points at every time instant. The pipe climbing robots discussed in this review also use a variety of sensors and feedback mechanisms to control the robot. This subsection discusses the different kinds of sensors and feedback mechanisms used by pipe climbing robots.

The snake robot of [Lipkin et al. \(2007\)](#) and [Wright et al. \(2007\)](#) uses a current sensor on the controller board to limit the current drawn by the servo motor in case of a power surge. This helps to protect the servo motor. A temperature

sensor is also used which reports the user about the temperature of each module. [Goldman and Hong \(2008\)](#) and [Takemori et al. \(2016\)](#) propose the future use of a camera sensor on the head of the robot so that it can overcome obstacles and can also climb from one pole to the other.

In the inchworm robot of [Saltarén et al. \(1999\)](#), [Aracil et al. \(2000, 2003\)](#) and [Almonacid et al. \(2003\)](#), three ultrasonic sensors are used in each of the two rings. These sensors calculate and compensate the deviation of robot's center with respect to the pipe's center. In the robot of [Qiaoling et al. \(2019, 2020\)](#), accelerometers are mounted on the two grippers of the robot. Accelerometers are used to provide an absolute reference for the pitch, roll components for the estimated orientation. [Khalid et al. \(2015\)](#) use an infra red (IR) sensor and a force sensitive resistor (FSR) sensor in each of the two grippers of their robot. IR sensor detects the degree of travel by the climbing robot and accordingly directs the Arduino to stop the robot when it reaches the pre-assigned degree of travel. Also, FSR sensor detects the pressure put by the gripper on the pole and accordingly directs the Arduino about the correct gripping force. An ultrasonic proximity sensing is used by [Das et al. \(2016\)](#) in their robot to detect the amount of travel with respect to the ground. The sensor allows the robot to climb till a prescribed height is reached. Raupi robot by [Maempel et al. \(2009\)](#) and [Mampel et al. \(2009\)](#) uses tactile sensors that detect the relative position between the gripping module and the pipe surface. 3DCLIMBER by [Tavakoli et al. \(2008, 2010, 2011\)](#) uses sixteen FSR sensors in two grippers, eight in each gripper. FSR sensors are used to know about the force distribution on the surface of the gripper. These sensors help the robot during the calibration and assembly of the gripper. In addition to FSR sensors, this robot also uses two strain gauges, each in each gripper, to know the grasping force of each gripper. Other sensors used in 3DCLIMBER are optoelectronic sensors and sharp range finder sensors. FSR sensors are also used in Climbot by [Guan et al. \(2009, 2011, 2016\)](#) to know the grasping force between the gripper fingers and the gripped object. [Kim et al. \(2012, 2016, 2018\)](#) in PiROB robot use six proximity sensors in each of the two grippers. The proximity sensor detects the distance between the palm of each gripper and the pipe surface. Other sensors used in PiROB are inclinometer and visual camera. In the soft robot of [Singh et al. \(2019\)](#), a pressure sensor is used to measure the pressure inside the soft pneumatic actuator. The length of the actuators is measured using a camera. iCrawl by [Khan et al. \(2020\)](#) uses a Hall sensor, inertial encoders and a current sensor. Hall sensor helps the robot to differentiate between a metal and a non-metal surface.

Table 1.4: A summary of pipe climbing robots

Pipe climbing robots	Weight (kgf)	Payload (kgf)	Diameter (mm)	Material	Velocity (m min ⁻¹)	Energy (J)/Power (W) consumed	Simulation/Experimental
Ripin et al. (2000)	6.5	7.51 ($\mu = 0.2$) 21.52 ($\mu = 0.4$)	150	PVC	0.6	—	Experimental
Tavakoli et al. (2008, 2010, 2011)	42	—	200-350	—	1	—	Both
Lau et al. (2013)	3	—	350	PVC	0.225-0.226	—	Simulation
Das et al. (2016)	20	—	114.3	PVC	2.18	—	Experimental
Guan et al. (2009, 2011, 2016)	17.5	2.5	50-115	Steel	2.2 (Swinging around gait)	272.3 J (Inchworm gait) 128.24 J (Swinging around gait) 147.1 J (Flipping over gait)	Both
Kim et al. (2012, 2016, 2018)	3.8	4.5	76.2-127	—	1.08	—	Experimental
Faizal et al. (2015)	8.63	—	100	Wood	0.11	—	Both
Qiaoling et al. (2019, 2020)	1.07	2.72	8-55	PVC, Iron, Wood	0.48	—	Experimental
Khan et al. (2020)	1.42	0.08	120-220	Metal	1.5	—	Experimental
Jiang et al. (2020)	0.205	0.675	105-117	PVC, Rubber, Metal	—	—	Experimental
Xie et al. (2020)	0.0125	0.1	18-36	Acrylic	0.84	—	Experimental
Aracil et al. (2000, 2003)	10-70	5.1-30.58	150-750	Wood	12-24	240-1500 W	Simulation
Lee (2013)	20	—	300-500	Polyethylene	≥ 1.8	—	Experimental
Sebastian et al. (2015)	< 7	—	200	Wood	3.6	—	Simulation
Mishra et al. (2018)	1.776	0.19	101.6	Ferromagnetic	—	—	Experimental
Robot of Suzuki et al. (2006)	5.26	—	216.3	Steel	0.84	—	Experimental
and Yukawa et al. (2006a)	2	10	50-130	—	0.52-0.6	—	Both
Sadeghi et al. (2008, 2012)	10.5	1	100-300	Steel, Wood	3.96	—	Experimental
Fauroux and Morillon (2010a,b)	1.241 (Prototype-I) 0.946 (Prototype-II)	0.082 0.37	Flat-300 1200-2100	Metal	11	—	Experimental
Tavakoli et al. (2013)	0.38	0.155	60.5-101.6	Steel	—	6.59 W	Experimental
Imajo et al. (2015)	38.8	—	820-1676	Steel	—	—	Experimental
Fan et al. (2018)	0.8	2.2	100-130	—	—	—	Both
Jayasundara et al. (2020)	5.4	—	250	Wood	12.6	—	Experimental
Haynes et al. (2009)	5.37	1	—	Steel	—	—	Both
Kamagalah et al. (2012)	0.142	0.005	50-∞	Acrylic	0.498	—	Experimental
Liu et al. (2015, 2016a)	3	—	150	Wood	0.07	—	Experimental
Ito and Ninomiya (2021)	0.55	0.45	14-61	Wood	—	—	Experimental
Ito et al. (2020)	0.210/unit	—	150	soft urethan	2.16 (lateral rolling) 1.44 (helical climbing)	—	Both
Kamegawa et al. (2009)	3	—	14.5	—	1	—	Experimental
Polchankajorn and Maneewarn (2011a,b)	30	10	150	—	10.8	—	Experimental
Han et al. (2016, 2013)	—	—	—	—	—	—	—

Sebastian et al. (2015) propose the future use of ultrasonic sensors and inertial measurement units (IMU) in their wheeled robot. Mishra et al. (2018) also propose the future use of an IR sensor in their robot to detect the change in pipe diameter. The sensors used in the robot of Khan and Prabhu (2018) are a camera, a laser and two ultrasonic sensors. Tavakoli et al. (2013) propose the future use of IMU or other exteroceptive sensors to improve the accuracy of trajectory following of the OmniClimbers robot. In one of the latest prototypes of the OmniClimbers robot, Tavakoli et al. (2015) use accelerometers and optical flow sensors to ensure that the trajectory tracking of the robot is accurate. Some of the microrobots in Takeda and Shimoyama (2019)'s robot have flaw-detection sensors. Encoders are the only sensors found in the wheeled robot of Baghani et al. (2005), Mahdavi et al. (2007) and Noohi et al. (2010). The encoders are on the active wheels of the robot. The wheeled robot of Suzuki et al. (2006) and Yukawa et al. (2006b,a) has four distance sensors, twelve limit switches and one tilt sensor. The distance sensor detects the presence of flanges as the robot moves. The underwater wheeled robot of Fan et al. (2018) uses a liquid level transmitter and an acceleration sensor to achieve the depth and the posture of the robot, respectively.

A current sensor is used in each module of the snake cum wheeled robot of Polchankajorn and Maneewarn (2011a,b) to measure the current going into the motor. Han et al. (2013, 2016) in their inchworm cum wheeled robot use electromagnetic acoustic transducers (EMATs) to carry out non-destructive testing of pipelines. They also use a strain gauge attached on the climbing arm to know the gripping state of the robot.

1.3.5 Bistable Grippers

This subsection reviews the literature on bistable grippers and grippers which are actuated using bistable mechanisms. A bistable mechanism is one which has two stable equilibrium states with an in between unstable equilibrium state (Mavanthoor and Midha, 2006). No power is required to maintain the two stable equilibrium states. Power is required only to actuate the bistable mechanism from its one stable equilibrium state to the other stable equilibrium state and vice-versa (Choi et al., 2021). The grippers can be classified into various ways. While some bistable grippers have been inspired from the trapping movement of the leaves of venus flytrap (Kim et al., 2010; Wang et al., 2019; Zhang et al., 2019b; Baumgartner et al., 2020; Wang et al., 2020), there are grippers which have a two and three finger like configuration (Thuruthel et al., 2019; Zhang et al., 2019a, 2020; Sun et al., 2020; Nguyen et al., 2020; Faber et al., 2020; Wang et al., 2020; Lerner et al., 2020; Balakuntala et al., 2021). The grippers of Hao and Kong (2012) and Chang et al. (2020) are compliant parallel grippers whereas the grippers of Plumiers et al. (2012); Liu and Xu (2016); Liu et al. (2016b); Xu (2017); Hao et al. (2017); Yang and Xu (2017) are constant force grippers. The bistable grippers are actuated

using shape memory alloys (Kim et al., 2010; Thomas et al., 2018; Welsch et al., 2018; Zimmer et al., 2020; Scholtes et al., 2020; Lerner et al., 2020), dielectric elastomer actuators (Follador et al., 2015; Wang et al., 2019; Baumgartner et al., 2020), through pneumatic means (Rothmund et al., 2018; Jitosho et al., 2019; Wang et al., 2020; Nguyen et al., 2020; Faber et al., 2020), piezoelectric stack actuator (Liu and Xu, 2016; Liu et al., 2016b) and electro thermal actuator (Yang and Xu, 2017). The following paragraph briefly reviews the salient features of these grippers.

The gripper of Kim et al. (2010) uses an unsymmetrically laminated carbon fiber reinforced prepreg (CFRP) composite, which acts as the bistable structure. It has two bistable structures that mimic the motion of the leaves of venus flytrap. Similar motion is mimicked by two dielectric elastomer membranes in the gripper of Wang et al. (2019) and two bistable morphing structures in the gripper of Zhang et al. (2019b). In the gripper of Zhang et al. (2019b), each bistable morphing structure is a cylindrical shell made of carbon fibre reinforce polymer, which acts as a compliant finger. Each shell is an anti-symmetric shell and has a neodymium magnet attached to it. A non-contact magnetic actuation is used to actuate the compliant fingers. The soft gripper of Baumgartner et al. (2020) consists of coupled balloons, one of which is made of rubber and the other balloon is a dielectric elastomer membrane, which also acts as the trigger actuator. The rubber balloon exhibits bistability with its volume suddenly increasing after a critical pressure, controlled by the trigger actuator. The gripper action is very fast. The gripper of Wang et al. (2020) is a two-fingered gripper. Each finger is a soft pneumatic reinforced bistable actuator. It consists of two actuation chambers and these chambers sandwich a pre stressed steel shell to achieve bistability. The gripper of Thuruthel et al. (2019) has four fingers made of silicone. The four fingers are attached by a pre stressed thin layer of silicone and also the four fingers are attached by a ring, also made of silicone. The pre stressed layer and the ring give bistability to the gripper. Zhang et al. (2019a) have designed and developed a compliant bistable gripper for passive perching of micro-aerial vehicles. The bistable gripper has three sets of fingers which are connected to soft silicone tubes. The gripper grasps and moves from one stable equilibrium state to the other by making contact with the target object. The gripper is attached on top of a quadcopter. The gripper opens when the quadcopter generates a downward thrust. As an improvement of the previous work (Zhang et al., 2019a), Zhang et al. (2020) redesign the previous gripper and the present gripper has two sets of fingers, in place of three. The grasping technique remains the same as the old gripper. Also, the redesigned gripper has a motor driven lever to open the gripper. Sun et al. (2020) have developed a soft gripper with two modules as fingers. Each module consists of a flexible plastic sheet which is sandwiched between two soft bodies. The soft bodies have channels which hold a twisted and coiled actuator. A linear spring is also attached on the plastic sheet. The potential energies stored

in linear spring and the soft bodies induce bistability to the gripper. [Nguyen et al. \(2020\)](#) have developed an underactuated soft gripper which has three stable states : open, pinching and wrapping. It uses a bistable buckling spring. [Faber et al. \(2020\)](#) have developed dome patterned meta material sheets which are used to make a two fingered gripper. The domes exhibit bistability and hence the gripper requires power only to switch it from one stable state to the other, which is done pneumatically. The gripper of [Lerner et al. \(2020\)](#) is a variable stiffness bistable gripper. The gripper has four fingers, made of silicone. The gripper can become both rigid and soft by varying its stiffness. When the gripper is soft, it exhibits bistability and grasps the target object without an actuator but with the contact force of the target object. A shape memory polymer (SMP) is used to vary the stiffness of the gripper and also to switch the gripper between open and closed states. In addition to SMP, a DC motor is also used to open the gripper. Due to variable stiffness, the gripper can grasp both rigid and soft objects. [Balakuntala et al. \(2021\)](#) have developed a passive compliant gripper based on an as-fabricated bistable shell. Four grasping arms are attached on the bottom surface of the bistable shell. The bistable shell opens to grasp an object when the switching mechanism switches the bistable shell from its stress-free stable equilibrium state to the stressed second equilibrium state. The open gripper makes a contact with the object to be grasped and comes back to its stress-free stable equilibrium state, thus grasping the object. The object is released when the switching mechanism switches the gripper. The gripper can grasp objects of various shapes. In the compliant parallel gripper of [Hao and Kong \(2012\)](#), a bistable mechanism is used in the design of the gripper so as to avoid over loading the gripped delicate objects. [Chang et al. \(2020\)](#) have developed a compliant parallel gripper (CPG), which consists of an eight bar linkage mechanism and a bistable mechanism. The bistable mechanism consists of four support beams and a shuttle mass. The gripping takes place when the bistable mechanism moves from one stable equilibrium state to the other. [Pluimers et al. \(2012\)](#) utilise a pre-loaded bistable mechanism to generate negative stiffness in the statically balanced gripper. [Liu and Xu \(2016\)](#) have developed a constant force gripper which has two modules : gripper module and a constant force mechanism module. The constant force is generated by a bistable beam mechanism. In the constant force grippers of [Liu et al. \(2016b\)](#) and [Hao et al. \(2017\)](#), the bistable mechanism consists of fixed-guided inclined straight beams which generate the negative stiffness. [Xu \(2017\)](#) has designed and developed a constant force micro gripper for biological micro manipulation. Similar to the previous constant force grippers of [Pluimers et al. \(2012\)](#), [Liu and Xu \(2016\)](#), [Liu et al. \(2016b\)](#) and [Hao et al. \(2017\)](#), this gripper also uses a bistable mechanism for generating negative stiffness. The gripper of [Yang and Xu \(2017\)](#) is a constant force micro gripper, used for microelectromechanical systems (MEMS). The micro gripper consists of inclined bistable beams, straight leaf flexures and Z-shaped beams, which act as electrothermal actuators. The vacuum gripper of

Welsch et al. (2018) consists of a bistable spring which is attached to a membrane. Levers are attached on the two ends of the bistable spring. The levers are actuated by antagonistically arranged shape memory alloy wires, which in turn actuate the bistable spring. This deflects the membrane and vacuum is generated. The compliant industrial gripper of Scholtes et al. (2020) is actuated by a bistable shape memory alloy actuation unit. In the actuation unit, a bundle of shape memory alloy wires move a leaf spring from one stable position to the other, which in turn actuates the gripper. The vacuum gripper of Zimmer et al. (2020) uses the same principle of gripping as in their previous work (Welsch et al., 2018) but in the present case, the shape memory alloy vacuum suction cups are installed on a robot UR-5. Follador et al. (2015) have developed a bistable minimum energy structure (BiMES) which uses a combination of dielectric elastomer actuator and elastic elements made of spring steel. Two units of BiMES are combined to form a gripper. The reflexive gripper of Jitosho et al. (2019) uses a reflexive gripper for mobile robots. The gripper makes use of pre-stressed bistable bands. A pneumatic actuation system is used for reopening the gripper. A containment mechanism is used to close the gripper. Rojas et al. (2019) have developed a bio inspired spring origami gripper. The bistable function of the gripper is similar to that of an earwig wing. The gripper is actuated with a very low energy and has a very high payload. Rothmund et al. (2018) have developed a soft gripper which is actuated pneumatically. The elastomeric valve in the pneumatic circuits contains a bistable membrane. This valve, by controlling the airflow, enables the gripper to grasp objects. Thomas et al. (2018) propose a self-activating bistable buckled beam, which could be used as a micro-gripper. The beam is made of shape memory alloy. The buckled beam is actuated by putting a thermal load, by passing current through the beam. The gripper of Nguyen and Wang (2016) is based on a compliant bistable mechanism. The mechanism consists of a release bar which pushes the adhered object from the end-effectors. The mechanism could be driven using electrothermal, electromagnetic or electrostatic actuators. The gripper of Ngo et al. (2018) is similar to the gripper of Nguyen and Wang (2016) except that in the gripper of Ngo et al. (2018), an impact pestle is added to the impact bar and an impact anvil is added to the end-effector. The impact pestle moving with the the impact bar strikes the impact anvil causing vibrations in the end-effector which releases the adhered object from the end-effector. Stavenuiter et al. (2017) have developed an under actuated grasper with self-adaptability. They use a bistable mechanism to change the actuation type of the grasper. Choi et al. (2021) have developed a 3D printed aerial docking mechanism which is based on a bistable gripper type mechanism.

1.3.6 Bistable Compliant Mechanisms

This subsection reviews a few bistable compliant mechanisms. Compliant mechanisms are mechanisms which have flexible bars and flexible joints. These mechanisms are generally one piece mechanisms and transfer energy through deformation and motion ([Chen et al., 2011](#); [Liu et al., 2017](#)). A bistable compliant mechanism is one which has two stable equilibrium states in its range of motion ([Jensen et al., 1999](#); [Masters and Howell, 2003](#)). Generally, bistable compliant mechanisms are of two types. One is the bistable buckled beam ([Vangbo, 1998](#); [Park and Hah, 2008](#); [Cazottes et al., 2009](#)) and the other is bistable curved beam ([Qiu et al., 2004](#); [Palathingal and Ananthasuresh, 2017](#)). A bistable buckled beam is realized by pre-buckling a straight column and then putting transverse loads on the buckled column so as to toggle it between the two stable equilibrium states. A bistable curved beam is one in which the beam is fabricated as the fundamental mode shape of the straight column buckling problem. Bistable compliant mechanisms are generally used in MEMS as micro-relays, micro-actuators, switches, micro-valves and micro-grippers ([Howell et al., 1994](#); [Cazottes et al., 2009](#); [Qiu et al., 2004](#); [Palathingal and Ananthasuresh, 2017, 2016](#)). They are also used for binary actuation in robots ([Hafez et al., 2003](#)) and in many consumer products ([Palathingal and Ananthasuresh, 2018](#)). In subsection 1.3.5, the grippers of [Balakuntala et al. \(2021\)](#); [Chang et al. \(2020\)](#); [Wang et al. \(2020\)](#); [Zhang et al. \(2019a, 2020, 2019b\)](#); [Jitosho et al. \(2019\)](#); [Thomas et al. \(2018\)](#); [Nguyen and Wang \(2016\)](#); [Ngo et al. \(2018\)](#); [Yang and Xu \(2017\)](#); [Welsch et al. \(2018\)](#); [Liu and Xu \(2016\)](#); [Liu et al. \(2016b\)](#); [Xu \(2017\)](#); [Hao et al. \(2017\)](#); [Hao and Kong \(2012\)](#); [Follador et al. \(2015\)](#); [Pluimers et al. \(2012\)](#); [Kim et al. \(2010\)](#); [Zimmer et al. \(2020\)](#) are examples of bistable compliant mechanisms. Bistable compliant mechanisms are also used for micromechanical non-volatile memory ([Charlot et al., 2008](#); [Roodenburg et al., 2009](#)) for morphing and aerospace applications ([Diaconu et al., 2007](#); [Daynes et al., 2008](#); [Pontecorvo et al., 2013](#)), and for energy harvesting ([Cottone et al., 2012](#); [Liu et al., 2013](#); [Andò et al., 2014](#)). The next paragraph briefly looks into the actuation techniques of some of these bistable compliant mechanisms.

[Huang and Yang \(2012\)](#) use a V-beam actuator to drive a MEMS push-on-push-off bistable compliant device. The V-beam actuator used is a thermal actuator. The bistable device comprises a lever and two curved beams. [Sarojini et al. \(2016\)](#) have developed a compliant sit-to-stand easy-chair. The proposed bistable mechanism is a two port bistable mechanism. Port 1 force used to switch from one stable equilibrium state to the other stable equilibrium state is obtained from the weight of the person and port 2 force, used to move back to the first stable equilibrium state, is applied using a lever attached to the armrests. The bistable arch of [Pontecorvo et al. \(2013\)](#) for morphing applications is actuated using shape memory alloy. The unsymmetric composite laminates of [Schultz and Hyer \(2004\)](#) is actuated using piezoelectric MFC actuators.

1.3.7 Adaptive Neuro-Fuzzy Inference System (ANFIS) based Inverse Kinematics of Serial Robots

This subsection reviews the literature relating to ANFIS and its use in solving inverse kinematics of robot. ANFIS is a soft computing technique which is based on Takagi and Sugeno's approach ([Pratihari, 2013](#)). It combines the learning ability of neural networks and reasoning ability of fuzzy systems ([Sivanandam and Deepa, 2007](#)). ANFIS is widely used in the field of robotics to solve inverse kinematics ([Khan, 2021](#)), in aerospace applications for the estimation of short duration forces ([Ramesh et al., 2019](#)) and aerodynamic coefficients ([Nanda et al., 2019](#)), in the field of pharmaceuticals for drug design ([Grosan et al., 2006](#)), in the field of sports economics to forecast the attendance of a sporting event ([Şahin and Erol, 2017](#)), and many others. ANFIS can be used to model any real world complex ill-defined system ([Buragohain and Mahanta, 2008](#)).

It is well-known that the inverse kinematic study of a robot is more complicated than the direct kinematics problem as depending upon the configuration of the robot, the robot may have multiple solutions ([Mittal and Nagrath, 2003](#)). Also, the conventional methods like geometric, algebraic and iterative techniques of solving inverse kinematics problems may not work for each and every kind of robot configuration ([Narayan et al., 2018](#)). Hence, researchers are gradually relying more on neuro-fuzzy systems to solve the inverse kinematics problem in robots in recent years. A neuro-fuzzy system does not require any mathematical model. It just requires a training data set which relates the input and the output of a given problem. Previously, [Narayan and Singla \(2017\)](#) and [Refaai \(2021\)](#) have used ANFIS to solve inverse kinematics of SCARA robot. ANFIS has also been used by [Abbas et al. \(2019\)](#) to solve the inverse kinematics of a Scorbob-ER 5 Plus robotic arm. [Mukhtar et al. \(2021\)](#) have also used ANFIS to solve inverse kinematics of an ambidextrous robot.

1.3.8 Trajectory tracking of joints of RP class of serial manipulators

This subsection reviews the literature relating to trajectory tracking of serial chain robots where the last joint is prismatic. Accurate trajectory tracking is a primary expectation from industrial robots and such tracking requires stable controllers. The design and analysis of such controllers is an important area of study in the field of robot control ([Slotine et al., 1991](#)) to ensure that tracking errors are kept as minimal as possible. Trajectory tracking requires proper tuning of the feedback gains, i.e. determining feedback gains such that a given control objective is satisfied. The experimental methods of tuning PID (Proportional-Integral-Derivative) controllers are found in ([Cohen and Coon, 1953](#); [Ziegler and Nichols, 1993](#)). But given the nonlinear nature of robot manipulators, these tuning methods cannot

be used for satisfactory results. One of the problems with methods for designing feedback gains has been their lack of generality, i.e. their application for a large class of robots. Tuning by designing controller gains has been done in literature using a large number of techniques for robot manipulators ([Abdallah et al., 1991](#); [Craig et al., 1987](#); [Lewis et al., 2003](#); [Sadegh and Horowitz, 1990](#); [Spong et al., 2004](#)) but these control laws use stability methods for determining the feedback gains for stable tracking which require the inertia matrix and/or the Jacobian of the gravity vector to be uniformly bounded. This criteria of uniform boundedness of the inertia matrix is not true for all robot manipulators ([Ghorbel et al., 1998](#)). It can be demonstrated that the inertia matrix of a revolute-prismatic (RP) joint robot is not uniformly bounded ([Ghorbel et al., 1998](#)). The inertia matrix of robots where the final link in the serial chain is prismatic, is not uniformly bounded. Further, there have been tuning rules proposed in literature ([Cervantes and Alvarez-Ramirez, 2001](#)) where the bounds of the Jacobian of the gravity vector are not required, but the bounds of the inertia matrix are still required. Even when the specific case of the RP robot is considered for establishing global stability using PID control ([Kasac et al., 2004, 2006](#)), it has been for regulator problems using the Lasalle's invariance principle, which does not apply to trajectory tracking problems (tracking a desired time-varying trajectory in joint space). Moreover, in several cases dealing with the development of tuning rules, planar manipulators are considered instead of manipulators moving in 3-D space. Even optimization algorithms which have been proposed for tuning feedback gains - ([Ayala and dos Santos Coelho, 2012](#); [Sharma et al., 2014](#)), the Teacher Learning Based Optimization Algorithm (TLBO)([Rao et al., 2011](#)) and the Flower Pollination Optimization Algorithm (FPO)([Yang, 2012](#)), have been used for planar manipulators instead of those moving in 3-D space. Attempts to use complex controllers which incorporate the robot dynamics in the control law, of the form of the Computed Torque controller, will inevitably run into practical problems, given uncertainties in the estimation of the robot parameters. For this reason, industrial robots routinely use the simple linear PID controllers which do not require the incorporation of the robot dynamics into the control law. PID controllers take up about 90 percent or more of the industry share owing to the simplicity of operation, low-cost and easy designing ([Kumar et al., 2011](#)).

1.3.9 Summary of Literature Review

This subsection summarises the literature review that is carried out on the existing external pipe and pole climbing robots, grippers used in these robots along with their actuation, followed by a review on bistable grippers, bistable compliant mechanisms, ANFIS and tracking stability. The takeaways of this literature review are as follows-

- Most of the already existing pipe climbing robots have either wheeled locomotion or inchworm locomotion. It is observed that the robots which are heavy or have a very high payload have inchworm locomotion whereas the lighter robots which can move at higher speeds have wheeled locomotion.
- Almost all the existing pipe climbing robots are made of rigid components except a few that do use some flexible parts along with rigid members. This literature review found only four soft pipe climbing robots, all of which were published after 2019.
- The researchers, over the last two years, have worked mainly with soft pipe climbing robots. The soft pipe climbing robots have a very high payload to weight ratio but one of the major limitations of these kinds of robots is that their overall load-bearing capacity is very low, which makes them unfit for industrial applications.
- From the literature survey, it can be concluded that there are very few pipe climbing robots that can carry NDT equipment along with them.
- The inchworm robots capable of moving bend pipes generally have four degrees of freedom climbing mechanism. However, some robots also use five degrees of freedom climbing mechanism, and these robots exhibit typically two or more gaits like flip-over gait in addition to the inchworm gait.
- The researchers have mainly used electrical actuation for gripping and climbing of the robot. A very few researchers have also used pneumatic actuation for gripping and climbing of the robots.
- The highly manoeuvrable robots use a variety of sensors like cameras, IR sensors, accelerometers, IMU, tactile sensors, strain gauges, FSR sensors, and many more to detect the presence of any obstacles like flanges, turns, bends, T-junctions and also to have position control of the joints and force control of the grippers.
- The bistable grippers are mostly used in the field of biomicromanipulation and are used for gripping soft objects of smaller dimensions. Some bistable grippers are also used for docking of micro aerial vehicles. Most of these bistable grippers, along with bistable compliant grippers and bistable compliant mechanisms used in other applications, are generally actuated using shape memory alloys, dielectric elastomer actuators, through pneumatic means, piezoelectric actuator and electro thermal actuator.
- None of the researchers have used bistable grippers or bistable compliant grippers for pipe climbing applications.

- Most of the researchers have not carried out the dynamic analysis of the climbing mechanism of inchworm type pipe climbing robots.
- Soft computing techniques like adaptive neuro-fuzzy inference system (ANFIS) have also not been used by many researchers for the inverse kinematic study of pipe climbing robots.
- It is observed that for tuning the feedback gains of a control law for stable tracking of the joints of RP class of serial robots, the control laws use stability methods which require the inertia matrix and/or Jacobian of the gravity vector to be uniformly bounded.

1.4 Technical gaps

On the basis of scientific analysis of the literature, the following technical gaps have been identified-

- There are not too many pipe climbing robots which have a payload to weight ratio greater than 0.5 or 1. It may be noted that a pipe climbing robot with a greater payload to weight ratio would enable the robot to carry heavy equipment other than its own weight.
- The grippers in most of the pipe climbing robots consume energy throughout the operation of the robot. Hence, there is a need to develop a gripper for a pipe climbing robot that consumes less energy.
- There is a need to synthesize mechanisms that could ensure automatic actuation of the gripping and climbing mechanisms of the robot with minimal of electronic components so that the developed robot is light and swift.
- Most of the pipe climbing robots reported in literature could climb only straight pipes and not ninety degree bend pipes. Hence, a robot has to be developed that has the capability of climbing ninety degree bend pipes.
- Not many researchers have carried out the dynamic analysis of the climbing mechanism of inchworm type pipe climbing robots. Hence, there is a need to carry out research on the dynamic analysis of such mechanisms.
- The climbing mechanism of an inchworm type pipe climbing robot requires multiple links and hardly any of the researchers before have used soft computing techniques for carrying out analysis of such multi-link mechanisms. Hence, research on soft computing techniques for real time analysis of systems is also to be carried out.

- After developing the robot, there is a need to develop a design procedure, using which the feedback gains of a suitable control law could be tuned to control the path of the robot. The existing methods of tuning generally depend on the bounds of the inertia matrix. Hence, a procedure is needed which is independent of the bounds of the inertia matrix and/or Jacobian of the gravity vector.

1.5 Objective

The objective of the present work is to design and develop a pipe climbing robot by using a compliant bistable gripping mechanism. To accomplish this objective, the following sub-objectives have been identified. They are as follows :-

- Design of the gripping mechanism involving the use of bistable buckled beam, which should ensure that the robot has a payload to weight ratio higher than 0.5
- Design of mechanical drive systems to automate the gripping mechanism.
- Design of climbing mechanism capable of climbing straight vertical pipes and pipes with ninety degree bends.
- Control of the climbing mechanism of the robot.
- Fabrication and testing of the pipe climbing robot.

1.6 Thesis Organisation

The thesis is organized into five chapters. Chapter 1 gives a brief overview of the thesis. This chapter also documents the state of the art in the field of pipe climbing robots and also looks into the grippers in different fields that could be used for pipe climbing applications. The design of the gripper is discussed in chapter 2. Chapter 3 looks into the design aspects of the climbing mechanism that could be integrated with the designed gripper. After the completion of the design process, a pipe climbing robot is developed. The manufacturing processes involved, the electronics integration, mode of operation of the robot and the experiments carried out on the developed pipe climbing robot are documented in chapter 4. Chapter 5 concludes the thesis with a discussion about the work that can be extended from the thesis to be carried out in future.

Chapter 2

Design of a Gripping Mechanism

2.1 Introduction

This chapter presents the design of a novel gripper for pipe or pole climbing robots. The mechanism of the gripper involves the use of a pre-stressed buckled column, also known as bistable buckled beam, which is a type of bistable compliant mechanism. There is a need for research on a new gripping mechanism as an effective gripping mechanism would ensure that the pipe climbing robot has a greater payload. Other than gripping, this chapter also proposes the design of two mechanical drive systems to automate the actuation of the bistable buckled beam. The mechanical design and working of the gripper are presented in section 2.2. This section also discusses about the experimental and numerical determination of the design parameters of the bistable buckled beam. Section 2.3 is about the design of two mechanical drive systems which automate the gripping and ungripping operation of the gripper. One of the drive systems is inspired from camshaft whereas the other mechanism is inspired from Scotch Yoke and beam engine mechanisms.

2.2 Mechanical Design of the Gripper

The isometric view of the three-dimensional (3-D) computer aided design (CAD) model of the gripper is shown in Fig. 2.1. It consists of two plates for clamping the bistable buckled beam. The two plates are clamped using six bolts, three on each side as can be seen in Figs. 2.1 and 2.2. There are four nuts on each bolt. The function of the nuts is to position the plates according to the size of the pipe. A rubber pad is attached at the centre of the beam. A different rubber pad is also attached at the opposite end on the plate. The dummy plate has been used in the design for static balancing. The nuts are fitted in a way that two nuts in each bolt are clamping the plates for the pre-stressed buckled beam and the other two nuts in each bolt are clamping or holding the two plates together at the opposite end.

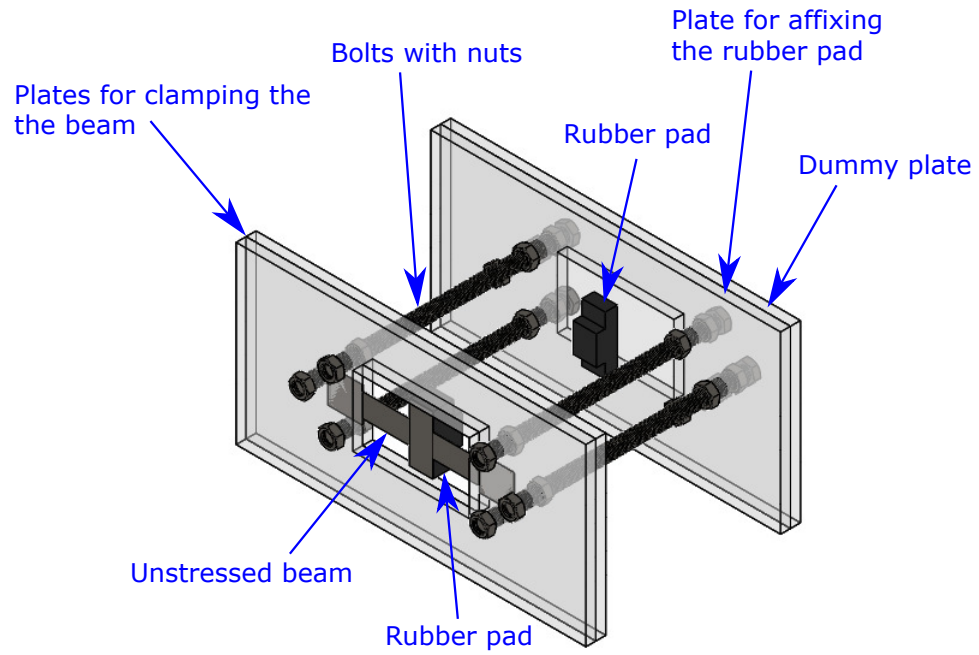


Figure 2.1: Isometric view of the 3-D CAD model of the gripper

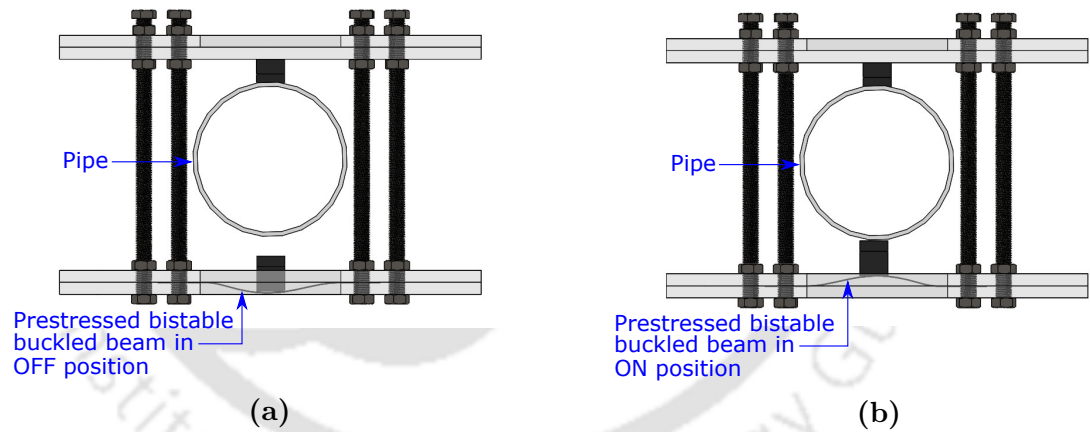


Figure 2.2: Top view of the gripper in (a) ungripped and (b) gripped positions

2.2.1 Working

Fig. 2.2 shows the working of the gripper. The gripper shown in Fig. 2.1 shows the beam or column in unstressed state. It is buckled manually only once in the beginning, during which the nuts are loosened and the beam is stressed along its length till it buckles and then tightening the nuts so that the beam remains in buckled state. Fig. 2.2 shows the top view of the gripper with the bistable buckled beam. The bistable buckled beam can remain in its two stable equilibrium positions without any input of energy. Figs. 2.2a and 2.2b show the two stable

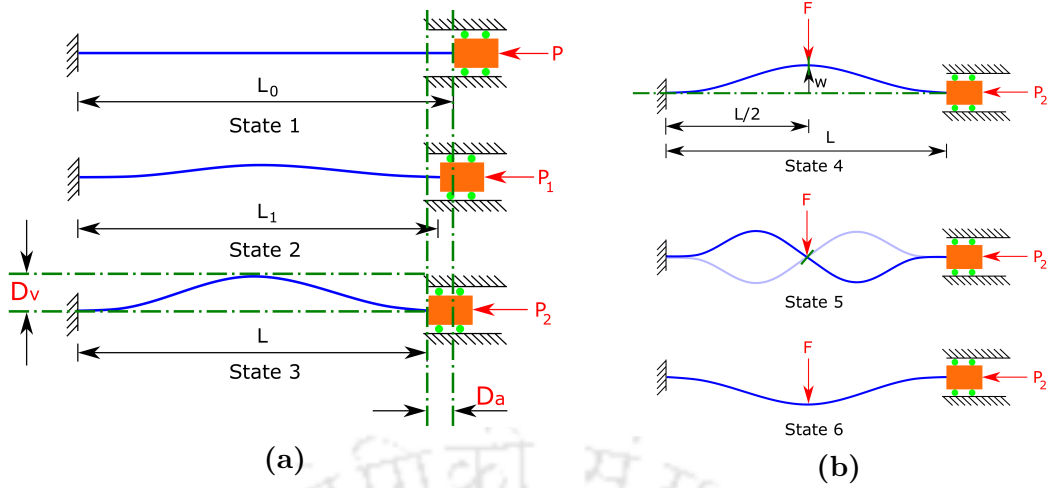


Figure 2.3: (a) Bifurcation buckling process of a straight unstressed column, (b) Snap through buckling process of the buckled beam

equilibrium states of the bistable buckled beam. In the strain energy profile of a bistable buckled beam, there is also an unstable equilibrium position between the two stable equilibrium positions. However, energy or power is required only to actuate the buckled beam from its one stable equilibrium position to its other stable equilibrium position and vice-versa. On putting a transverse load on the bistable buckled beam, the buckled beam snaps through and jumps to its other stable equilibrium state through its unstable equilibrium state. The presented gripper has a one-sided actuation as power is required to actuate the gripper only on one of its sides, as shown in Fig. 2.2 and not on both the sides.

2.2.2 Design Parameters

The two most important design parameters of the gripper are :- 1) vertical displacement of the mid-point of the beam, D_v and 2) the snapping load of the beam when actuated at the mid-point, L_s , as shown in Fig. 2.3. L_s is that value of F at which the snap-through buckling (Simites and Hodges, 2006) sets in. Both D_v and L_s are related to axial displacement, D_a and dimensions of the beam.

The buckling of a column results in an arch (Palathingal and Ananthasuresh, 2017). It is an example of bifurcation buckling (Simites and Hodges, 2006), as shown in Fig. 2.3a. The process of putting transverse load on an as-fabricated arch leads to snap-through buckling (Simites and Hodges, 2006) and the arch moves from one stable equilibrium state to the other, as shown in Fig. 2.3b. Thus, the functioning of bistable buckled beam can be taken as a combination of bifurcation buckling followed by snap-through buckling of the resultant arch, as shown in Fig. 2.3.

The gripping force, F_g exerted by the buckled beam on the pipe, as shown in Fig. 2.2b is equivalent to the normal reaction, N . A greater N would ensure

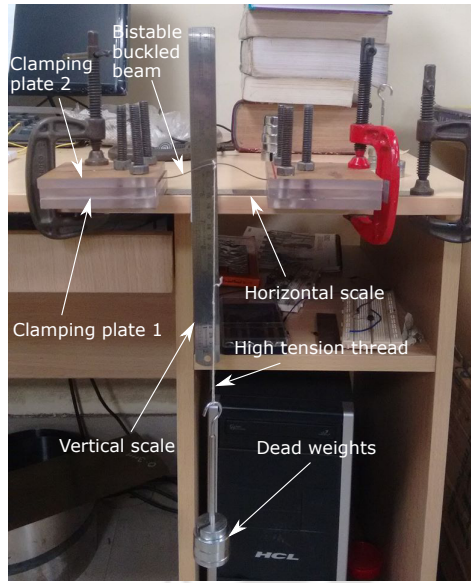
a greater friction force, F_f , which would overcome the weight of the robot, W and hence would help in vertical climbing, $F_f \geq W$. A larger L_s or a switching point (Palathingal and Ananthasuresh, 2017) would give a greater F_g . However, F_g would always remain less than the switch-back point (Palathingal and Ananthasuresh, 2018). If F_g becomes larger than the switch-back point, the buckled beam would switch back to its first stable equilibrium state, as shown in Fig. 2.2a. In a bistable buckled beam, the magnitude of switching and switch-back points are same as L_s (Palathingal and Ananthasuresh, 2018). Hence, F_g is directly depended on L_s .

D_v helps in the assembly of the gripper. The buckled beam in its gripping position, as shown in Fig. 2.2b, doesn't touch the pipe. Rather, while assembling the gripper, it is ensured that bistable buckled beam doesn't reach its second equilibrium state. Only then the bistable buckled beam will apply a force on the pipe as the beam would try to come to its second equilibrium state but obstructed by the pipe. Hence, the gap between the pipe and the bistable buckled beam depends on D_v .

2.2.3 Experimental and Numerical Determination of Design Parameters

This subsection presents the experimental and numerical determination of L_s and D_v with respect to D_a for different dimensions of the beam.

Figure 2.4 shows the experimental set-up for determining the snapping load or the switching point. In the experimental set up, the horizontal scale is used for measuring the axial deflection and the vertical scale is for measuring the vertical deflection. The C clamp at the left end is totally fixed. The C clamp at the extreme right holds the horizontal scale in position. The red coloured C clamp is loosened and the column is given an axial deflection of known values from the right end and then it is clamped with the red coloured C clamp. The clamping plates at the right and left end, which are tightened by nuts and bolts, remained tightened throughout and they ensure that the column buckles with a fixed-fixed boundary condition. For a beam of particular width, D_v corresponding to a given D_a is recorded. Also, for a D_a , L_s is recorded. A high tension thread is attached at the mid-point of the beam. Weights in steps of 50 g are put into the hanger, as shown in Fig. 2.4. The moment the load in the hanger reaches the snapping load, the buckled beam moves to its other stable equilibrium state and L_s is recorded. This experiment is carried out three times. The values of D_v and L_s corresponding to beams of different dimensions and D_a can be found in the Tables of Appendix A for three trials of the experiment. The average values of the three trials are recorded in Tables 2.1, 2.2, 2.3 and 2.4. Tables 2.1 and 2.2 show the variation of D_v with D_a , and Tables 2.3 and 2.4 show the variation of L_s with D_a . In



(a)



(b)



(c)

Figure 2.4: Front view of the set up (a) before snapping, (b) after snapping and (c) top view of the set up before snapping

Tables 2.1 and 2.2, E , A and P correspond to experimental value, numerical value and percentage deviation of numerical values with respect to experimental ones, respectively. The initial length of all the beams is 100 mm. b corresponds to width of the beams.

For numerical determination of the design parameters, the profile of the bistable buckled beam, w , is approximated with the help of mode shapes, obtained by solving the bifurcation buckling eigen value problem. The governing equation of bifurcation buckling problem (Simites and Hodges, 2006) is given as-

$$\frac{d^4 w}{dx^4} + k^2 \frac{d^2 w}{dx^2} = 0 \quad (2.1)$$

where $k^2 = \frac{P}{EI}$, E is the Young's modulus of the beam, I is the minimum second moment of cross-sectional area of the beam, P is the compressive force given along the longitudinal axis of the beam and $w(x)$ is the vertical deflection of the beam.

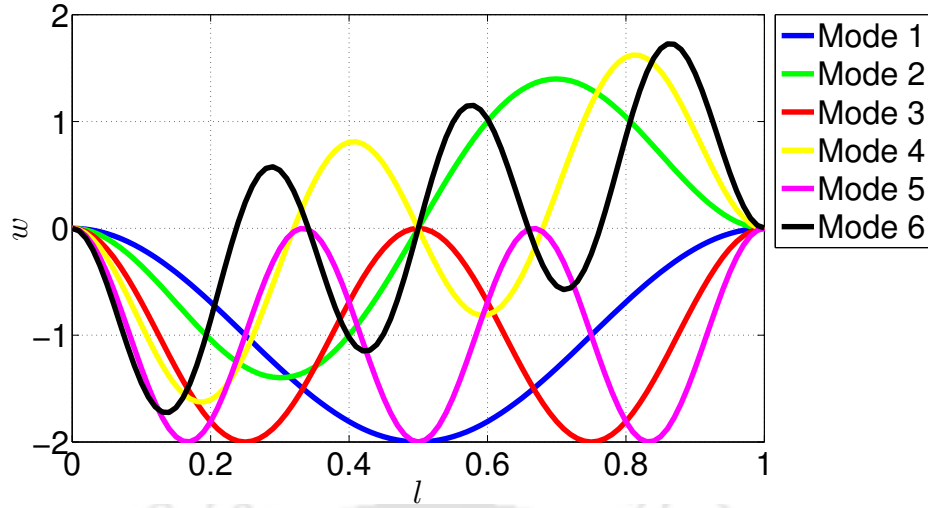


Figure 2.5: Mode shapes of bifurcation buckling problem

The process of bifurcation buckling for a fixed-fixed straight unstressed column is shown in Fig. 2.3a. The eigen functions or mode shapes of Eq. 2.1 can be divided into symmetric and asymmetric mode shapes. The symmetric mode shapes are derived as-

$$w_s = B_1 \left[1 - \cos \frac{2n\pi x}{l} \right], kl = 2n\pi, n = 1, 2, 3, \dots \quad (2.2)$$

where B_1 is any arbitrary constant.

The asymmetric mode shapes are derived as-

$$w_{as} = B_2 \left[\cos kx - 1 + \left(\frac{-\sin kl}{1 - \cos kl} \right) (\sin kx - kx) \right], \quad (2.3)$$

$$kl \approx 2.86\pi, 4.92\pi, 6.94\pi, \dots$$

where B_2 is any arbitrary constant.

Fig. 2.5 shows the first six mode shapes or eigen functions of Eq. 2.1. As can be seen in Fig. 2.5, modes 1, 3 and 5 correspond to the first three symmetric mode shapes, as given by Eq. 2.2 and modes 2, 4 and 6 correspond to the first three asymmetric mode shapes, as given by Eq. 2.3.

There are three energy terms in a bistable buckled beam, subjected to a transverse load. These three energy terms are:- bending energy, E_b and compression energy, E_c which together constitute the strain energy of the beam, E_s and the work potential, W_p which is the negative of the work done by the external forces.

- Bending energy, E_b

$$E_b = \int_0^L \frac{1}{2} EI \left(\frac{d^2 w(x)}{dx^2} \right)^2 dx \quad (2.4)$$

- Compression energy, E_c

$$E_c = \frac{1}{2} EA \epsilon_2^2 L_0 \quad (2.5)$$

where $\epsilon_2 = \frac{s-L_0}{L_0}$. s is the length of the bistable buckled beam. It is given as-

$$s = \int_0^L \sqrt{1 + \left(\frac{dw(x)}{dx} \right)^2} dx \quad (2.6)$$

Considering $\frac{dw(x)}{dx}$ to be very small and by using binomial approximation, Eq. 2.6 can be simplified as-

$$s \simeq L + \frac{1}{2} \int_0^L \left(\frac{dw(x)}{dx} \right)^2 dx \quad (2.7)$$

- Work potential, W_p

$$W_p = -Fw \left(\frac{L}{2} \right) \quad (2.8)$$

The potential energy equation of the bistable buckled beam under the transverse load at $x = L/2$, as shown in Fig. 2.3b, is given as-

$$\pi_1[w] = \int_0^L \frac{1}{2} EI \left(\frac{d^2 w}{dx^2} \right)^2 dx + \frac{1}{2} EA \epsilon_2^2 L_0 - Fw|_{x=\frac{L}{2}} \quad (2.9)$$

The above functional can be solved for w approximately by using Rayleigh-Ritz method. For that, w is approximated as the sum of the mode shapes, obtained in Eqs. 2.2 and 2.3. However, to save computational time and cost, the present work uses the numerical approach by Cazottes et al. (2009) to get an approximate value of w . According to this approach, w is the sum of a general solution, w_g and a particular solution, w_p . First, Eq. 2.9 is solved for w_p without taking into account the E_c term. w_p is approximated by taking the first six mode shapes of Eq. 2.1.

$$w_p = A_1 w_{s1} + A_2 w_{as1} + A_3 w_{s2} + A_4 w_{as2} + A_5 w_{s3} + A_6 w_{as3} \quad (2.10)$$

w_p is substituted in Eq. 2.9 to get the following equation-

$$\pi_p(w) = \int_0^L \frac{1}{2} EI \left(\frac{d^2 w_p}{dx^2} \right)^2 dx - Fw_p \left(\frac{L}{2} \right) \quad (2.11)$$

On extremizing π_p , the following linear algebraic equations are obtained.

$$\frac{\partial \pi_p}{\partial A_1} = 0, \frac{\partial \pi_p}{\partial A_2} = 0, \frac{\partial \pi_p}{\partial A_3} = 0, \frac{\partial \pi_p}{\partial A_4} = 0, \frac{\partial \pi_p}{\partial A_5} = 0, \frac{\partial \pi_p}{\partial A_6} = 0 \quad (2.12)$$

The solved weights $A_1, A_2, A_3, A_4, A_5, A_6$ are put in Eq. 2.10 to get w_p .

For getting w_g , the first two modes of Eq. 2.1 are selected. This is because the bistable buckled beam in the gripper would make use of asymmetric switching using both modes 1 and 2. The expression for w is given as-

$$w = a_1 w_{s1} + a_2 w_{as1} + w_p \quad (2.13)$$

In the above equation, w_p is already known. On substituting w in Eq. 2.10, the following equation is obtained.

$$\pi(w) = \int_0^L \frac{1}{2} EI \left(\frac{d^2 w}{dx^2} \right)^2 dx + \frac{1}{2} EA \epsilon_2^2 L_0 - Fw \left(\frac{L}{2} \right) \quad (2.14)$$

Extremizing Eq. 2.14 gives rise to two nonlinear algebraic equations.

$$\frac{\partial \pi}{\partial a_1} = 0, \frac{\partial \pi}{\partial a_2} = 0 \quad (2.15)$$

The nonlinear algebraic equations in Eq. 2.15 can be solved for a_1 and a_2 by using Newton's method for a system of nonlinear equations (Burden and Faires, 2011). After knowing the values of a_1 and a_2 , w can be obtained and plotted for different values of transverse load, F . Figures 2.6 and 2.7 show the $w - F$ relation and the relation between w and weights a_1, a_2 , respectively for a bistable buckled beam of dimensions of length 100 mm, width 20 mm, thickness 0.4 mm and an axial deflection of 2 mm. Young's modulus E for all the beams is equal to 190 GPa. From Fig. 2.6, $L_s = 38\text{N}$ and $D_v = 8.9\text{mm}$. Many such plots are generated, as shown in Figs. 2.6 to 2.15 to obtain D_v , the values of which are recorded in Tables 2.1 and 2.2. From Tables 2.1 and 2.2, it can be seen that D_v obtained experimentally matches reasonably well with D_v obtained numerically. L_s obtained experimentally should only be considered for further analysis as L_s obtained numerically overestimates the L_s obtained experimentally. Similar observations have also been reported by Hao et al. (2017) and Cazottes et al. (2009) previously. Some of the reasons for this non-agreement are beam fabrication errors as the beam thickness may vary along the length of the beam which would directly impact the stiffness of the beam and hence the snapping load, as stated by Hao et al. (2017). The bistable buckled beam is very thin and hence a very little deviation in thickness would have a large impact in the area moment of inertia and subsequently the stiffness of the beam. Other possible factors may be uncertainty in Young's Modulus of the material and small slope consideration in Eqs. 2.4 and 2.6. Considering all possible nonlinearities would make Eq. 2.9 very difficult to solve. Hence, experimental results are chosen over analytical results for design purpose.

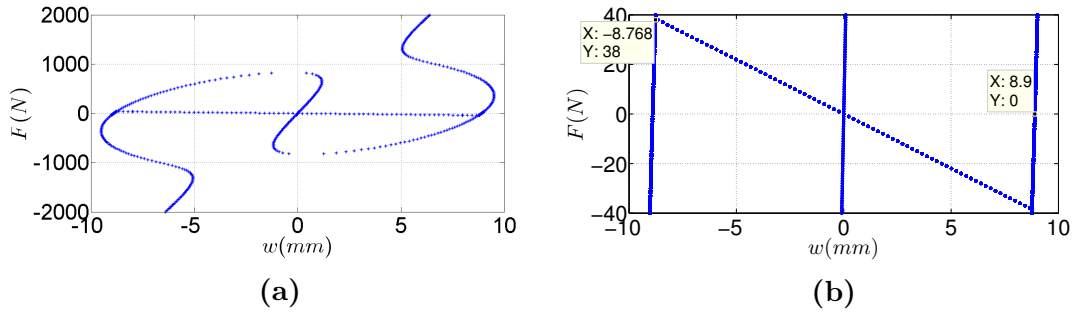


Figure 2.6: $w - F$ relation (a) for full range of force and (b) for force between -40 N and +40 N

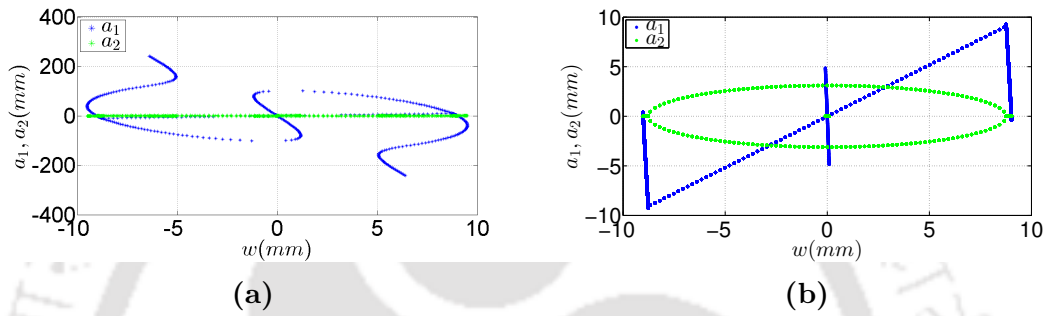


Figure 2.7: Relation between w and weights a_1, a_2 (a) for full range of force and (b) for force between -40 N and +40 N

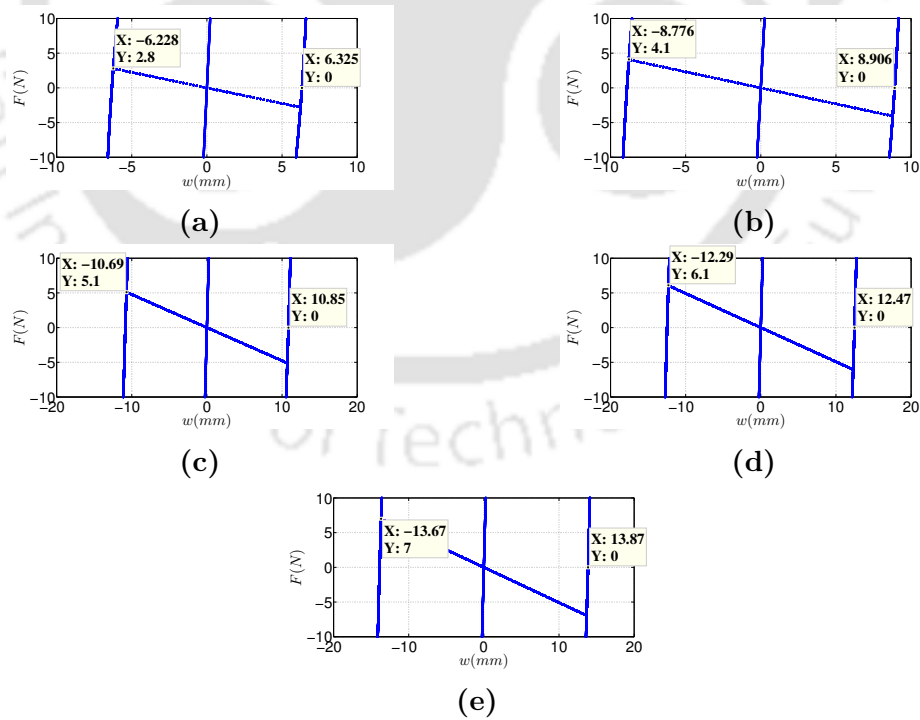


Figure 2.8: $w - F$ relation for a buckled beam of thickness 0.3 mm and width 5 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

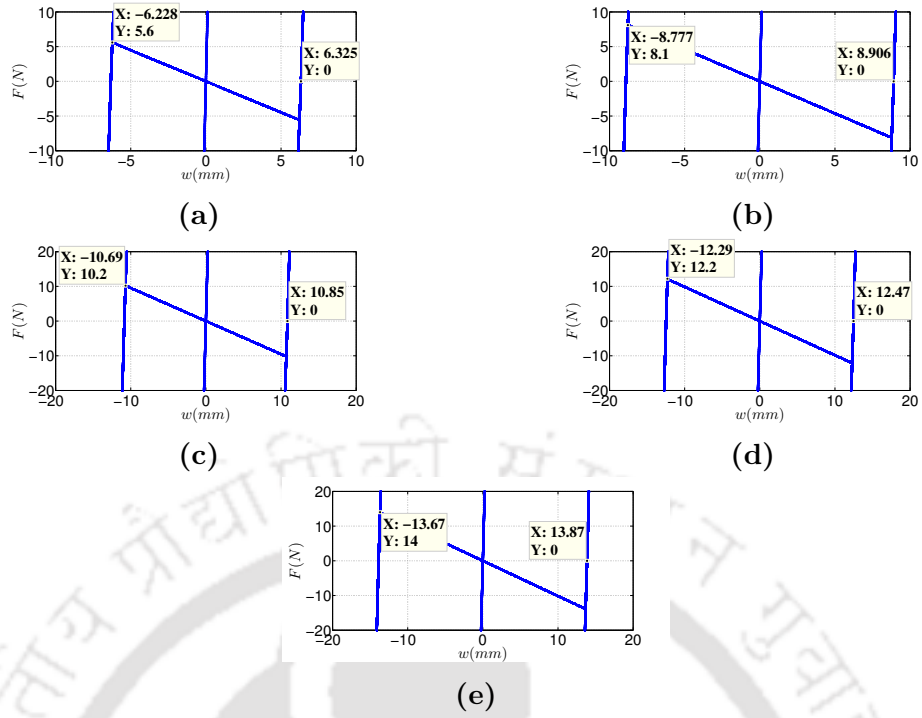


Figure 2.9: $w - F$ relation for a buckled beam of thickness 0.3 mm and width 10 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

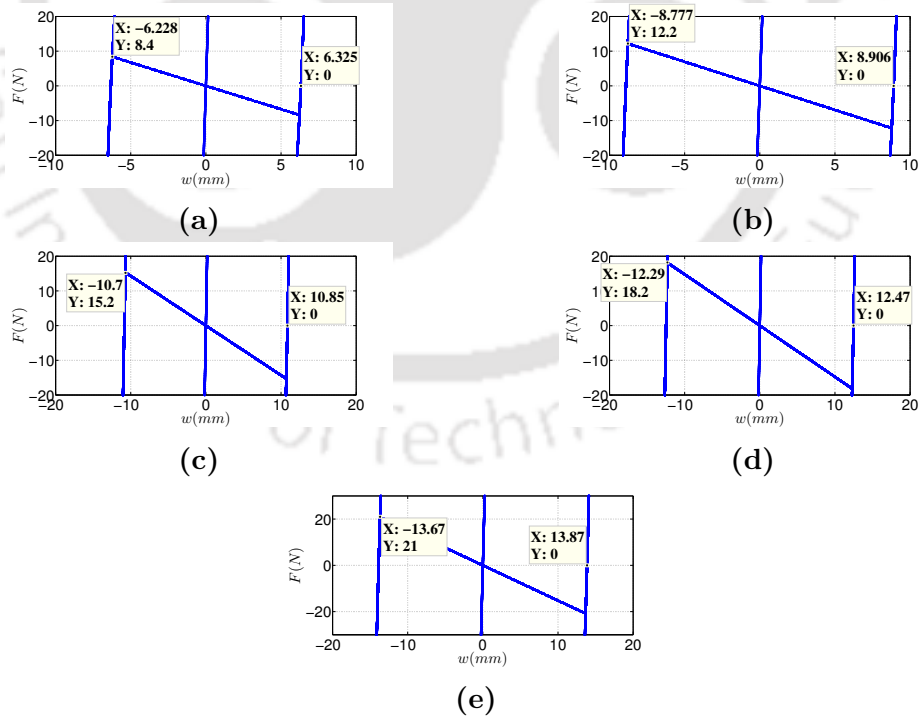


Figure 2.10: $w - F$ relation for a buckled beam of thickness 0.3 mm and width 15 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

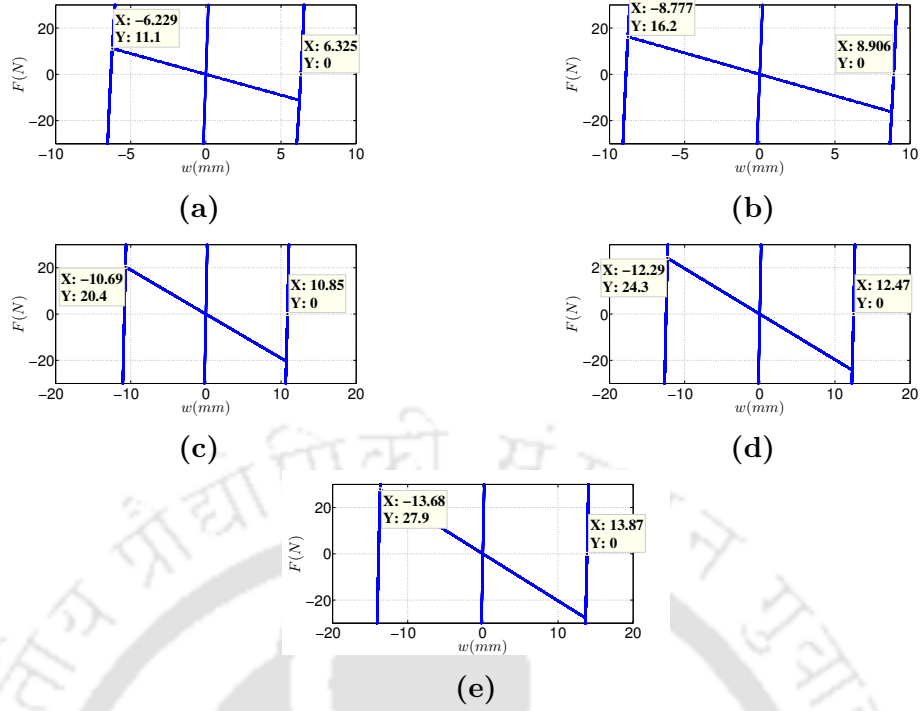


Figure 2.11: $w - F$ relation for a buckled beam of thickness 0.3 mm and width 20 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

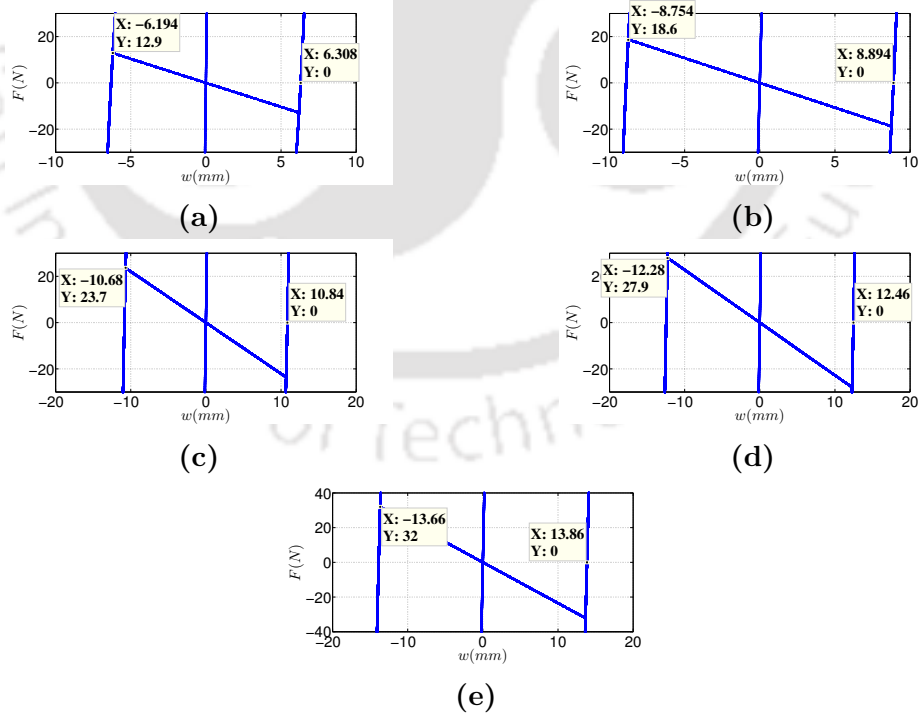


Figure 2.12: $w - F$ relation for a buckled beam of thickness 0.5 mm and width 5 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

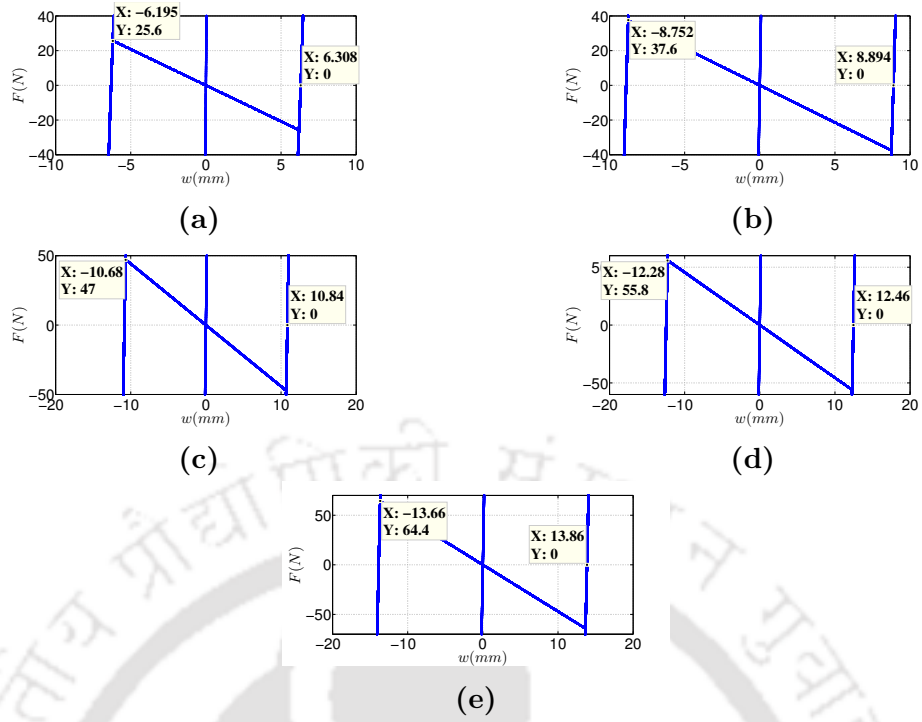


Figure 2.13: $w - F$ relation for a buckled beam of thickness 0.5 mm and width 10 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

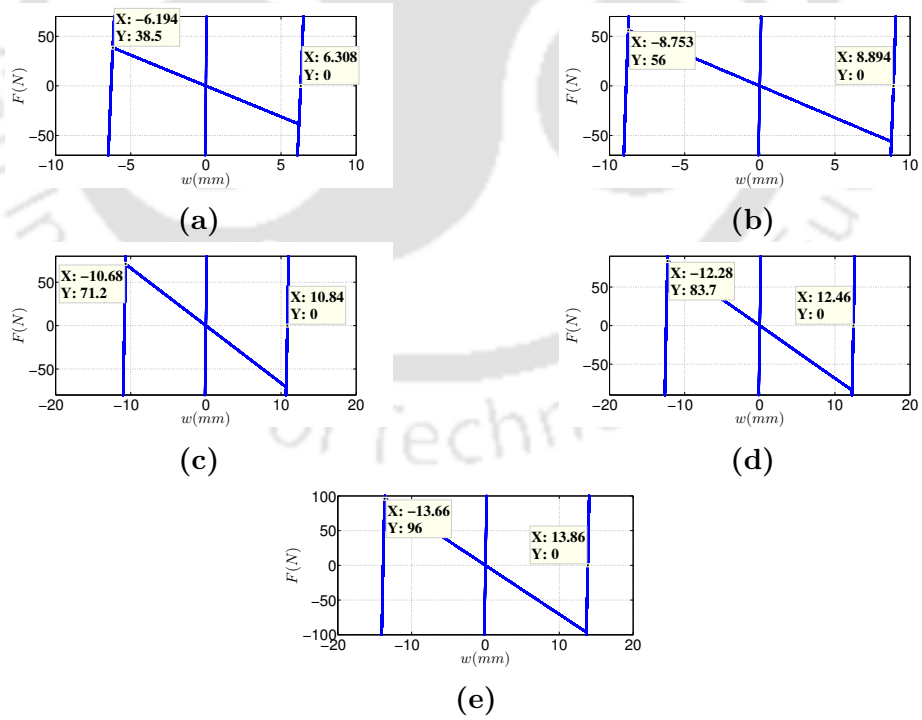


Figure 2.14: $w - F$ relation for a buckled beam of thickness 0.5 mm and width 15 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

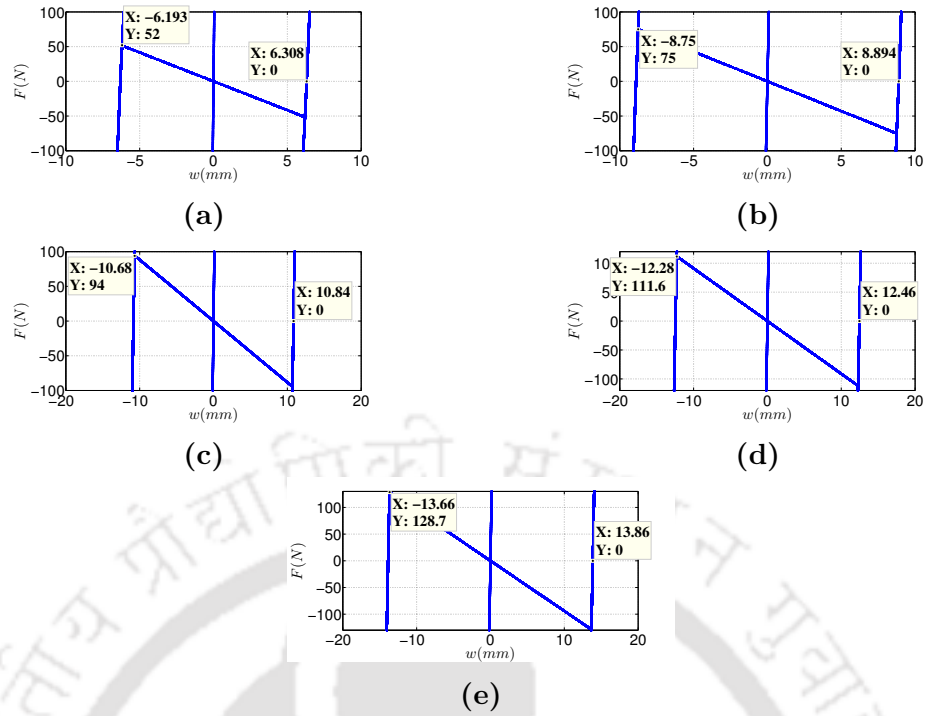


Figure 2.15: $w - F$ relation for a buckled beam of thickness 0.5 mm and width 20 mm with D_a of (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm and (e) 5 mm

Table 2.1: Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness

D_a (mm)	D_v (mm)					A	P
	E						
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm	Average		
1	6.33	6.33	6.83	6.83	6.58	6.325	3.88
2	8.83	9.17	9.17	9.17	9.08	8.906	1.92
3	10.5	10.83	11	11.33	10.92	10.85	0.64
4	12.33	12.5	12.67	13	12.63	12.47	1.27
5	13.5	14	14	14.33	13.96	13.85	0.79

Table 2.2: Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness

D_a (mm)	D_v (mm)					A	P
	E						
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm	Average		
1	6.67	6.33	6.5	5.33	6.21	6.308	1.58
2	9	9.33	9.33	8.5	9.04	8.894	1.62
3	10.83	10.67	11.17	10.5	10.79	10.84	0.46
4	12.5	12.33	12.83	11.83	12.37	12.46	0.73
5	14	13.67	13.67	13.17	13.63	13.86	1.69

Table 2.3: Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	1.14	2.78	5.72	8.18
2	1.64	4.41	8.01	11.94
3	2.29	6.05	10.14	16.19
4	2.94	7.52	11.45	18.48
5	3.76	8.34	13.08	20.11

Table 2.4: Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	8.34	11.45	17.66	20.93
2	11.94	24.53	27.96	34.99
3	16.35	37.77	40.88	45.78
4	22.89	44.31	50.03	51.5
5	27.96	53.46	57.88	60.5

2.3 Design of Mechanical Drive Systems to Automate the Gripping

This section presents two conceptual designs of a mechanical drive system to automate the gripping mechanism. The toggling of the two stable equilibrium

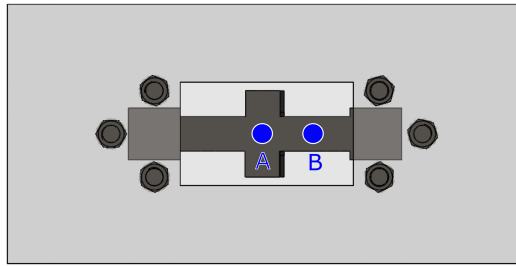


Figure 2.16: Front view of the gripper with the actuation points

states of the bistable buckled beam, can be automated by using two electric motors. The positions of actuation of the bistable buckled beam are shown in Fig. 2.16.

In Fig. 2.16, point A corresponds to the central actuation of the bistable buckled beam and point B corresponds to the offset actuation of the bistable buckled beam. The actuator in point A takes the bistable buckled beam from its ungripped position to the gripped position and the actuator in point B takes the bistable buckled beam from its gripped position to the ungripped position. Two electric motors with translatory mechanisms could be placed in points A and B. However, to keep the gripper compact and the overall weight of the robot low, it is decided to use one motor for each gripper. Hence, a mechanism is designed by which the bistable buckled beam could be actuated alternately (Point A for taking the buckled beam from ungripped to gripped position and point B for taking the buckled beam from gripped to ungripped position), by using a single electric motor. Through simulation and repetitive experiments, it is found that the distance between points A and B should lie between 10 mm and 20 mm.

Two mechanisms are modelled in Solidworks 2019, which could ensure the alternate actuation of the bistable buckled beam. The working of the two models is checked using “animation, basic motion and motion analysis” in Solidworks 2019. The first mechanism shown in Fig. 2.17 has been modelled by combining the Scotch Yoke mechanism and a beam engine inspired mechanism. This mechanism involves only one DC motor and actuates the two positions (A and B) of the bistable buckled beam alternately. It works in a way that when the slider corresponding to the beam engine inspired part of the mechanism goes down, the slider corresponding to the Scotch Yoke goes up. In doing so, the slider corresponding to beam engine inspired part of the mechanism pushes the bistable buckled beam at point A and takes the bistable buckled beam to its gripped position. In the next half of the cycle of the DC motor, the slider corresponding to the beam engine inspired part of the mechanism goes up and the slider corresponding to the Scotch Yoke goes down. In doing so, the slider corresponding to Scotch Yoke strikes the lever, which then pulls the bistable buckled beam through point B and brings back the bistable buckled beam from its gripped to ungripped position, as shown

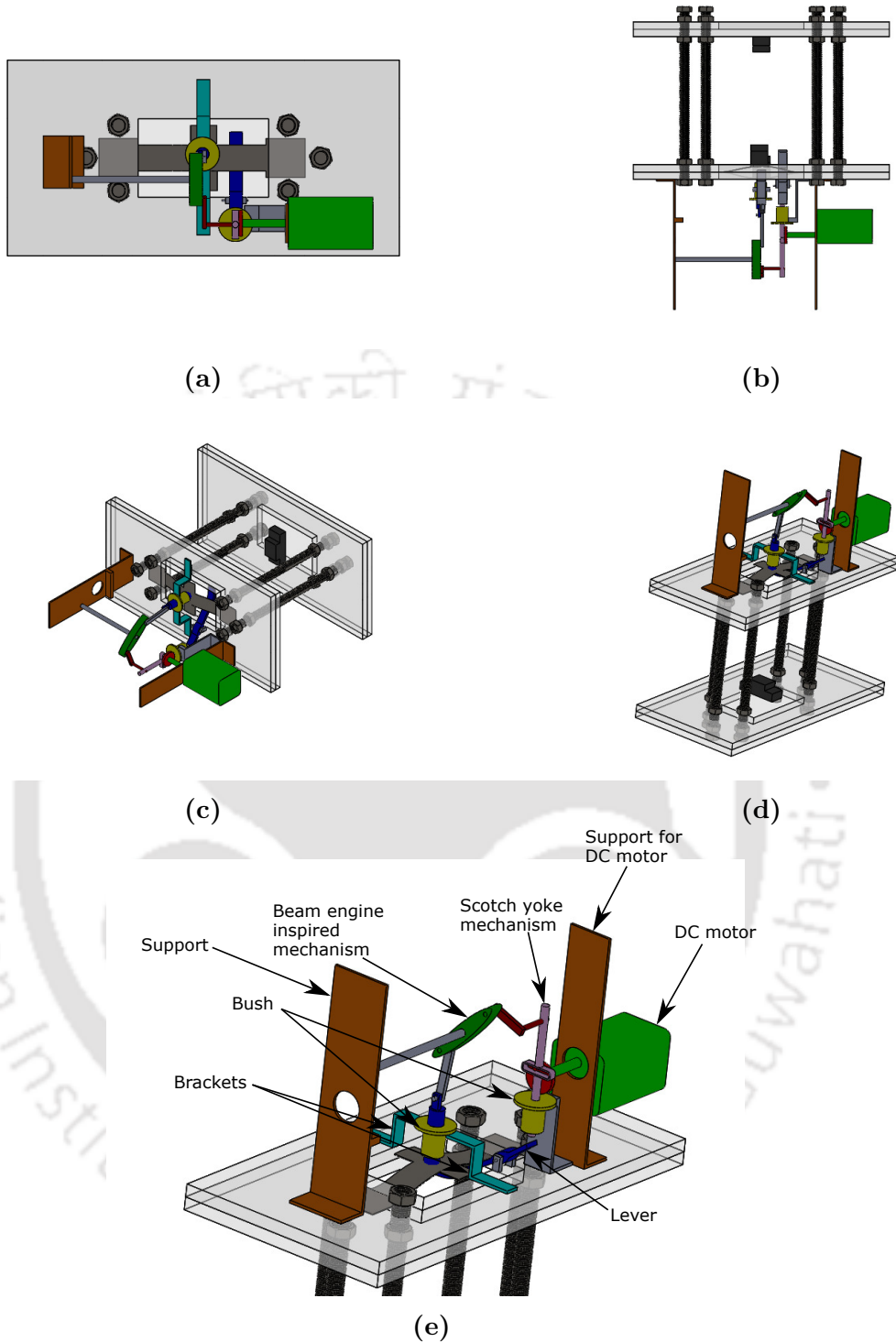


Figure 2.17: (a) Front view, (b) Top view, (c) Isometric view and (d) A different view (e) Close up view of the gripper with Scotch Yoke cum beam engine inspired actuating mechanism

in Fig. 2.17e.

The mechanism shown in Fig. 2.18 involves a camshaft with two cams installed in it. The cam in the central position actuates the point A and the other cam

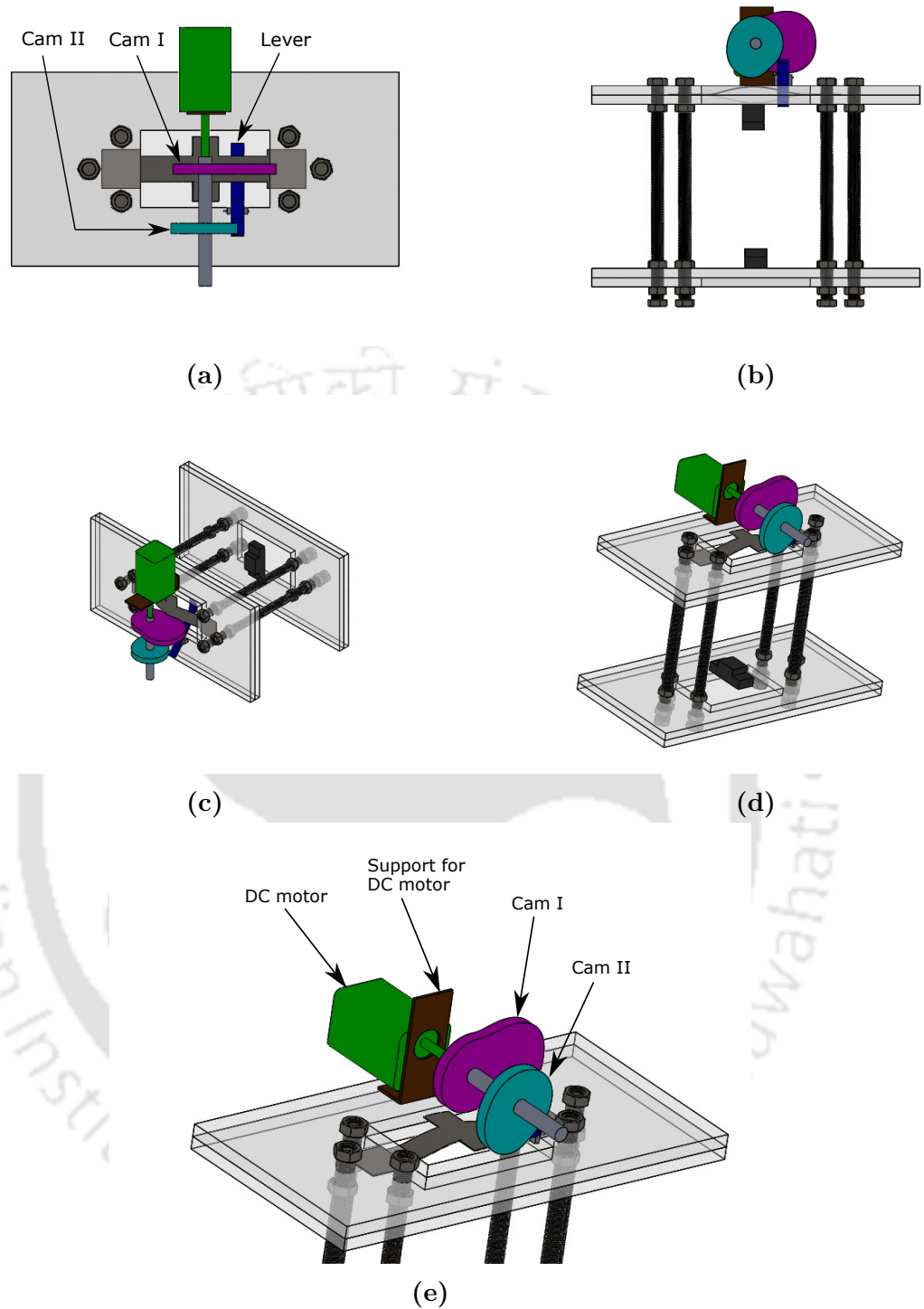


Figure 2.18: (a) Front view, (b) Top view, (c) Isometric view and (d) A different view (e) Close up view of the gripper with cams

actuates the point B of the bistable buckled beam through the lever. The two cams actuate the the points A and B alternately.

2.3.1 Design of Scotch Yoke cum Beam Engine Inspired Mechanism

The proposed Scotch Yoke cum beam engine inspired mechanism has completely constrained one degree of freedom motion. Scotch Yoke mechanism is one of the inversions of double slider crank chain (Uicker et al., 2003) and beam engine is one of the inversions of four bar chain (Singh, 1999). The alternate actuation of the points A and B of the bistable buckled beam is also evident from the plots of Fig. 2.19. From Fig. 2.19, it can be observed that the sliders of both the Scotch Yoke and the beam engine inspired mechanism operate alternately. The slider of the beam engine inspired mechanism actuates the point A and the slider of the Scotch Yoke mechanism actuates the point B in the buckled beam through the lever, as can be seen in Fig. 2.17. Figures 2.19, 2.20 and 2.21 show the displacement versus time, velocity versus time and acceleration versus time plots, respectively of the sliders of Scotch Yoke cum beam engine inspired mechanism. These plots have been obtained through motion analysis option in Solidworks. The dimensions of the proposed mechanism can be found in Fig. 2.22. The distance between the crank center and the pin is 7 mm.

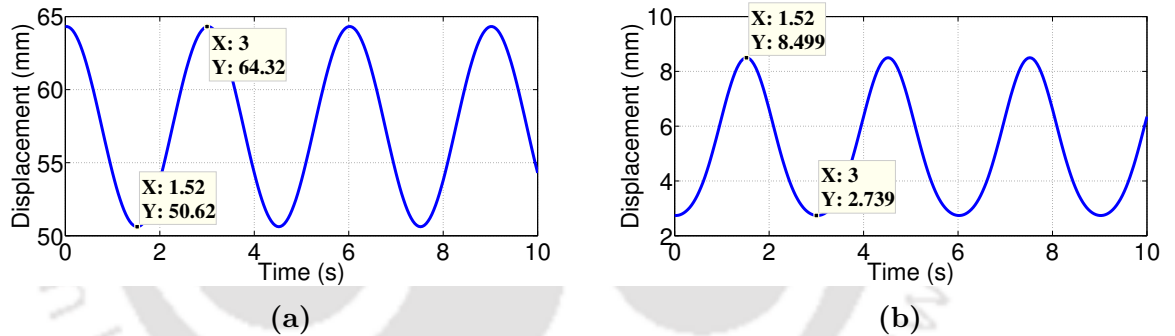


Figure 2.19: Displacement versus time plots of the slider of (a) Scotch Yoke mechanism and (b) beam engine inspired mechanism

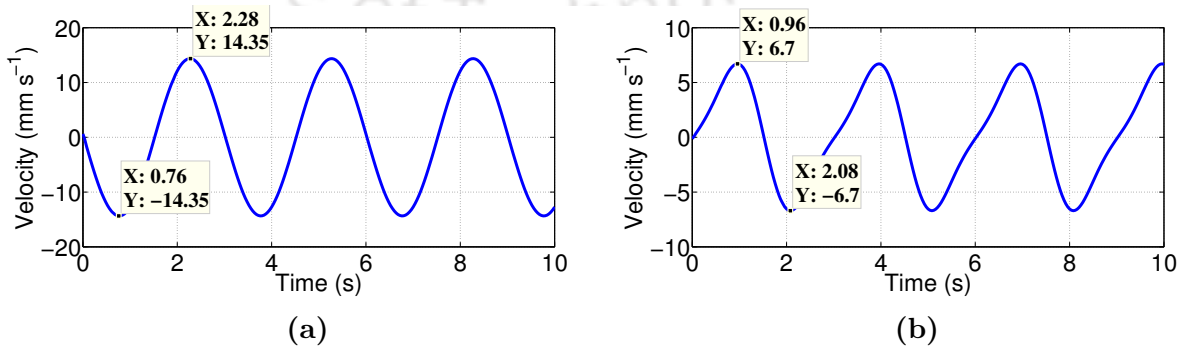


Figure 2.20: Velocity versus time plots of the slider of (a) Scotch Yoke mechanism and (b) beam engine inspired mechanism

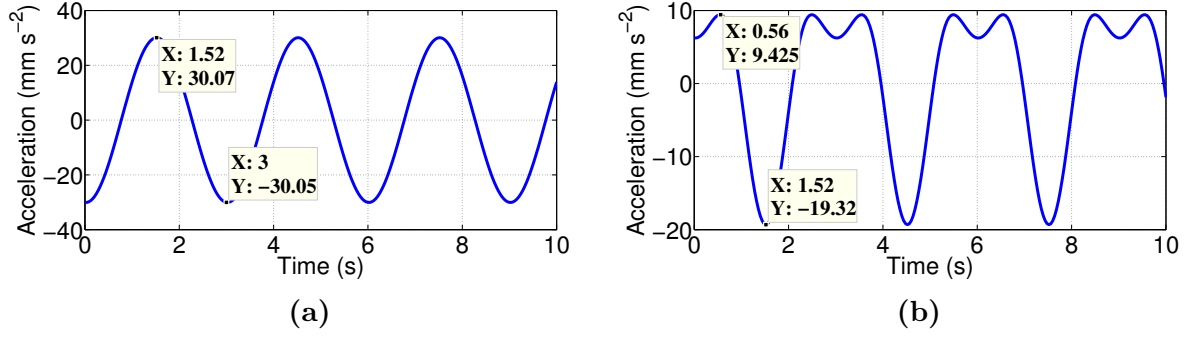


Figure 2.21: Acceleration versus time plots of the slider of (a) Scotch Yoke mechanism and (b) beam engine inspired mechanism

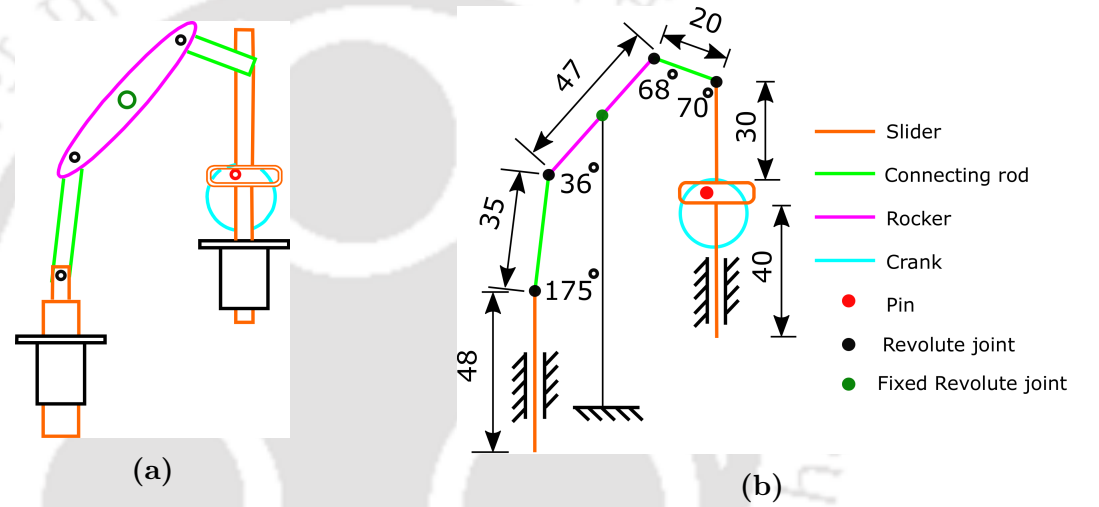


Figure 2.22: (a) 2-D schematic and (b) kinematic diagram of the proposed Scotch Yoke cum beam engine inspired mechanism

2.3.2 Design of Cams

From the results of the subsection 2.2.3, the dimensions of the bistable buckled beam to be used in the gripper are chosen as - $(100 \times 20 \times 0.5) \text{ mm}^3$, subjected to $D_a = 3 \text{ mm}$. These values and the corresponding D_v are considered while deciding the dimensions and displacement diagrams for the cams. The cam profiles have been designed following the procedure given in Uicker et al. (2003).

In Fig. 2.18, the cams have been designed by assuming that cam I mates with a radial reciprocating follower whereas cam II mates with an offset reciprocating follower. The offset distance for cam II is 20 mm, measured horizontally to the right of cam center. It is also assumed that the points A and B of the bistable buckled beam act as knife edge followers in a typical cam follower set-up. The cam profiles, the displacement diagrams and the kinematic coefficients (K.C.) of the two cams in the camshaft are shown in Figs. 2.23 and 2.24. If the camshaft

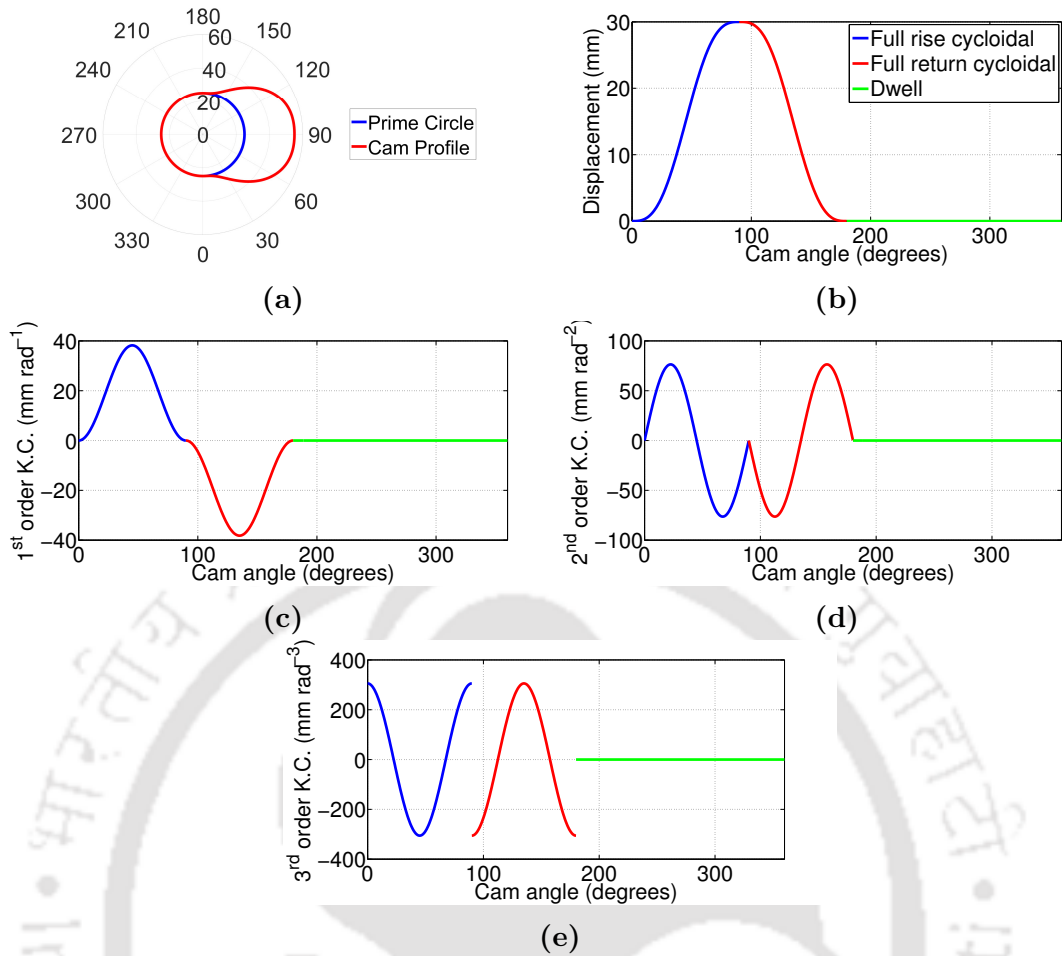


Figure 2.23: (a)Cam profile,(b)Displacement diagram and plots of (c) First order,(d)Second order, (e)Third order kinematic coefficient (K.C.) of cam I

rotates at a constant angular velocity, the first order, the second order and the third order kinematic coefficients are proportional to the velocity, acceleration and jerk of the followers corresponding to the cams (Uicker et al., 2003). For cam I, the prime circle radius is 25 mm and the lift is 30 mm. For the offset cam, the prime circle radius is 25 mm and the lift is 10 mm and the left edge of the lever is 20 mm to the right (offset distance). The camshaft rotates in clockwise direction. The lift of the cams have been decided by taking the help of the data in Tables 2.1 and 2.2. While designing the displacement diagrams of the cams, cycloidal and eighth order polynomial functions have been selected as these functions ensure a continuous velocity and acceleration across the entire interval which makes the jerk finite (Norton and Han, 1999). This is also evident from the kinematic coefficients plots of Figs. 2.23 and 2.24. The shape and dimensions of the lever are decided based on a repetitive experimental analysis. Figure 2.25 shows the final CAD model of the lever.

Since, the mechanism shown in Fig. 2.18 has less number of parts as compared to the mechanism of Fig. 2.17, the mechanism of Fig. 2.18 is selected for the

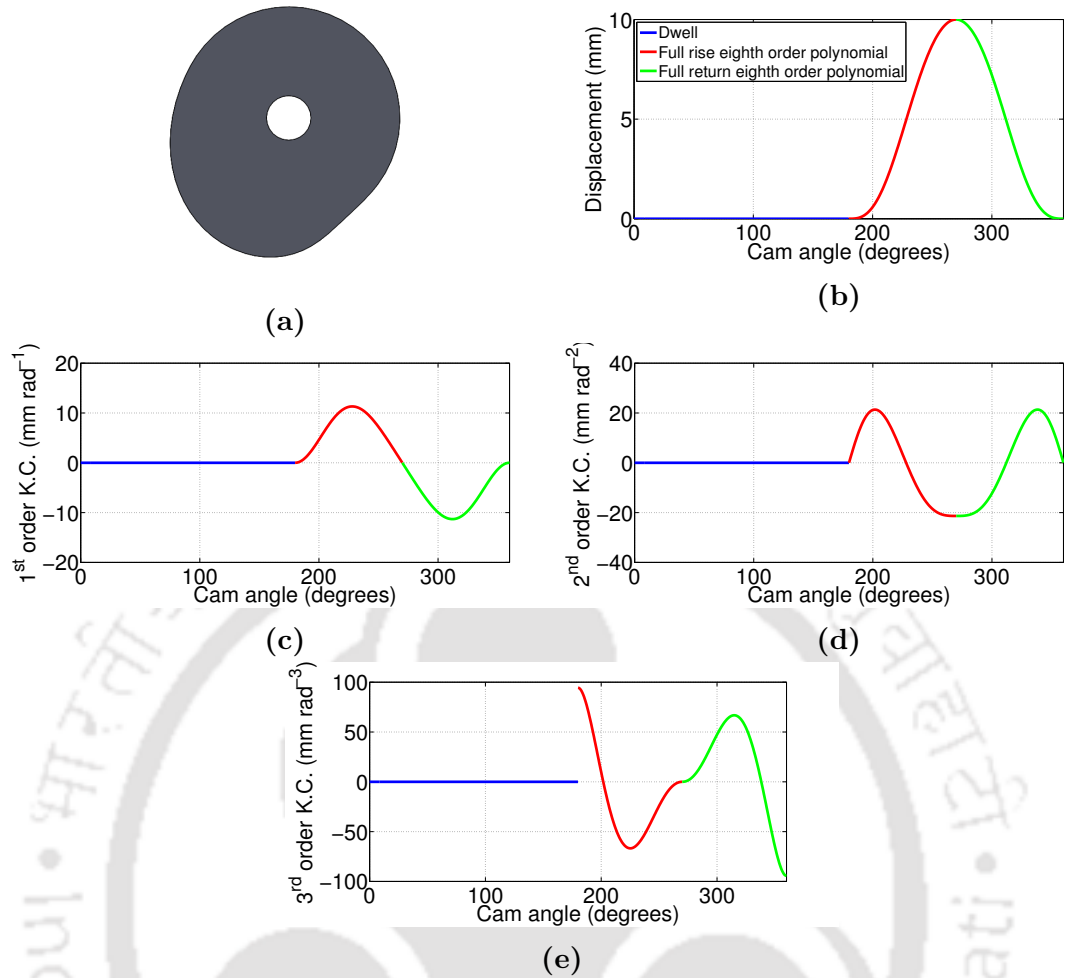


Figure 2.24: (a)Cam profile,(b)Displacement diagram and plots of (c) First order,(d)Second order, (e)Third order kinematic coefficient (K.C.) of cam II



Figure 2.25: Isometric view of a 3-D CAD model of the lever

automatic actuation of the gripping mechanism.

2.4 Summary

In this chapter, the design of the gripper is presented. The gripper makes use of a bistable buckled beam. Both experiments and numerical computations are carried out to find the variation of the vertical deflection of the mid-point of the beam, D_v , and snapping load of the beam when actuated at mid-point, L_s , with axial deflection, D_a . The experimental and numerical results have helped in selecting a beam of the required dimensions. Based on the results, a beam with dimensions $(100 \times 20 \times 0.5) \text{ mm}^3$, subjected to $D_a = 3 \text{ mm}$, is chosen to be used in the gripper as this bistable buckled beam gives the highest snapping load. The snapping load would have been much higher had the chosen beam be subjected to $D_a = 5 \text{ mm}$ but to avoid plastic deformation, the chosen beam is subjected to $D_a = 3 \text{ mm}$. Gripping force is directly depended on snapping load. A maximum gripping force of 45.78 N is obtained when the chosen beam is subjected to $D_a = 3 \text{ mm}$. After designing the gripper and selecting a beam of the required dimensions, two mechanical drive systems are modelled and designed for the automatic actuation of the bistable buckled beam between its two stable equilibrium states. The working of both the mechanisms is checked and verified using Solidworks. While the dimensions of the links in the Scotch Yoke cum beam engine inspired mechanism are obtained from Solidworks, the dimensions of the cams or the cam profiles are designed from their respective displacement diagrams. Out of the two mechanical drive systems, the system involving camshaft with a lever is chosen over the Scotch Yoke cum beam engine inspired mechanism as using camshaft involves lesser number of parts and makes the robot compact and its overall weight low.

Chapter 3

Design of a Climbing Mechanism

3.1 Introduction

This chapter presents two climbing mechanisms which are compatible to the designed gripping mechanism, which is discussed in the previous chapter. One of the climbing mechanisms is the prismatic joint (or lead screw) based which can climb only on straight vertical pipes. The second one involves a novel serial chain revolute-revolute-revolute-prismatic (RRRP) robot with three dimensional (3-D) workspace, which can move both on straight vertical and ninety degree bend pipes. A detailed research on the RRRP climbing mechanism is necessary as not many inchworm type pipe climbing robots have the capability to move on ninety degree bend pipes. The computer aided design (CAD) models of the proposed climbing mechanisms are presented in section 3.2. This section also discusses about the direct kinematics, inverse kinematics, trajectory planning and torque estimation in the joints of the RRRP climbing mechanism. Section 3.3 discusses about a design procedure to tune the feedback gains of a PID controller, used to control the joint displacements of a RRRP serial chain pick and place manipulator, which could be applied to the RRRP climbing mechanism.

3.2 CAD Models of the Climbing Mechanisms

Figure 3.1 shows the climbing of the robot on a straight vertical pipe with two prismatic joints. The model of the robots shown in Figs. 3.1 and 3.2 have an inchworm type locomotion. The inchworm type locomotion has been explained with the help of Fig. 1.1 in section 1.2. The linear translation in Fig. 1.1 has been shown by a prismatic joint in Fig. 3.1. The prismatic joint can be replaced by an extensor contractor pneumatic artificial muscle (Al-Fahaam et al., 2018) or a stepper motor driven lead screw, as shown in Figs. 3.2a and 3.2b, respectively. It may be noted that in Fig. 3.2, the grippers are modelled along with the Scotch Yoke cum beam engine inspired mechanism, as discussed in chapter 2. Also, the two identical grippers are assembled opposite to each other to ensure that the

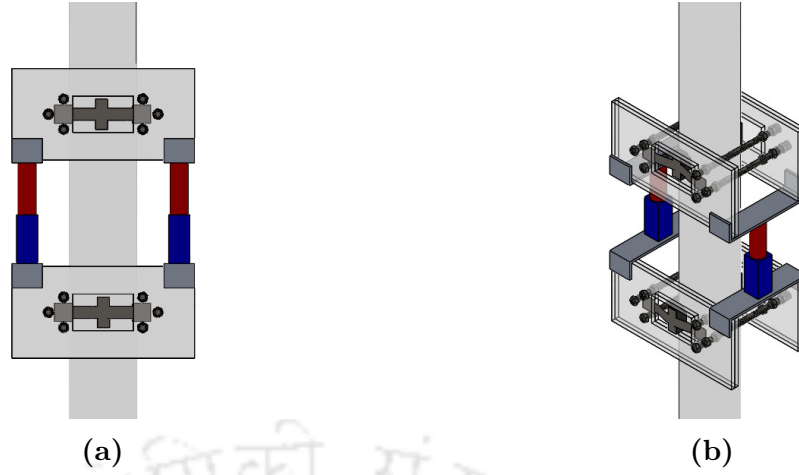


Figure 3.1: CAD model of the climbing mechanism with prismatic joints (a) front view, (b) isometric view

center of gravity lies at the center of the robot. The pipe climbing robots shown in Figs. 3.1 and 3.2 can climb only straight vertical pipes or pipes with bends of very low curvature. Thus, the climbing mechanism based on the prismatic joint cannot climb ninety degree bend pipes as in such cases, it will interfere with the pipe. Furthermore, the bolts in the gripper will also interfere with the pipe. Hence, a minor modification is made in the gripper. The 3-D CAD model of the modified gripper is shown in Fig. 3.3. The modified gripper is precisely the same as the gripper of Fig. 2.1 except that five bolts of nominal length 200 mm are replaced by bolts of nominal length 25 mm. The modified grippers are combined with a serial chain revolute-revolute-revolute-prismatic (RRRP) manipulator with 3-D workspace. The modified grippers along with the RRRP climbing mechanism can move both on straight vertical pipes and ninety degree bend pipes, as shown in Figs. 3.4 and 3.5, respectively. As the RRRP climbing mechanism has a 3-D workspace, it can also move on pipes bend at any angle between zero and ninety degree, and also in any direction.

3.3 RRRP Climbing Mechanism

The RRRP climbing mechanism, along with the modified grippers, used for climbing ninety degree bend pipes, also follows an inchworm motion. Referring to Fig. 3.4a, when the lower gripper is in the gripped state and the upper gripper is ungripped, the climbing mechanism is an RRRP serial manipulator, with its end-effector at the tip of link 4. When the upper gripper is in the gripped state and the lower gripper is ungripped, the climbing mechanism is a PRRR serial manipulator, with its end-effector at the tip of link 1. Thus, during the motion of the pipe climbing robot, the climbing mechanism keeps on changing alternately from being an RRRP serial manipulator to a PRRR serial manipulator.

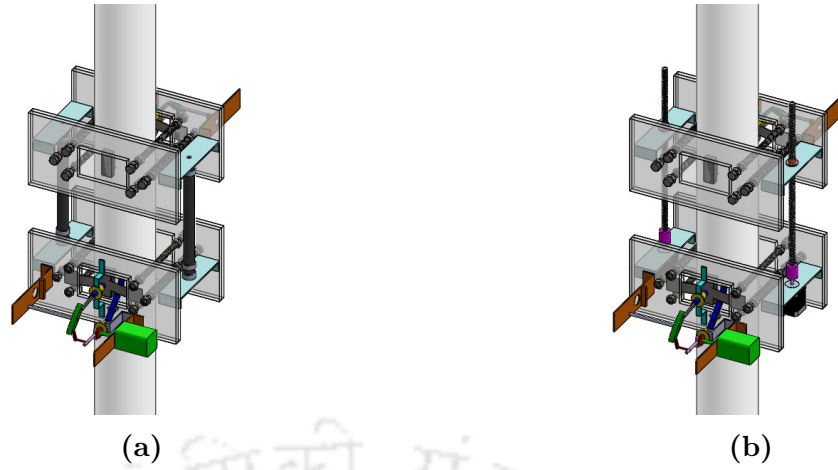


Figure 3.2: Trimetric view of the 3-D CAD model of the pipe climbing robot with (a) extensor contractor pneumatic artificial muscle and (b) stepper motor driven lead screw

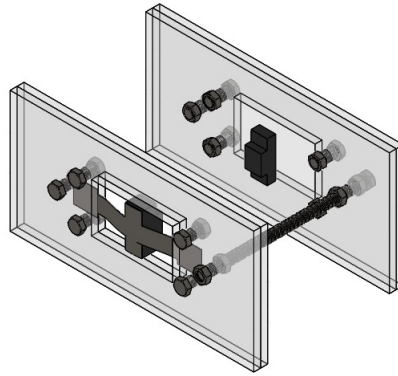


Figure 3.3: Isometric view of the 3-D CAD model of the modified gripper

3.3.1 Direct Kinematics

Figures 3.6a and 3.6b show the schematic diagram of the RRRP and PRRR serial configurations, respectively, of the climbing mechanism. For both the configurations of the climbing mechanism, the coordinate frames have been placed at each of the joints following the Denavit-Hartenberg (D-H) representation of [Fu et al. \(1987\)](#). And using this representation, the four parameters, a_i , α_i , d_i , and θ_i , associated with each link of both the RRRP and PRRR configurations of the climbing mechanism are given in Tables 3.1 and 3.2, respectively. The initial joint angles are given inside square brackets, as given in [Saha \(2014\)](#). The range of motion is also provided for each joint.



Figure 3.4: (a) Front view and (b) Isometric view of RRRP climbing mechanism for straight vertical climbing

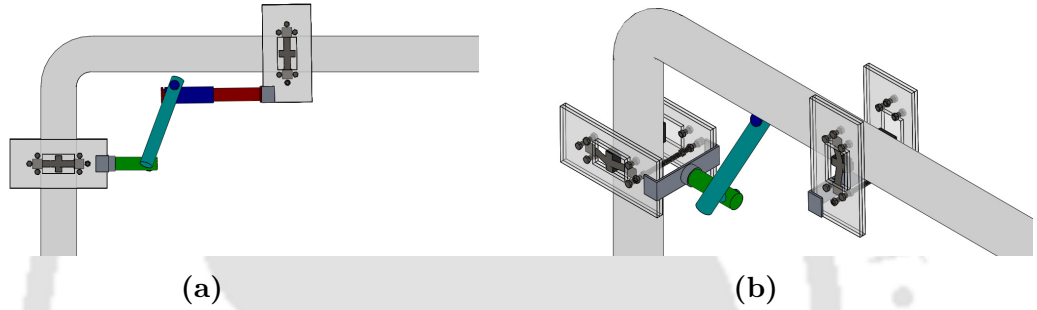


Figure 3.5: (a) Front view and (b) Isometric view of RRRP climbing mechanism for climbing ninety degree bend pipes

Table 3.1: RRRP serial configuration link coordinate parameters

Joint i	θ_i	α_i	a_i	d_i	Joint range
1	$\theta_1 [0^\circ]$	90°	0	$-l_1$	$0^\circ - 90^\circ$
2	$\theta_2 [-90^\circ]$	0°	l_2	0	$-90^\circ - 90^\circ$
3	$\theta_3 [90^\circ]$	90°	0	0	$0^\circ - 180^\circ$
4	0°	0°	0	$d_4 [0.2\text{m}]$	$0.2\text{m} - 0.5\text{m}$

Table 3.2: PRRR serial configuration link coordinate parameters

Joint i	θ_i	α_i	a_i	d_i	Joint range
1	90°	90°	0	$-D_1 [0.2\text{m}]$	$0.2\text{m} - 0.5\text{m}$
2	$\Theta_2 [90^\circ]$	0°	$-L_2$	0	$90^\circ - 180^\circ$
3	$\Theta_3 [-90^\circ]$	90°	0	0	$-90^\circ - -270^\circ$
4	$\Theta_4 [0^\circ]$	0°	0	L_3	$0^\circ - 90^\circ$

3.3.2 Steps For Climbing 90° bend pipes

Table 3.3 shows the steps involved in the climbing of the robot. In Fig. 3.6a, the coordinate system $\{x, y, z\}$ represents the global coordinate frame. The coordinate systems $\{x_0, y_0, z_0\}$ and $\{x_4, y_4, z_4\}$ represent the base coordinate frame and

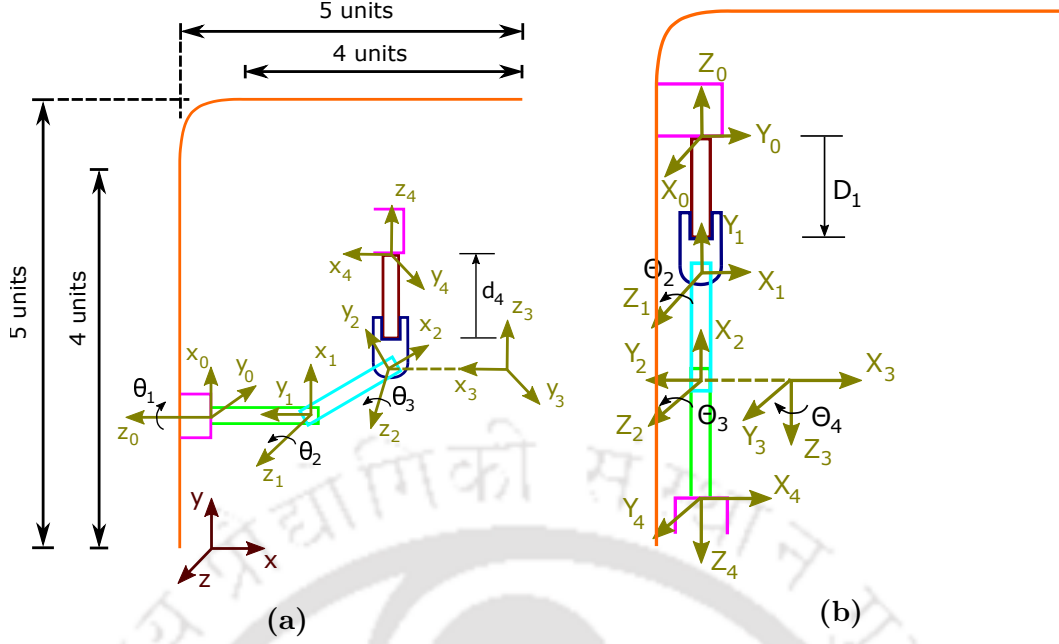


Figure 3.6: Schematic diagram of the climbing mechanism (a) with the lower gripper gripped and the upper gripper ungripped (RRRP serial configuration) and (b) with the upper gripper gripped and the lower gripper ungripped (PRRR serial configuration)

the hand coordinate frame of the RRRP configuration of the climbing mechanism, respectively. The coordinate systems $\{X_0, Y_0, Z_0\}$ and $\{X_4, Y_4, Z_4\}$ represent the base coordinate frame and the hand coordinate frame of the PRRR configuration of the climbing mechanism, respectively. As is evident in Fig. 3.6a, the frame $\{x_0, y_0, z_0\}$ is attached to the lower gripper and the frame $\{x_4, y_4, z_4\}$ is attached to the upper gripper in RRRP configuration. The frame $\{X_0, Y_0, Z_0\}$ is attached to the upper gripper and the frame $\{X_4, Y_4, Z_4\}$ is attached to the lower gripper in PRRR configuration, as can be seen in Fig. 3.6b. The positions of the base frame or the gripper and the hand frame or end-effector at each step are recorded in Table 3.3 for both RRRP and PRRR configurations. The positions of the gripper and end-effector for each configuration are with respect to the global coordinate frame. As is evident from Table 3.3, the climbing mechanism changes its configuration between RRRP and PRRR at each step.

The column vector $(0, 0.5, 0)^T_{\{x,y,z\}}$ denotes the position of a point with respect to global coordinate frame $\{x, y, z\}$. In step 3 of Table 3.3, the gripper is fixed at the point $(0, 0.5, 0)^T_{\{x,y,z\}}$ and the end-effector moves from $(0, 1, 0)^T_{\{x,y,z\}}$ to $(0, 1.5, 0)^T_{\{x,y,z\}}$. This is because before the beginning of the step 3, the gripper in step 2 is ungripped which in step 3 acts as the end-effector position and is moved from point $(0, 1, 0)^T_{\{x,y,z\}}$ to $(0, 1.5, 0)^T_{\{x,y,z\}}$. Likewise, in step 5, the gripper is at position $(0, 1, 0)^T_{\{x,y,z\}}$ and the end-effector is moved from $(0, 1.5, 0)^T_{\{x,y,z\}}$ to $(0, 2, 0)^T_{\{x,y,z\}}$. Same kind of motion is executed by the RRRP configuration in steps 1, 3, 5, 7 and so on till step 13 and this kind of motion can be des-

Table 3.3: Steps involved in climbing

Steps	Positions with respect to $\{\mathbf{x}, \mathbf{y}, \mathbf{z}\}$		Configuration	Motion type
	Base frame/Gripper	Hand frame/End-effector		
1	(0,0,0)	(0,1,0)	RRRP	I
2	(0,1,0)	(0,0.5,0)	PRRR	i
3	(0,0.5,0)	(0,1.5,0)	RRRP	I
4	(0,1.5,0)	(0,1,0)	PRRR	i
5	(0,1,0)	(0,2,0)	RRRP	I
6	(0,2,0)	(0,1.5,0)	PRRR	i
7	(0,1.5,0)	(0,2.5,0)	RRRP	I
8	(0,2.5,0)	(0,2,0)	PRRR	i
9	(0,2,0)	(0,3,0)	RRRP	I
10	(0,3,0)	(0,2.5,0)	PRRR	i
11	(0,2.5,0)	(0,3.5,0)	RRRP	I
12	(0,3.5,0)	(0,3,0)	PRRR	i
13	(0,3,0)	(0,4,0)	RRRP	I
14	(0,4,0)	(0,3.5,0)	PRRR	i
15	(0,3.5,0)	(1,5,0)	RRRP	II
16	(1,5,0)	(0,4,0)	PRRR	ii
17	(0,4,0)	(1.5,5,0)	RRRP	III
18	(1.5,5,0)	(0.5,4.5,0)	PRRR	iii
19	(0.5,4.5,0)	(2,5,0)	RRRP	IV
20	(2,5,0)	(1,5,0)	PRRR	iv
21	(1,5,0)	(2.1,5,0)	RRRP	V
22	(2.1,5,0)	(1.5,5,0)	PRRR	v
23	(1.5,5,0)	(2.6,5,0)	RRRP	VI
24	(2.6,5,0)	(2,5,0)	PRRR	v
25	(2,5,0)	(3.1,5,0)	RRRP	VI
26	(3.1,5,0)	(2.5,5,0)	PRRR	v
27	(2.5,5,0)	(3.6,5,0)	RRRP	VI
28	(3.6,5,0)	(3,5,0)	PRRR	v
29	(3,5,0)	(4.1,5,0)	RRRP	VI
30	(4.1,5,0)	(3.5,5,0)	PRRR	v
31	(3.5,5,0)	(4.6,5,0)	RRRP	VI

ignated as type-I motion, as can be seen in Table 3.3. In type-I motion, the RRRP configuration of the climbing mechanism moves the end-effector from points $(0.5, 0, 0)_{\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}}^T$ to $(1, 0, 0)_{\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}}^T$ in every step. In type-II motion or step 15, the gripper is at point $(0, 3.5, 0)_{\{\mathbf{x}, \mathbf{y}, \mathbf{z}\}}^T$ and the end-effector is moved from $(0.5, 0, 0)_{\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}}^T$ to $(1.5, 0, -1)_{\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}}^T$. In type-III motion, the end-effector is moved from $(1, 0, -1)_{\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}}^T$ to $(1, 0, -1.5)_{\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}}^T$. The orientation of the base frame in types I, II and III motion are shown in Fig. 3.7a. In type-IV motion, due to the position of the gripper, the base frame $\{\mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0\}$ gets rotated counter clockwise about the $\mathbf{y}_0$ axis by an angle of 45° as shown in Fig. 3.7b. The end-effector positions are obtained with respect to the rotated base frame by multiplying the positions with the transformation matrix. For the present case, the transformation matrix is derived following the procedure given in Sadd (2009) and is denoted by the matrix $[Q_y]$. $[Q_y]$ is given as-

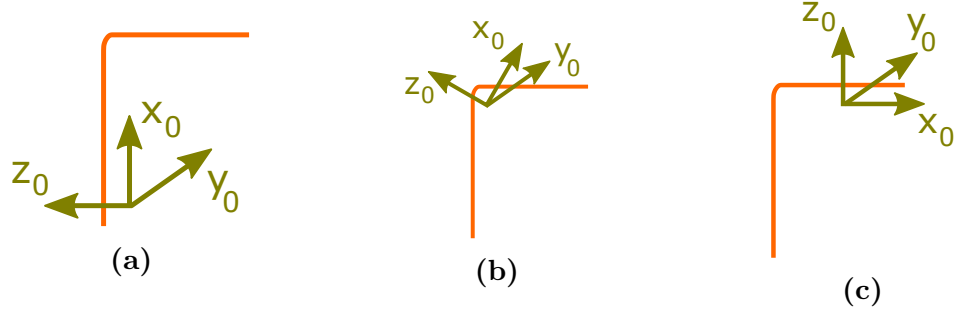


Figure 3.7: Orientation of the base frame of RRRP configuration for types (a) I, II, and III; (b) IV and, (c) V, and VI motions

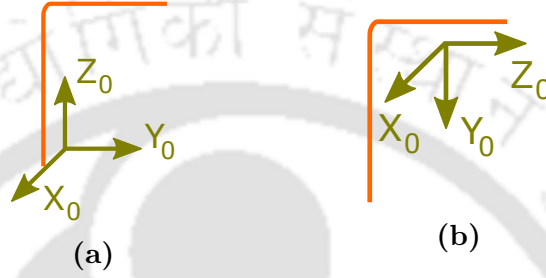


Figure 3.8: Orientation of the base frame of PRRR configuration for types (a) i, and, (b) ii, iii, iv, and v motions

$$[Q_y] = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \quad (3.1)$$

With the rotated base frame as the gripper, the end-effector is moved from $(1.0607, 0, -0.3536)^T_{\{x_0, y_0, z_0\}}$ to $(1.4142, 0, -0.7071)^T_{\{x_0, y_0, z_0\}}$. In type-V motion, the orientation of the base frame is as shown in Fig. 3.7c. The gripper is at position $(1, 5, 0)^T_{\{x, y, z\}}$ and the end-effector is moved from $(1, 0, 0)^T_{\{x_0, y_0, z_0\}}$ to $(1.1, 0, 0)^T_{\{x_0, y_0, z_0\}}$. In type-VI motion, the end-effector is moved from $(0.6, 0, 0)^T_{\{x_0, y_0, z_0\}}$ to $(1.1, 0, 0)^T_{\{x_0, y_0, z_0\}}$.

In step 2 of Table 3.3, the gripper is fixed at $(0, 1, 0)^T_{\{x, y, z\}}$ and the PRRR configuration pulls the end-effector from $(0, 0, 0)^T_{\{x, y, z\}}$ to $(0, 0.5, 0)^T_{\{x, y, z\}}$. In the local base frame of the PRRR configuration, the end-effector is moved from $(0, 0, -1)^T_{\{x_0, y_0, z_0\}}$ to $(0, 0, -0.5)^T_{\{x_0, y_0, z_0\}}$. Same type of motion is executed by the PRRR configuration till step 14 and this type of motion is classified as type-i motion, as can be seen in Table 3.3. The orientation of the gripper for different types of motion of PRRR configuration is shown in Fig. 3.8. In type-ii motion, the gripper is at position $(1, 5, 0)^T_{\{x, y, z\}}$ and the end-effector is moved from $(0, 1.5, -1)^T_{\{x_0, y_0, z_0\}}$ to $(0, 1, -1)^T_{\{x_0, y_0, z_0\}}$. In type-iii motion, the end-effector is moved from $(0, 1, -1.5)^T_{\{x_0, y_0, z_0\}}$ to $(0, 0.5, -1)^T_{\{x_0, y_0, z_0\}}$. The end-effector is moved from $(0, 0.5, -1.5)^T_{\{x_0, y_0, z_0\}}$ to $(0, 0, -1)^T_{\{x_0, y_0, z_0\}}$ and from

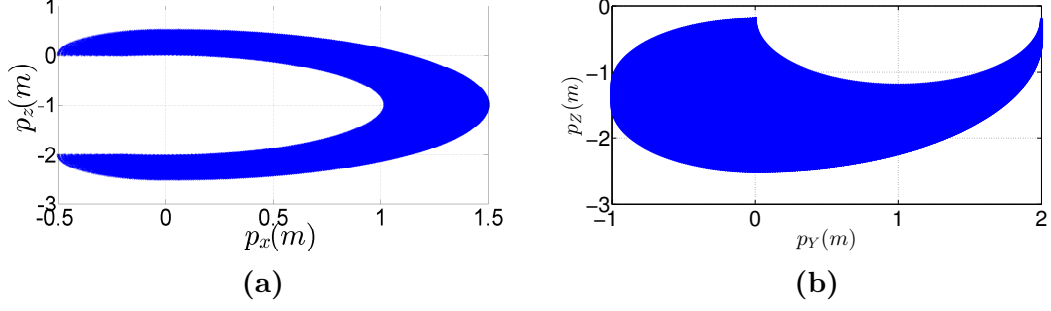


Figure 3.9: Workspaces of (a) RRRP and (b) PRRR configurations of the climbing mechanism

$(0, 0, -1.1)^T_{\{X_0, Y_0, Z_0\}}$ to $(0, 0, -0.6)^T_{\{X_0, Y_0, Z_0\}}$ in types iv and v motions, respectively. In types ii, iii, iv, and v motions, the base frame $\{X_0, Y_0, Z_0\}$ gets rotated clockwise about the X_0 axis by an angle of 90° as shown in Fig. 3.8b. The end-effector positions are obtained with respect to the rotated base frame by multiplying the positions with the transformation matrix, $[Q_x]$. $[Q_x]$ is given as-

$$[Q_x] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \quad (3.2)$$

The workspace of the RRRP and PRRR configurations of the climbing mechanism are given in Fig. 3.9. The workspaces have been obtained by making use of Eqs. 3.3 and 3.4, and the algorithms can be found in Appendix B. The end-effector positions corresponding to the RRRP configuration are :- $(0.5, 0, 0)^T_{\{x_0, y_0, z_0\}}$, $(1, 0, 0)^T_{\{x_0, y_0, z_0\}}$, $(1.5, 0, -1)^T_{\{x_0, y_0, z_0\}}$, $(1, 0, -1)^T_{\{x_0, y_0, z_0\}}$, $(1, 0, -1.5)^T_{\{x_0, y_0, z_0\}}$, $(1.0607, 0, -0.3536)^T_{\{x_0, y_0, z_0\}}$, $(1.4142, 0, -0.7071)^T_{\{x_0, y_0, z_0\}}$, $(1.1, 0, 0)^T_{\{x_0, y_0, z_0\}}$ and $(0.6, 0, 0)^T_{\{x_0, y_0, z_0\}}$. All the end-effector positions lie in the workspace except $(1, 0, -1)^T_{\{x_0, y_0, z_0\}}$ which lies very near to the boundary of the reachable workspace of the RRRP configuration, as can be seen in Fig. 3.9a. The end-effector positions corresponding to the PRRR configuration are :- $(0, 0, -1)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 0, -0.5)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 1.5, -1)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 1, -1)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 1, -1.5)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 0.5, -1)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 0.5, -1.5)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 0, -1.1)^T_{\{X_0, Y_0, Z_0\}}$ and $(0, 0, -0.6)^T_{\{X_0, Y_0, Z_0\}}$. All the end-effector positions lie in the workspace except $(0, 1.5, -1)^T_{\{X_0, Y_0, Z_0\}}$, $(0, 1, -1)^T_{\{X_0, Y_0, Z_0\}}$ and $(0, 0.5, -1)^T_{\{X_0, Y_0, Z_0\}}$ which, like in the previous case, lie very near to the boundary of the reachable workspace of the PRRR configuration, as can be seen in Fig. 3.9b. The joint angles corresponding to the end-effector positions of both the RRRP and PRRR configurations of the climbing mechanism can be obtained by using inverse kinematics, which is discussed in the next subsection.

3.3.3 Adaptive Neuro-Fuzzy Inference System (ANFIS) based Inverse Kinematics

The joint angles corresponding to the different end-effector positions of both the RRRP and PRRR configurations of the climbing mechanism, are obtained using adaptive neuro-fuzzy inference system, ANFIS. As the pipe climbing robot moves on a ninety degree bend pipe, as shown in Fig. 3.6, the end-effector of both the RRRP and PRRR configurations of the robot move in a two dimensional (2-D) space. Hence, θ_1 in RRRP configuration and Θ_4 in PRRR configuration are considered to be zero. Since, ANFIS is a multi-input single-output system (Nanda et al., 2016), hence six ANFIS models are designed and checked for the six joint variables, three each for each configuration of the climbing mechanism. The ANFIS models are designed by making use of the inbuilt *anfis* function in MATLAB 2017b. The vectors $\{p_x, p_y, p_z\}$ and $\{p_X, p_Y, p_Z\}$ represent the end-effector positions of the RRRP and PRRR configurations, respectively. The end-effector positions of RRRP and PRRR configurations can be obtained by making use of Eqs. 3.3 and 3.4, respectively.

$$\begin{aligned} p_x &= \cos(\theta_1)(l_2 \cos(\theta_2) + d_4 \sin(\theta_2 + \theta_3)) \\ p_y &= \sin(\theta_1)(l_2 \cos(\theta_2) + d_4 \sin(\theta_2 + \theta_3)) \\ p_z &= -l_1 - d_4 \cos(\theta_2 + \theta_3) + l_2 \sin(\theta_2) \end{aligned} \quad (3.3)$$

$$\begin{aligned} p_X &= 0 \\ p_Y &= -L_2 \cos(\Theta_2) + L_3 \sin(\Theta_2 + \Theta_3) \\ p_Z &= -D_1 - L_3 \cos(\Theta_2 + \Theta_3) - L_2 \sin(\Theta_2) \end{aligned} \quad (3.4)$$

From Fig. 3.9a, a total of 15,059 data points are taken to train the ANFIS models for RRRP configuration. Out of the 15,059 data points, 13,301 points are taken for training and 1,758 points are taken for checking the ANFIS models. The procedure for generating the training data set is given in Algorithm 1 in Appendix B. The data points for checking are extracted out from the prime number places of 15,059 data points. The checking data is used to ensure that the trained ANFIS model does not over fit the data points, which are used for training the ANFIS model (Sivanandam and Deepa, 2007). This ensures that the trained ANFIS model is able to generate satisfactory output for other data points, which are similar but not exactly same as the training data. The data points for training the three ANFIS models corresponding to RRRP configuration are of the form (p_x, p_z, θ_2) , (p_x, p_z, θ_3) and (p_x, p_z, d_4) . A generalized bell-shaped membership function (Jang et al., 2004) is used over other membership functions as better results are obtained with this membership function. Thirty membership functions are used to train the

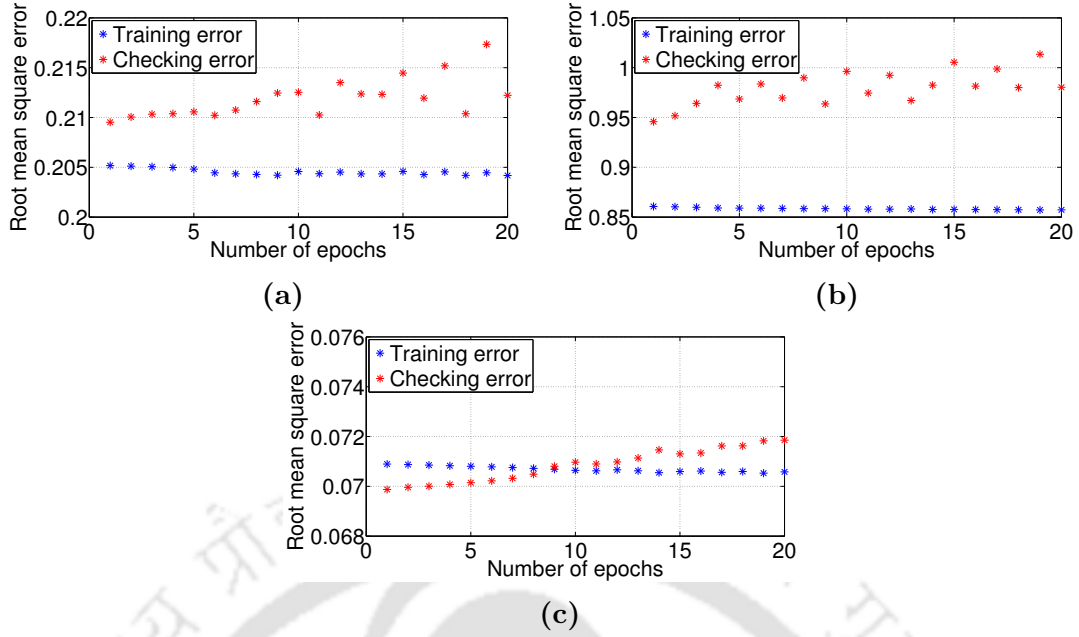


Figure 3.10: Error plots generated during the training of ANFIS models corresponding to outputs (a) θ_2 , (b) θ_3 , and (c) d_4

ANFIS models and the training is carried out for twenty epochs. Hybrid method is used to optimize the parameters associated with the membership functions. The initial fuzzy inference system, FIS, is generated using grid partition and nine hundred fuzzy rules get generated. Though the ANFIS models are trained for twenty epochs, that ANFIS model is considered as the final ANFIS model which gives the minimum checking error. Figure 3.10 shows the root mean square error plots corresponding to training data and checking data for the three ANFIS models. Since, in all the plots of Fig. 3.10, the minimum checking error occurs after first epoch. Hence, the trained ANFIS model after first epoch is considered for the determination of joint angles of the RRRP configuration of the climbing mechanism of the robot.

Table 3.4: Comparison of known data with predicted data for RRRP configuration

Known data			Predicted data		Absolute error	
Joint variables (in degrees, m) (θ_2, θ_3, d_4)	End-effector position (m) (p_x, p_z)	Joint variables (in degrees, m) (θ_2, θ_3, d_4)	End-effector position (m) (p_x, p_z)	Joint variables (in degrees, m) (θ_2, θ_3, d_4)	End-effector position (m) (p_x, p_z)	
(-77, 8, 0.3)	(-0.0551, -2.0819)	(-77.9566, 11.5566, 0.2858)	(-0.0532, -2.0924)	(0.9566, 3.5566, 0.0142)	($1.9 \cdot 10^{-3}$, 0.0105)	
(84, 165, 0.4)	(-0.2689, 0.1379)	(85.9093, 160.9782, 0.3682)	(-0.2673, 0.1420)	(1.9093, 4.0218, 0.0318)	($1.6 \cdot 10^{-3}$, $4.1 \cdot 10^{-3}$)	
(2, 95, 0.45)	(1.446, -0.9103)	(2.7445, 92.5384, 0.47)	(1.4669, -0.9088)	(0.7445, 2.4616, 0.02)	(0.0209, $1.5 \cdot 10^{-3}$)	
(-14, 88, 0.25)	(1.2106, -1.3108)	(-14.8683, 92.0915, 0.3410)	(1.2991, -1.3320)	(0.8683, 4.0915, 0.091)	(0.0885, 0.0212)	
(-57, 67, 0.33)	(0.6019, -2.1637)	(-63.4551, 92.8077, 0.3598)	(0.6233, -2.2082)	(6.4551, 25.8077, 0.0298)	(0.0214, 0.0445)	

Table 3.5: Comparison of known data with predicted data for PRRR configuration

Known data			Predicted data		Absolute error	
Joint variables (in m, degrees) (D_1, Θ_2, Θ_3)	End-effector position (m) (p_x, p_z)	Joint variables (in m, degrees) (D_1, Θ_2, Θ_3)	End-effector position (m) (p_x, p_z)	Joint variables (in m, degrees) (D_1, Θ_2, Θ_3)	End-effector position (m) (p_x, p_z)	
(0.25, 93, -133)	(-0.5905, -2.0147)	(0.3568, 96.5262, -142.1909)	(-0.6016, -2.0492)	(0.1068, 3.5262, 9.1909)	(0.0111, 0.0345)	
(0.42, 152, -248)	(-0.1116, -0.7849)	(0.3247, 151.7765, -244.3436)	(-0.1179, -0.7528)	(0.0953, 0.2235, 3.6564)	($6.3 \cdot 10^{-3}$, 0.0321)	
(0.33, 97, -97)	(0.1219, -2.3225)	(0.3494, 97.5862, -100.6572)	(0.0784, -2.3392)	(0.0194, 0.5862, 3.6572)	(0.0435, 0.0167)	
(0.48, 134, -172)	(0.0790, -1.9874)	(0.2836, 127.0935, -156.9732)	(0.1049, -1.9483)	(0.1964, 6.9065, 15.0268)	(0.0259, 0.0391)	
(0.22, 178, -186)	(0.8602, -1.2452)	(0.2298, 183.9481, -194.4619)	(0.8152, -1.1442)	($9.8 \cdot 10^{-3}$, 5.9481, 8.4619)	(0.045, 0.101)	

After obtaining the trained ANFIS models, they are verified with known data. Table 3.4 compares the joint angles and the end effector positions of the known data with the predicted data. The end-effector positions in the known data are obtained by putting a combination of joint angles, which have not been used to train the ANFIS models, into Eqs. 3.3 and 3.4. After obtaining the exact end-effector positions (p_x, p_y, p_z) , these positions are given as input to the ANFIS models to predict the joint angles. *evalfis* function in MATLAB is used to obtain the output of the ANFIS models. From Table 3.4, it can be observed that ANFIS predicts the joint angles reasonably well. The end-effector positions obtained by putting the predicted joint angles into Eq. 3.3, is almost same as the known end-effector positions. Thus, it can be concluded that the ANFIS models for the RRRP configuration have trained well and can be used to determine the joint for any end-effector position lying in the workspace of RRRP configuration. It is to be noted that the training error can be further reduced by either increasing the number of membership functions or by increasing the training data size. The training of any ANFIS model basically relies on a trade-off between the training error and the computation time (Mukhtar et al., 2021).

The ANFIS models corresponding to the joint angles of PRRR configuration are trained by taking 7,733 data points, out of which 6,752 data points are for training and 981 data points are for checking the ANFIS models. The procedure for generating the training data set for PRRR configuration is given in Algorithm 2 in Appendix B. The data points for training the three ANFIS models corresponding to PRRR configuration are of the form (p_Y, p_Z, D_1) , (p_Y, p_Z, Θ_2) and (p_Y, p_Z, Θ_3) . Thirty generalized bell shaped membership functions are used to train the ANFIS models and the training is carried out for twenty epochs. The parameters associated with the membership functions are optimized using hybrid method. The initial FIS is generated using grid partition and nine hundred fuzzy rules are generated. Figure 3.11 shows the root mean square error plots corresponding to training data and checking data for the three ANFIS models corresponding to PRRR configuration. The minimum checking error in Figs. 3.11a, 3.11b and 3.11c occurs at 20th, 3rd and 15th epochs. Hence, the trained ANFIS models for the determination of D_1 , Θ_2 and Θ_3 are considered after 20th, 3rd and 15th epochs. The trained ANFIS models are verified with known data in Table 3.5. The exact end-effector positions are obtained by putting the joint angles into Eq. 3.4.

From Table 3.5, it can be observed that the error between the actual and predicted results are within reasonable limits and hence, the trained ANFIS models for PRRR configuration can be used to determine the joint angles of any unknown end-effector position lying in the workspace of PRRR configuration.

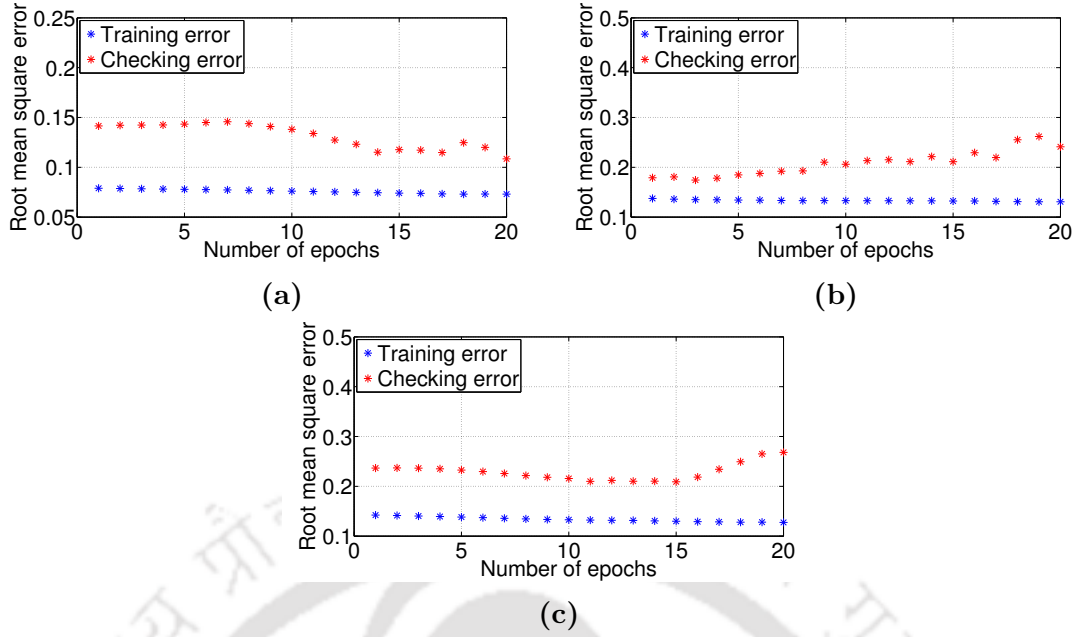


Figure 3.11: Error plots generated during the training of ANFIS models corresponding to outputs (a) D_1 , (b) Θ_2 , and (c) Θ_3

Table 3.6: Determination of joint angles for different motion types of RRRP configuration

Motion type	End-effector positions (p_x, p_z)		Joint angles (θ_2, θ_3, d_4)	
	From	To	From	To
I	(0.5, 0)	(1, 0)	(64.56, 88.08, 0.33)	(44.96, 90.33, 0.45)
II	(0.5, 0)	(1.5, -1)	(64.56, 88.08, 0.33)	(0, 89.86, 0.5)
III	(1, -1)	(1, -1.5)	(-13.99, 219.4, 0.08)	(-27.44, 96.21, 0.33)
IV	(1.0607, -0.3536)	(1.4142, -0.7071)	(31.11, 91.08, 0.34)	(11.72, 89.89, 0.47)
V	(1, 0)	(1.1, 0)	(44.96, 90.33, 0.45)	(42.14, 90.43, 0.49)
VI	(0.6, 0)	(1.1, 0)	(58.37, 93.75, 0.31)	(42.14, 90.43, 0.49)

3.3.4 Determination of Joint Angles for the End-Effector Positions

In this subsection, the joint angles are predicted for the end-effector positions of the different motion types, both for RRRP and PRRR configurations. The motion types of the climbing mechanism are discussed in subsection 3.3.2 and also jotted down in Table 3.3. The joint angles are predicted using ANFIS for the different motion types and are given in Tables 3.6 and 3.7.

The absolute error in the end-effector positions for the different motion types of RRRP configuration is less than 10^{-1} for most cases. It can easily be obtained by putting the predicted joint angles into Eq. 3.3 to obtain the end-effector positions and then subtracting it from the the given end-effector positions. For the point (1, -1) in Table 3.7, the predicted joint angles are out of range. This is because point

Table 3.7: Determination of joint angles for different motion types of PRRR configuration

Motion type	End-effector positions (p_Y, p_Z)		Joint angles (D_1, Θ_2, Θ_3)	
	From	To	From	To
i	(0, -1)	(0, -0.5)	(0.46, 163.86, -238.01)	(0.47, 144.67, -268.12)
ii	(1.5, -1)	(1, -1)	(-13.75, -237.43, 393.7)	(3.7, 314.06, -81.92)
iii	(1, -1.5)	(0.5, -1)	(0.46, 171.53, -174.47)	(-7.95, -27.22, 42.24)
iv	(0.5, -1.5)	(0, -1)	(0.38, 164.99, -191.95)	(0.46, 163.86, -238.01)
v	(0, -1.1)	(0, -0.6)	(0.37, 159.88, -228.16)	(0.39, 174.12, -257.36)

(1,-1) lies outside the workspace of the RRRP configuration and hence ANFIS predicts erroneous result. It is to be noted that for the point (-1,1), though the joint angles are out of range but the absolute error in end-effector position is within 10^{-1} . This anomaly can be avoided by increasing the workspace of the RRRP configuration. ANFIS is good at interpolation and hence it predicts accurate result only when there are sufficient number of data points around the input end-effector position (Jang et al., 2004). Hence, the input end-effector position should not only lie in the workspace but there should also be sufficient number of training data points around the input end-effector position. For PRRR configuration, the absolute error in the end-effector positions for most of the motion types is less than 10^{-1} except for the points (1.5, -1), (1, -1) and (0.5, -1). These exception points lie outside the workspace of the PRRR configuration.

3.3.5 Torque Estimation

After obtaining the joint angles corresponding to the end-effector positions for different motion types, it is desired to estimate the torque at each of the joints of the climbing mechanism. For determining the torque, a trajectory is planned between the *from* and *to* joint positions for different motion types of the climbing mechanism. These joint positions can be found in the last two columns of Tables 3.6 and 3.7. Though the trajectory between any start and end positions can be planned in many different ways, the trajectory in the present work is planned using the method of modified linear function with parabolic blends. The derived equations relating to the modified linear function with parabolic blends can be found in Appendix C. This method is also discussed in subsection 3.4.2. After obtaining the time history of joint displacements between the *from* and *to* positions, the joint displacements are put in Eq. 3.5, which is then solved to obtain the torque at the joints of the robot. The properties of the links of the climbing mechanism are same as given in Table 3.8. While determining the time history of joint displacements, the constant angular acceleration at the blends is taken as 0.1 rad s^{-2} for all the joints and for all the motion types. The start, end and the rest times are taken

as 0 s, 12 s and 1 s, respectively, for all the joints in all the motion types. The trajectories of the joints and the evaluated torque during different motion types are given in Figs. 3.12 to 3.19. The maximum torque acting at the joints can be found from the plots of Figs. 3.12 to 3.19. After finding the maximum torque at the joints, one can use an electric motor of the required torque at the joints. Many a time, due to operational requirements, the torque at the joints may become more than the theoretical value, hence it is always desirable to consider a safety factor of 1.5 or a suitable value depending on the requirement, and choose an electric motor so that the motor doesn't get damaged once it crosses its threshold torque.

In the present case, for a particular configuration of the climbing mechanism, the inertia matrix and the Coriolis vector would remain same for the motion types but the gravity vector would change depending upon the orientation of the base frame. While calculating the torques for motion types I and II, the gravity vector is $:- (-g, 0, 0, 0)^T$. The gravity vector is $:- (-g \cos(45^\circ), 0, -g \sin(45^\circ), 0)^T$ for motion type IV. for motion types V and VI, the gravity vector is $:- (0, 0, -g, 0)^T$. This change in coefficients of the gravity vector is also evident from Figs. 3.7 and 3.8. Similarly, the inertia matrix and the Coriolis vector would remain same for all the motion types of PRRR configuration. For PRRR configuration, the gravity vector is $(-g, 0, 0, 0)^T$ for motion type i. For motion types iv and v, the gravity vector is $:- (0, g, 0, 0)^T$.

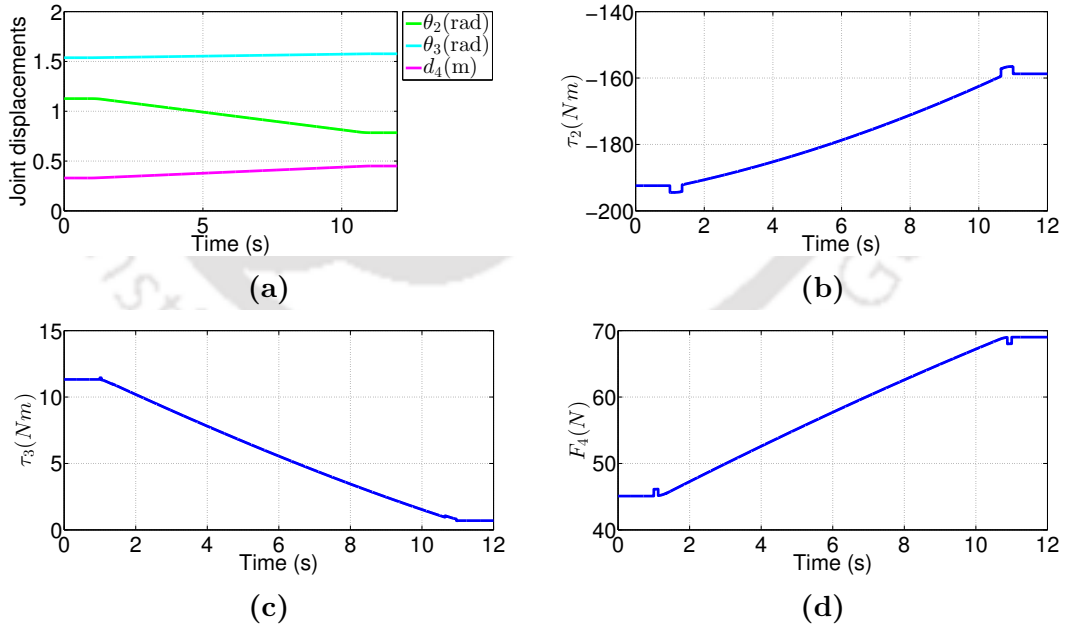


Figure 3.12: (a) Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-I

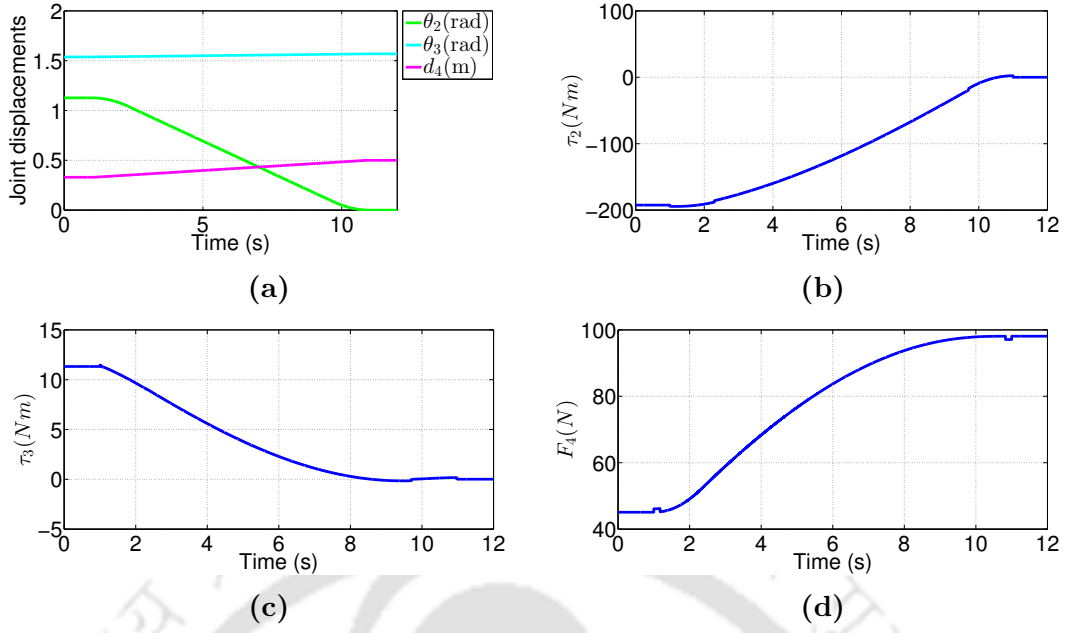


Figure 3.13: (a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-II

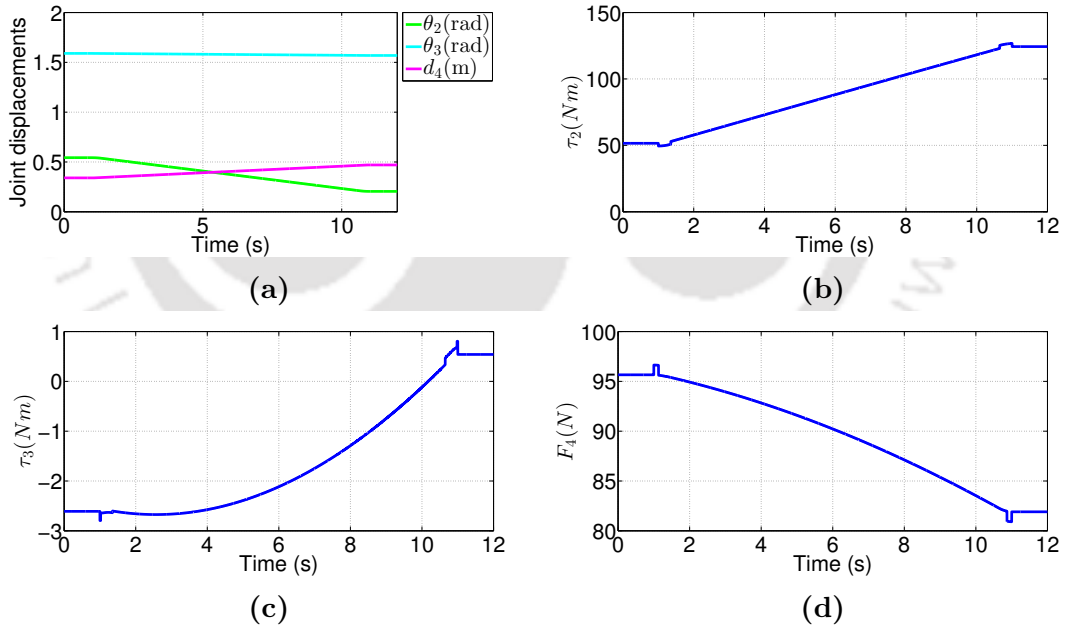


Figure 3.14: (a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-IV

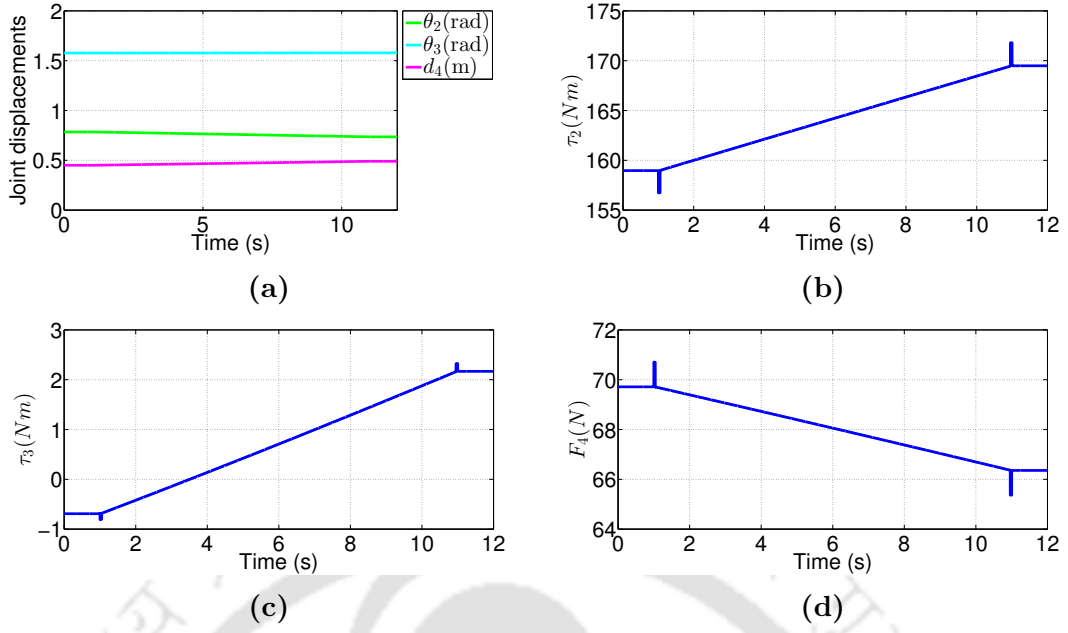


Figure 3.15: (a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-V

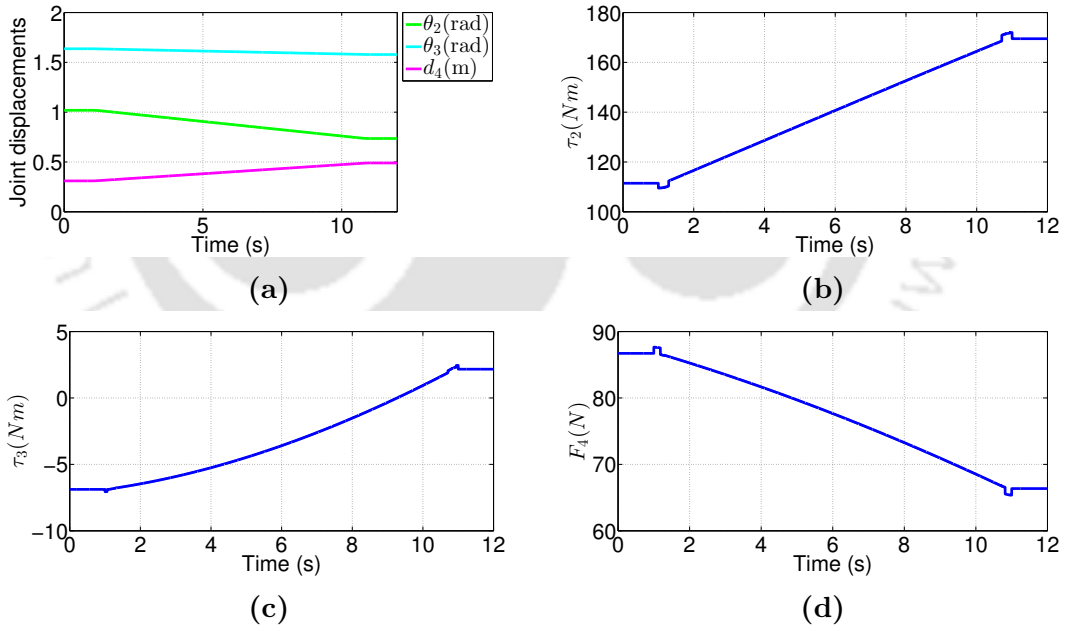


Figure 3.16: (a)Trajectories of the joint variables θ_2 , θ_3 and d_4 and, torque plots of the actuators in (b) joint 2, (c) joint 3 and (d) joint 4 for motion type-VI

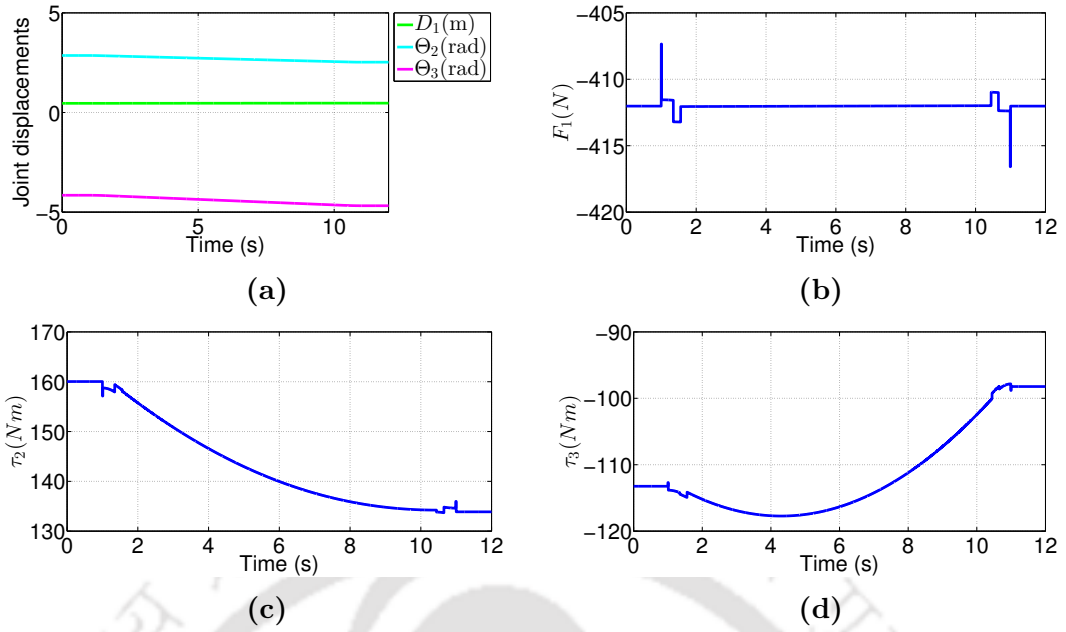


Figure 3.17: (a) Trajectories of the joint variables D_1 , Θ_2 and Θ_3 and, torque plots of the actuators in (b) joint 1, (c) joint 2 and (d) joint 3 for motion type-i

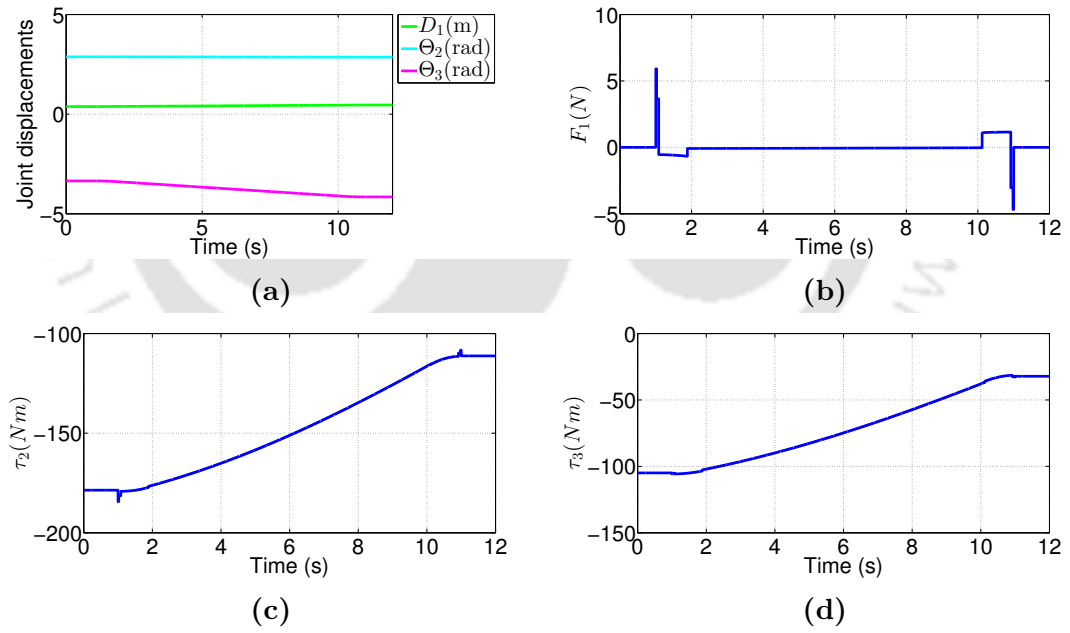


Figure 3.18: (a) Trajectories of the joint variables D_1 , Θ_2 and Θ_3 and, torque plots of the actuators in (b) joint 1, (c) joint 2 and (d) joint 3 for motion type-iv

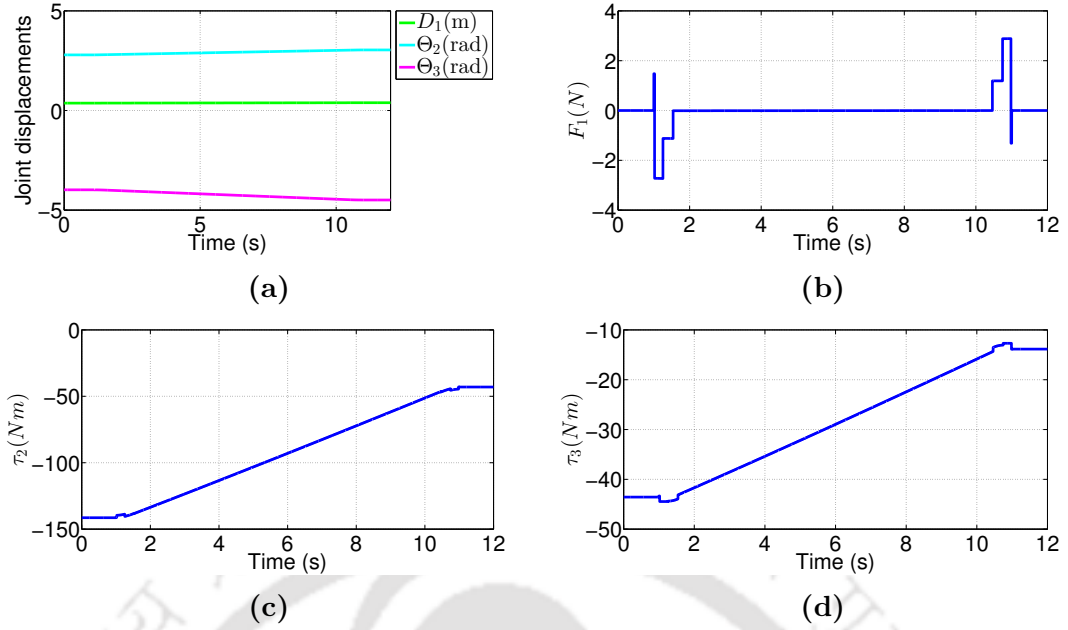


Figure 3.19: (a) Trajectories of the joint variables D_1 , Θ_2 and Θ_3 and, torque plots of the actuators in (b) joint 1, (c) joint 2 and (d) joint 3 for motion type-v

3.4 Tuning of Feedback Gains of a RRRP serial chain manipulator

This section controls an RRRP pick and place robot, having a three dimensional workspace, using a PID control law wherein the feedback gains are tuned using Floquet theory. Floquet theory ensures that the trajectory tracking errors are asymptotically stable. Floquet theory is straightforward compared to the complex derivations of the design criteria for tuning rules prescribed in literature. Moreover, tuning the feedback gains using Floquet theory does not require knowing the uniform bounds of the inertia matrix and the Jacobian of the gravity vector. Floquet theory can also be applied to the RRRP climbing mechanism.

3.4.1 Model of the RRRP pick and place robot

The schematic of the RRRP pick and place robot is shown in Fig. 3.20, comprising of three revolute joints and one prismatic joint. Links 1 and 2 are solid circular rods, link 3 is a hollow circular rod and link 4 is a solid circular prismatic rod. The mass moments of inertia of these links can be found by the procedure given in Pratihar (2017). The actuators produce torques τ_1, τ_2, τ_3 for the three revolute joints and force F_4 for the prismatic joint. The properties of the links can be found in Table 3.8. It may be noted that the RRRP pick and place robot shown in Fig. 3.20 is similar but not exactly same as the RRRP configuration of the climbing mechanism, shown in Fig. 3.6a. The coordinate frames placed at the

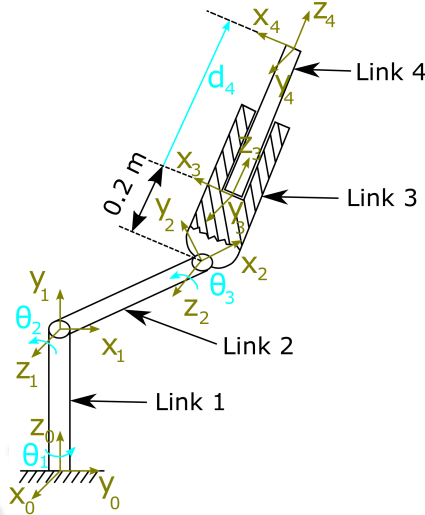


Figure 3.20: RRRP pick and place robot manipulator with 3-D workspace

Table 3.8: Properties of the RRRP pick and place robot

Quantity	Link 1	Link 2	Link 3	Link 4
Length (m)	1	1	0.4	1
Mass (kg)	12	10	8	10
Distance of centre of gravity of link i from the origin of basis i (m)	0.5	0.5	0.05	0.5
Radius (m)	0.05	0.05	0.04*	0.05

* indicates the radius of link 3, which is a hollow circular rod. The cross-sectional area of link 3 is equivalent to the cross-sectional area of a solid circular rod with a radius 0.04 m

joints of RRRP pick and place robot of Fig. 3.20 are different than the RRRP configuration of the climbing mechanism of Fig. 3.6a.

The equations of motion of the RRRP pick and place robot are derived using the Lagrange Euler formulation following the convention of Fu et al. (1987) as-

$$[M(q)]_{4 \times 4} [\ddot{q}]_{4 \times 1} + [C(q, \dot{q})]_{4 \times 1} + [G(q)]_{4 \times 1} = [\Gamma]_{4 \times 1} \quad (3.5)$$

In Eq. 3.5, the torque vector, $[\Gamma]$, can be written as the sum of the nominal torque, $[\Gamma]_n$ and the feedback torque, $[\Gamma]_f$.

$$[M(q)][\ddot{q}] + [C(q, \dot{q})] + G(q) = [\Gamma]_n + [\Gamma]_f \quad (3.6)$$

where q is the vector of joint variables $(\theta_1, \theta_2, \theta_3, d_4)$, $\dot{q}$ and $\ddot{q}$ represent the joint velocities and accelerations respectively, $[M(q)]$, $[C(q, \dot{q})]$ and $[G(q)]$ represent the mass matrix, coriolis vector and gravity vector respectively. The coefficients of mass matrix, coriolis vector and gravity vector are given in Appendix D. Assuming

a desired trajectory $q_d(t)$, $[\Gamma]_n$ is the nominal torque required to track q_d , which can be calculated by substituting $q(t)$ with $q_d(t)$ on the left hand side of Eq. 3.6. But given the highly nonlinear nature of the robot equations, tracking control requires an additional feedback term $[\Gamma]_f$ (to be added to $[\Gamma]_n$), given by-

$$[\Gamma]_f = -[K_P]_{4 \times 4}[e] - [K_V]_{4 \times 4}[\dot{e}] - [K_I]_{4 \times 4} \int [e] dt \quad (3.7)$$

where $[e]_{4 \times 1}$ is the vector of joint tracking errors, given by the difference between the actual and the desired trajectories, $[K_P]$, $[K_V]$, $[K_I]$ are diagonal feedback gain matrices comprising gains K_p, K_v, K_i . In this work, the diagonal elements in each of the feedback gain matrices are assumed to be the same. However, their units would depend upon the type of the joint. For the RRRP robot considered in this work, the units of the gains K_p, K_v, K_i , in their respective matrices $[K_P]$, $[K_V]$, $[K_I]$, for the first three revolute joints are Nm, Nms and Nms⁻¹ whereas for the last joint (which is prismatic) the units of K_p, K_v, K_i are Nm⁻¹, Nm⁻¹s and Nm⁻¹s⁻¹ respectively. The magnitude of the gains K_p, K_v, K_i , in their respective matrices $[K_P]$, $[K_V]$, $[K_I]$, are same for all the joints of the robot.

3.4.2 Periodic Trajectory Planning

Trajectory planning is required to extract the desired trajectories which are to be followed by the RRRP pick and place robot. Periodic trajectory planning is of special importance to the present work, since the method of Floquet theory requires the desired trajectories to be periodic. The trajectory of each of the joints of the RRRP robot between the pick and the place positions is planned using the method of “linear function with parabolic blends” as can be found in [Mittal and Nagrath \(2003\)](#). However, in this work, the equations of motion associated with the “linear function with parabolic blends” have been modified as a rest time has been considered at the beginning and at the end of the trajectory of each joint between the pick and the place positions of the RRRP robot. The equations of motion for the modified “linear function with parabolic blends” have been derived following the approach given in [Mittal and Nagrath \(2003\)](#) and are as follows-

Table 3.9: The values of joint variables at the *pick* and *place* positions

Joint variables	(<i>Pick</i> position)	(<i>Place</i> position)
θ_1	0°	60°
θ_2	0°	30°
θ_3	0°	20°
d_4	0m	0.3m

$$\begin{aligned}
 q &= q_{pi}, \quad t_{st} \leq t < t_r \\
 q &= q_{pi} + \frac{1}{2}\ddot{q}_{co}(t - t_r)^2, \quad t_r \leq t \leq t_{bl} \\
 q &= q_{pi} + \frac{1}{2}\ddot{q}_{co}(t_{bl} - t_r)^2 - \ddot{q}_{co}(t_{bl} - t_r)t_{bl} + \ddot{q}_{co}(t_{bl} - t_r)t, \\
 &\quad t_{bl} < t \leq t_{pl} - (t_{bl} - t_r) \\
 q &= q_{pl} - \frac{1}{2}\ddot{q}_{co}(t_{pl} - t)^2, \quad t_{pl} - (t_{bl} - t_r) < t \leq t_{pl} \\
 q &= q_{pl}, \quad t_{pl} < t \leq t_{end}
 \end{aligned} \tag{3.8}$$

wherein t_{st} is the start time, t_r is the rest time, t_{bl} is the blend time, t_{pl} is the time at place position, t_{end} is the end time, q_{pi} is the pick position, q_{pl} is the place position and $\ddot{q}_{co}$ is the constant acceleration at the parabolic blends. The blend time and the constraint on the acceleration at the blends can be found out by using the equations given below-

$$t_{bl} = \frac{1}{2}(t_{pl} + t_r) - \frac{1}{2}\sqrt{\frac{\ddot{q}_{co}(t_{pl} + t_r)^2 - 4\{(q_{pl} - q_{pi}) + \ddot{q}_{co}t_r t_{pl}\}}{\ddot{q}_{co}}} \tag{3.9}$$

$$|\ddot{q}_{co}| \geq \frac{4(|q_{pl} - q_{pi}|)}{(t_{pl} - t_r)^2}; \quad \ddot{q}_{co} \neq 0 \tag{3.10}$$

The pick (initial) position in metres, of the end-effector is chosen as (1.2, 0, 1) in Cartesian space with respect to the base co-ordinate frame. The place (final) position in metres, of the end-effector is chosen as (0.612, 1.06, 1.46) in Cartesian space with respect to the base co-ordinate frame. The values of joint variables of the robot for the pick and place positions can be found using the inverse kinematics procedure, as given in [Mittal and Nagrath \(2003\)](#). The values of the joint displacements, obtained using inverse kinematics, at the pick and place positions, are given in Table 3.9.

After obtaining the values of joint displacements for each of the joints of the robot, the trajectory of each of the joints can be obtained using the piecewise Eq. 3.8. The constant angular acceleration at the blends, $\ddot{q}_{co}$ is taken as 0.35 rad s^{-2} and the start time, t_{st} is taken as 0 s and the end time, t_{end} is taken as 12 s. The rest

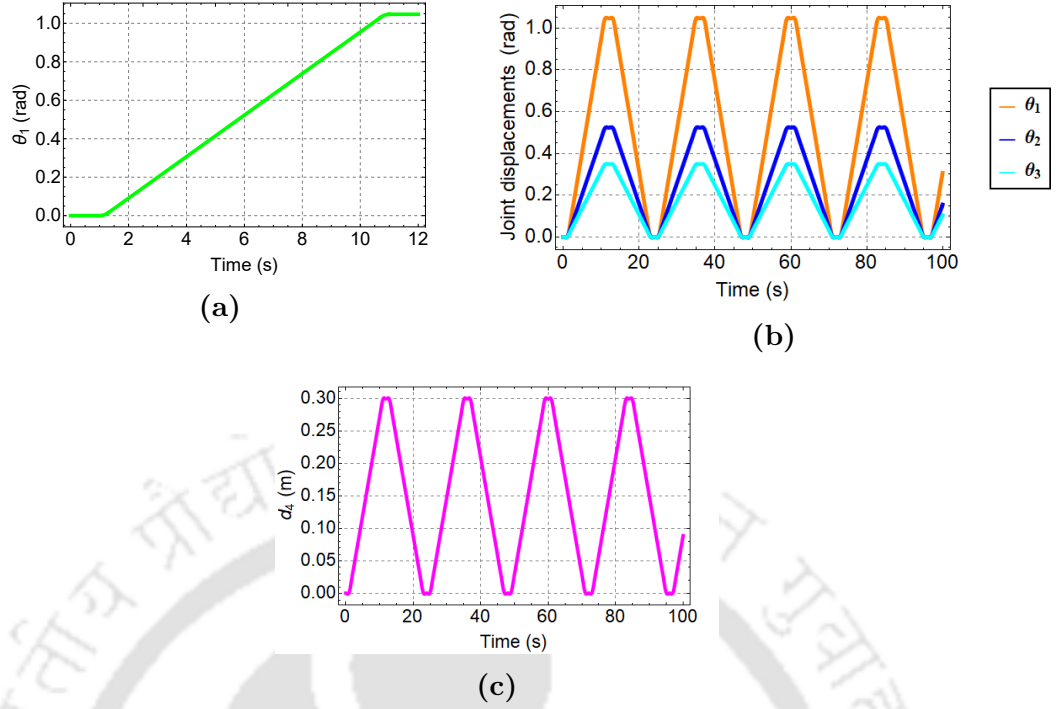


Figure 3.21: (a) The trajectory of the joint variable θ_1 from pick position to place position, (b) The periodic trajectories of the joint variables θ_1 , θ_2 and θ_3 till 100 s and, (c) The periodic trajectory of the joint variable d_4 till 100 s

time, t_r , at the beginning and towards the end of the trajectory is taken as 1 s. In this work, the magnitudes of $\ddot{q}_{co}$, t_{st} and t_{end} have been taken as same for all the joints but their units would change accordingly for the prismatic joint. The chosen acceleration satisfies the constraint, given by Eq. 3.10 and the blend time accordingly can be calculated using Eq. 3.9 before obtaining the trajectories of each joint. For joint 1, the pick position, q_{pi} is 0 rad and the place position, q_{pl} is $\frac{\pi}{3}$ rad, as given in Table 3.9. A plot of the trajectory of joint 1 is shown in Fig. 3.21a. Similarly, the trajectories of joints 2, 3 and 4 can also be obtained.

The trajectories of the joints of the RRRP robot obtained till now are from the pick position to the place position but each joint of the RRRP robot again returns to its pick position after reaching the place position and continues the same process. Many industrial robots work this way wherein they are required to perform repetitive tasks (Ma et al., 2019) and hence have periodic trajectories of their joints. The RRRP robot considered in this work also has a behaviour similar to any industrial robot performing a repetitive task. Then the trajectory of each of the joints of the RRRP robot would also become periodic. The periodic trajectories of the joint variables of the RRRP robot can be obtained by using the Fourier half range cosine series, as given in (Kreyszig, 1999). In simple words, Fourier half range series states that if one knows the half function of a cycle, the function of the entire cycle or series can be obtained from the half function. The Fourier half

range cosine series of a function with a period $2T$ is given as-

$$f(x) = a_0 + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi}{T} x \quad (3.11)$$

with coefficients $a_0 = \frac{1}{T} \int_0^T f(x) dx$ and $a_n = \frac{2}{T} \int_0^T f(x) \cos \frac{n\pi x}{T} dx$, $n=1,2,\dots$

In this work, the piecewise Eq. 3.8 is the half function and on using Fourier half range cosine series, the trajectory equation of the entire cycle can be obtained. The periodic trajectories of each of the joint variables of the RRRP robot are shown in Figs. 3.21b and 3.21c. Twenty terms are considered for obtaining the periodic trajectories of each of the joints of the RRRP robot using Eq. 3.11. In Figs. 3.21b and 3.21c, it can be seen that till 100 s, each joint of the RRRP robot reaches the pick position four times excluding the start position and the place position four times. The calculations are performed using Mathematica 10.4.1.

3.4.3 Application of Floquet theory to the RRRP robot

In applying the Floquet theory, the reference (Thomas et al., 2010) and the references (13, 14) contained therein are followed. To stabilize errors when tracking a desired trajectory, $q_d(t)$, the variation of the error trajectory with time must be tracked. Assuming $q(0) \approx q_d(0)$ and $\dot{q}(0) \approx \dot{q}_d(0)$ is satisfied, the stability of this zero solution must be analyzed by computing the error differential equations. Hence, a small perturbation about $q_d(t)$ is considered as-

$$q = q_d + e \Rightarrow \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} q_{1d} \\ q_{2d} \\ q_{3d} \\ q_{4d} \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} \quad (3.12)$$

For the RRRP robot discussed in the work, $[q_1, q_2, q_3, q_4]^T = [\theta_1, \theta_2, \theta_3, d_4]^T$. Substituting Eq. 3.12 into Eq. 3.6 and using Eq. 3.7,

$$\begin{aligned} & [M(q_d + e)][\ddot{q}_d + \ddot{e}] + [C(q_d + e, \dot{q}_d + \dot{e})] + [G(q_d + e)] \\ &= [\Gamma]_n - [K_P][e] - [K_V][\dot{e}] - [K_I] \int [e] dt \end{aligned} \quad (3.13)$$

In the above equation, $M(q_d + e)$ can be expanded as $\left(M(q_d) + \left[\frac{\partial M}{\partial q_1} \dots \frac{\partial M}{\partial q_4} \right]_{q=q_d} e \right)$ with similar expansions for the matrices C and G . Also, by the definition of nominal torque, $[\Gamma]_n = M(q_d)\ddot{q}_d + C(q_d, \dot{q}_d) + G(q_d)$. Furthermore, introducing the term $z = \int e dt$,

the terms $e, \dot{e}, \ddot{e}$ can be written as $\dot{z}, \dot{\ddot{z}}, \ddot{\ddot{z}}$ respectively. Making these changes and neglecting higher order terms in $z, \dot{z}, \ddot{z}$,

$$\begin{aligned}
& M(q_d) \ddot{\ddot{z}} + \left(\left[\frac{\partial M}{\partial q} \right]_{q=q_d} \dot{\ddot{z}} \right) \ddot{q}_d + \left[\frac{\partial C}{\partial q} \right]_{q=q_d} \dot{\ddot{z}} + \left[\frac{\partial C}{\partial \dot{q}} \right]_{\dot{q}=\dot{q}_d} \ddot{\ddot{z}} \\
& + \left[\frac{\partial G}{\partial q} \right]_{q=q_d} \dot{\ddot{z}} = -[K_P]\dot{\ddot{z}} - [K_V]\ddot{\ddot{z}} - [K_I]z \\
& \Rightarrow \dot{y} = [J_n(t)]y \quad (\text{In the form of } \dot{y} = f(y, t))
\end{aligned} \tag{3.14}$$

where $y = [z, \dot{z}, \ddot{z}]^T$, $[J_n(t)]$ is the Jacobian matrix which is a function of the desired trajectories, $q_d(t)$, and the feedback gains K_p, K_v, K_i . Since the desired trajectories, $q_d(t)$, obtained in subsection 3.4.2 are in periodic form, $[J_n(t)]$ is also periodic (with some period T). Hence, the stability of Eq. 3.14 can be analyzed using Floquet theory, by computing the Floquet multipliers (Thomas et al., 2010) as follows-

1. The following matrix differential equation is solved over one period ($t = 0$ to $t = T$) using the initial condition $X(0) = I$

$$\frac{dX}{dt} = [J_n(t)]X \tag{3.15}$$

where $X(t)$ is the fundamental solution matrix and the eigenvalues of $X(T)$ (Monodromy matrix) are known as the Floquet multipliers. It may be noted that $[J_n(t)]$ in Eq. 3.15 is same as $[J_n(t)]$ in Eq. 3.14.

2. If all Floquet multipliers are less than one, the zero solution is asymptotically stable, i.e. $y(t)$ (and hence $e(t)$ and $\dot{e}(t)$) $\rightarrow 0$ as $t \rightarrow \infty$.
3. If any of the Floquet multipliers are greater than one, the zero solution is unstable, i.e. $y(t)$ (and hence $e(t)$ and $\dot{e}(t)$) $\rightarrow \infty$ as $t \rightarrow \infty$.

Hence, given that $[J_n(t)]$ comprises gains K_p, K_v, K_i , the tuning problem reduces to finding such gains at which the Floquet multipliers are lesser than one. This is a simple numerical search problem since the integration of Eq. 3.15 is only from $t = 0$ to $t = T$.

3.4.4 Numerical Simulation Results for Trajectory Tracking

Numerical simulations for tracking the desired trajectories are presented in this section. All numerical simulations are carried out in MATLAB 2019a using the

inbuilt *ode15s* solver. The relative and absolute tolerances are kept at 10^{-9} and 10^{-9} respectively. The results are checked for smaller values of tolerance and convergence is observed.

The following tuning procedure is adopted to conduct the numerical study to derive the feedback gains that guarantee stability of an RRRP robot in tracking a desired time-varying trajectory-

1. A small perturbation is applied around the desired trajectory to derive the error equation, as given in Eq. 3.14 and hence the Jacobian matrix $[J_n(t)]$ is obtained.
2. A numerical search is conducted for different values of feedback gains K_p, K_v, K_i for which the largest Floquet multiplier, as calculated by using Eq. 3.15, is lesser than one, i.e. where the system is asymptotically stable. To conduct the search, it is necessary to identify broadly, the ranges where asymptotic stability can (or cannot) be expected to occur. In a prior work in literature (Lankalapalli and Ghosal, 1997), ranges of controller gains are identified for which a 2R planar robot driven by PD and model based control would exhibit chaotic motions (i.e. lack of asymptotic stability). The authors in (Lankalapalli and Ghosal, 1997) determined a crucial result - namely that chaos occurred for low values of derivative gain and relatively higher values of proportional gain. Here, a PID controller has been used which has an integral term in addition to the proportional and derivative terms. Furthermore, this work deals with 3D motion of the robot, whereas the research in (Lankalapalli and Ghosal, 1997) dealt with 2D motions. Nonetheless, result from (Lankalapalli and Ghosal, 1997) in literature can be used as a starting point i.e., the search can be started from very low values of both derivative and proportional gains up till relatively higher values. Here, the search is conducted for $0 \leq K_p \leq 500$, $0 \leq K_v \leq 5$ and $0 \leq K_i \leq 10$.
3. This search is presented by 2D plots in K_p vs. K_v space for different values of K_i . Eq. 3.15 is integrated from $t = 0$ to $t = 24$ s. The time period is 24 s as is evident from Figs. 3.21a and 3.21b. A flowchart depicting the steps to be followed for carrying out the numerical search is shown in Fig. 3.22. The overall algorithm for the numerical search is given in Appendix E. It may be noted that the plots in Fig. 3.23 have been generated by putting $K_{pmax}=500$, $K_{vmax}=5$ and $T=24$.
4. As mentioned in the first part of subsection 3.4.3, Floquet theory requires that $q(0) \approx q_d(0)$ and $\dot{q}(0) \approx \dot{q}_d(0)$ for all the joints of the RRRP robot and the same has been ensured in all of the calculations made for the results presented in this work.

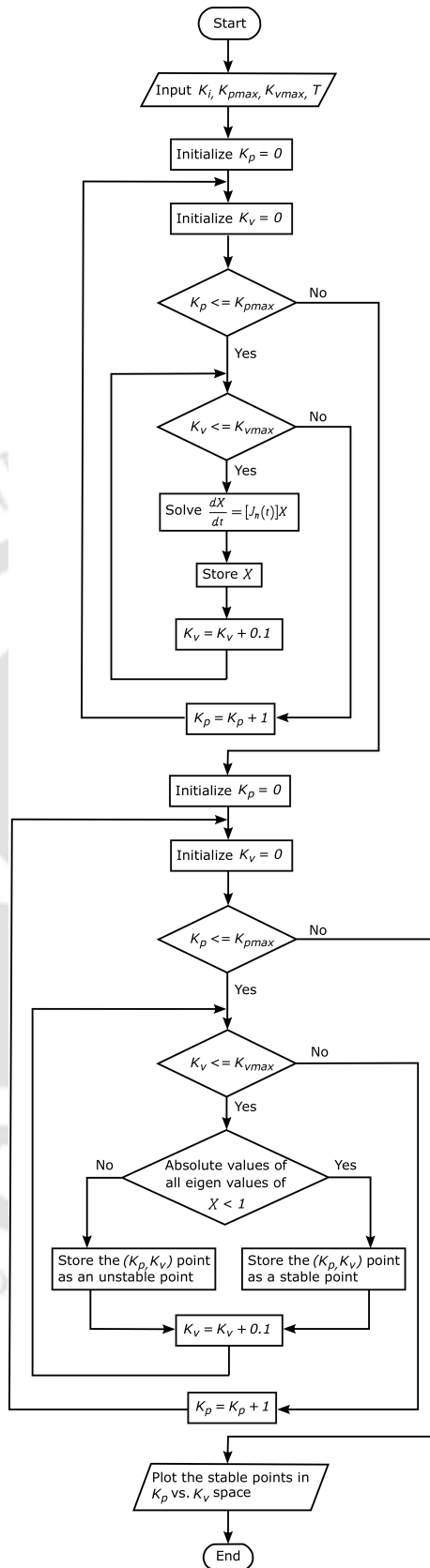


Figure 3.22: Flowchart depicting the steps for carrying out the numerical search to generate the K_p versus K_v map

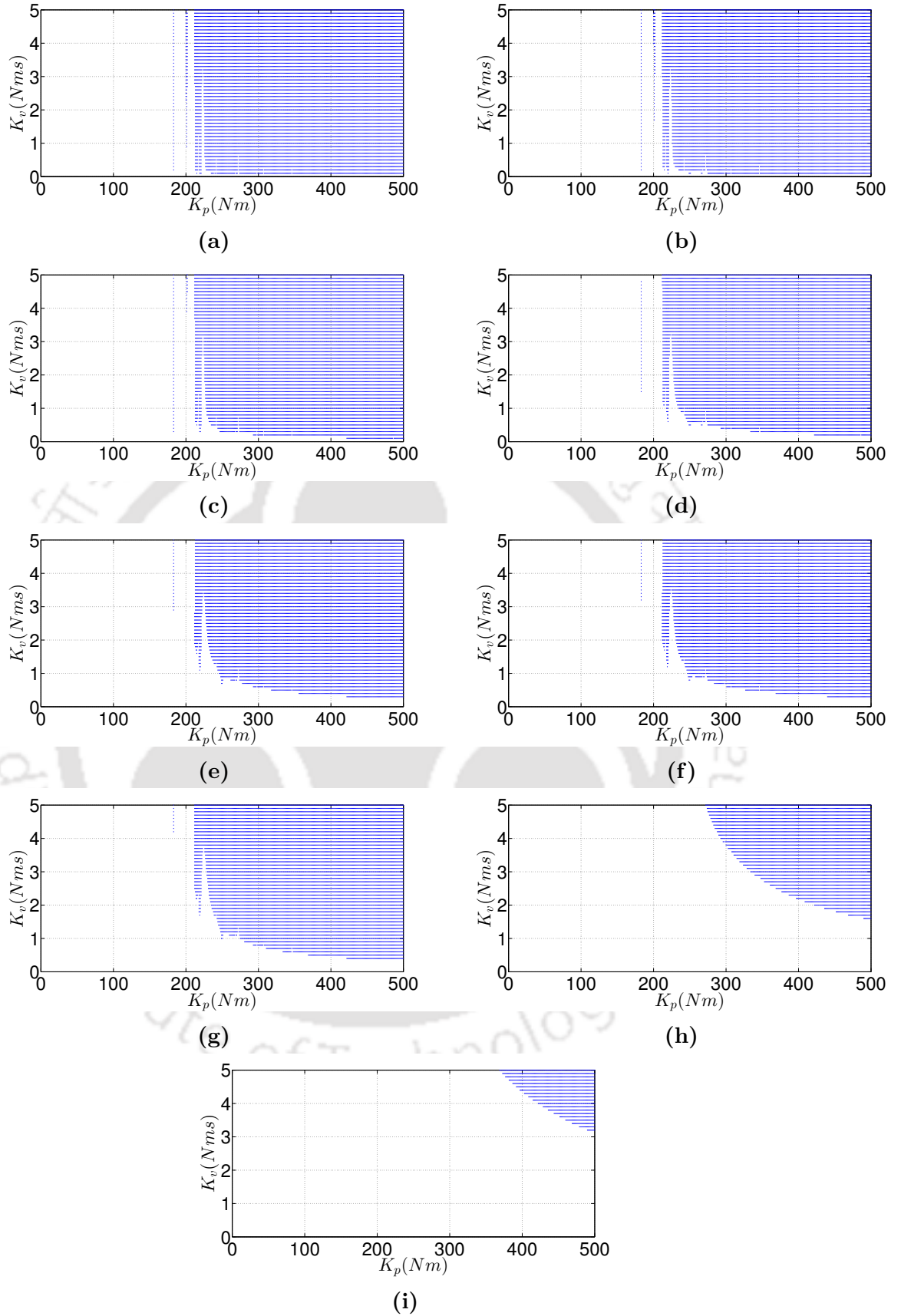


Figure 3.23: Regions of stability for K_p versus K_v plots, corresponding to 1st joint of the robot, for various values of K_i (a) $K_i = 0.05$, (b) $K_i = 0.1$, (c) $K_i = 0.25$, (d) $K_i = 0.5$, (e) $K_i = 0.75$, (f) $K_i = 0.8$, (g) $K_i = 1$, (h) $K_i = 5$ and (i) $K_i = 10$

Figure 3.23 shows the parametric instability regions in K_p vs. K_v plane for varying K_i , corresponding to 1st joint of the robot, where the region with dots represent the stable state, i.e. for those values of K_p and K_v , the tracking error corresponding to the 1st joint of the RRRP robot goes to zero asymptotically. It may be noted that the regions of stability for K_p vs. K_v plots for various values of K_i , for the remaining three joints of the robot are exactly similar to the plots of Fig. 3.23, corresponding to the 1st joint of the robot. This is because as stated towards the end of subsection 3.4.1, the magnitude of the feedback gains K_p, K_v, K_i , in their respective matrices $[K_P], [K_V], [K_I]$, are same for all the joints of the robot, only their units change depending upon the type of the joint. Many such K_p vs. K_v plots are generated in 2D for various other values of K_i (not presented here). It is evident from Fig. 3.23 that as K_i increases, the region of stability in the K_p vs. K_v map shifts towards higher values of K_p and K_v .

To verify the accuracy of the aforementioned plots, a particular value of K_p and K_v (say $K_p = 280$ and $K_v = 5$ in Fig. 3.23d) is chosen and the tracking errors and their respective velocities are computed using Eq. 3.5. These tracking error plots are as shown in Fig. 3.24. The plots indicate that the tracking error and its velocity for each of the joints approach zero asymptotically for the above mentioned values of K_p and K_v . The same is confirmed by phase portraits also shown in Figs. 3.24c, 3.24f, 3.24i and 3.24l.

In Fig. 3.24, it can be seen that the error plots do show certain sinusoidal behaviour. This may lead to an erroneous conclusion that asymptotic stability is not achieved. To verify whether the errors go to zero asymptotically, the error differential equations, with the values of controller gains corresponding to the plots in Fig. 3.24, are integrated for larger times and the ensuing error plots are shown in Fig. 3.25. From Fig 3.25, it can be observed that the errors go to zero asymptotically.

The accuracy of the plots in Fig. 3.24 can be further confirmed by choosing a value of K_p and K_v (say $K_p = 180$ and $K_v = 0.5$ in Fig. 3.23d) in the unstable zone and plotting the tracking errors and their respective velocities for such values. These response plots are shown in Fig. 3.26. The plots clearly show that the system is unstable as the system responses increase with time or the tracking errors are unbounded.

It is pertinent to note that computation of the regions of stability are made using the Jacobian $[J_n(t)]$ derived from subsection 3.4.3, and did not require the bounds of the inertia matrix and/or Jacobian of the gravity vector. This demonstrates the use of Floquet theory in overcoming the requirement of the bounds of the inertia matrix and the Jacobian of the gravity vector.

The following observations can be made from the results of response plots as part of the numerical search mentioned earlier in this section -

1. Figure 3.23 clearly indicates that for higher values of K_i , the region of sta-

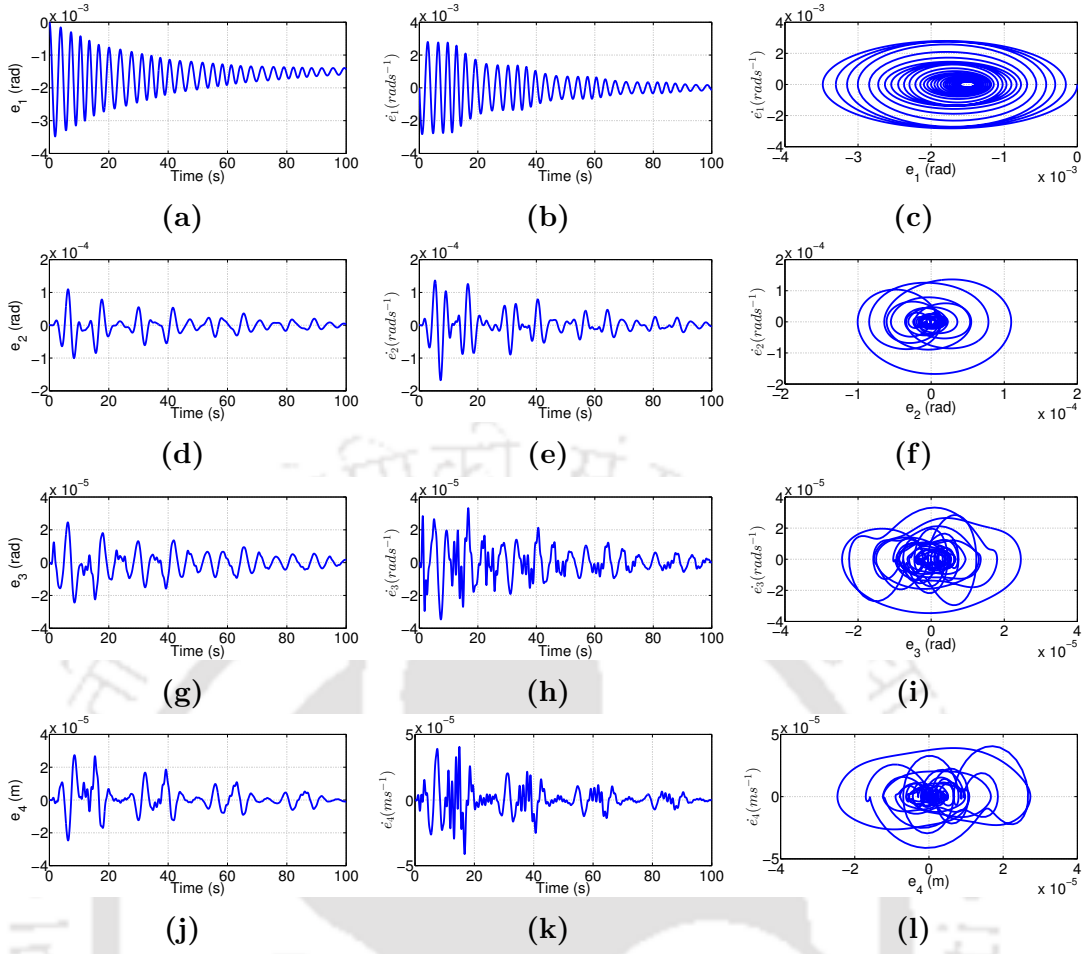


Figure 3.24: Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=280$, $K_v=5$ and $K_i=0.5$

bility exists only for higher values of K_p and K_v . For $K_i=5$, the region of stability in the K_p vs. K_v map ($0 \leq K_p \leq 500$, $0 \leq K_v \leq 5$) was smaller as compared to lower values of K_i , with the stable region appearing as a quadrant at the upper right corner of the K_p vs. K_v map. For $K_i=10$, the K_p vs. K_v map ($0 \leq K_p \leq 500$, $0 \leq K_v \leq 5$) was much smaller with fewer dots at the upper right corner of the K_p vs. K_v map. Thus, the region of stability of the system shifts right and up, towards higher values of K_p and K_v as K_i increases.

2. It is also observed that the region of stability shifts towards higher values of K_p and K_v for a fixed K_i for heavier links in the RRRP robot.
3. In Fig. 3.24, it can be seen that the overshoot of e_1 is higher as compared to e_2 , e_3 and e_4 . e_1 is in the order of 10^{-3} which is quite small. Fig. 3.25 clearly shows that for larger time, e_1 goes to zero asymptotically and so do errors e_2 , e_3 , e_4 and their velocities.

The nominal torque plots of the actuators are shown in Fig. 3.27.

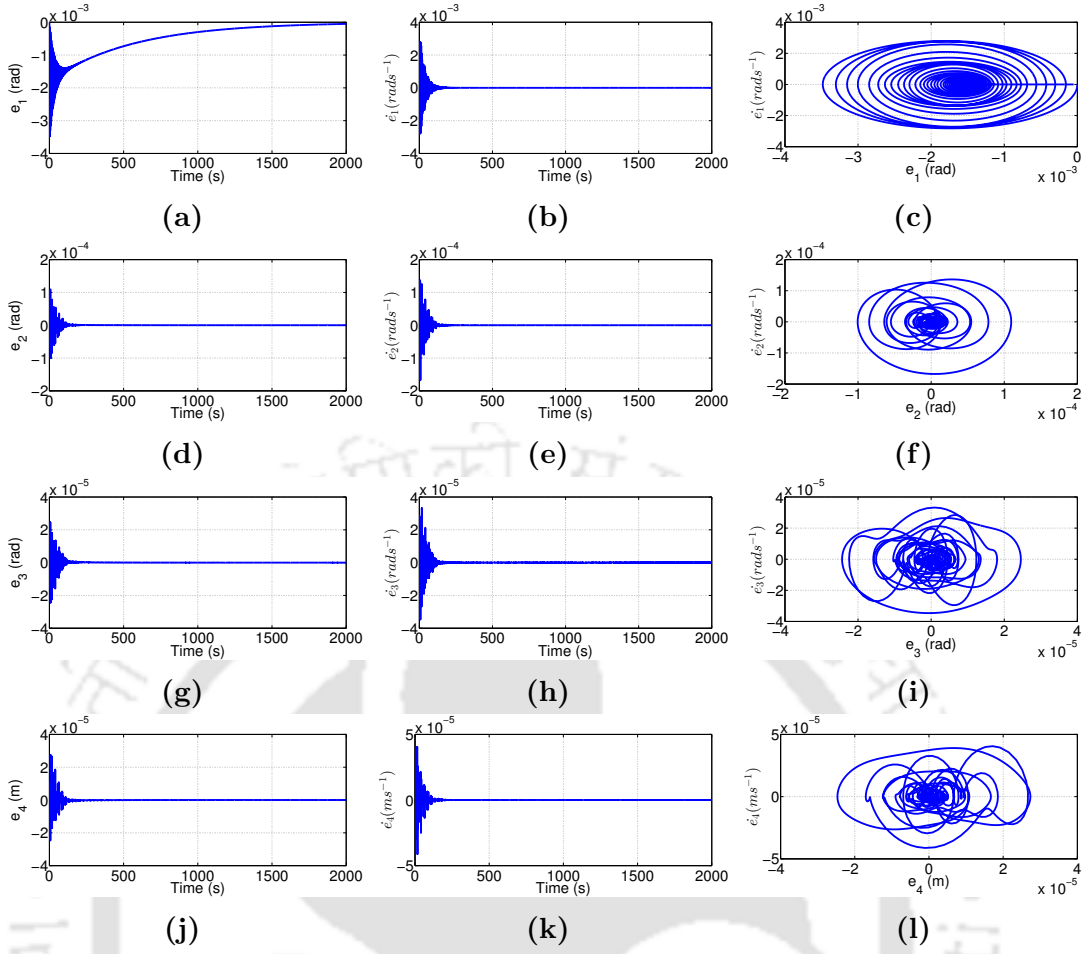


Figure 3.25: Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=280$, $K_v=5$ and $K_i=0.5$ for a greater time

The use of Floquet theory in overcoming the requirements of the bounds on the inertia matrix and the Jacobian of the gravity vector can be further demonstrated by carrying out the numerical search for a different inertia of the robot as compared to the design inertia, i.e. where the lengths, masses, distances of centre of gravity of the links from the bases and radii of the links have been changed randomly as compared to these properties in Table 3.8. The new and changed properties of the RRRP robot are given in Table 3.10. The absolute percentage change in properties of the RRRP robot of Table 3.10 with respect to the properties of the RRRP robot of Table 3.8 can be found in Table 3.11. Then, Floquet theory is applied to the RRRP robot with different inertia and the regions of stability are obtained (not presented here). From such regions of stability, a particular point is chosen, namely $K_p = 350$, $K_v = 4$, $K_i = 0.25$, and the error plots are computed as shown in Fig. 3.28. From Fig. 3.28, it can be observed that the errors and their respective velocities go to zero asymptotically, thereby establishing asymptotic stability. Thus, robustness to change in inertia of the RRRP robot can

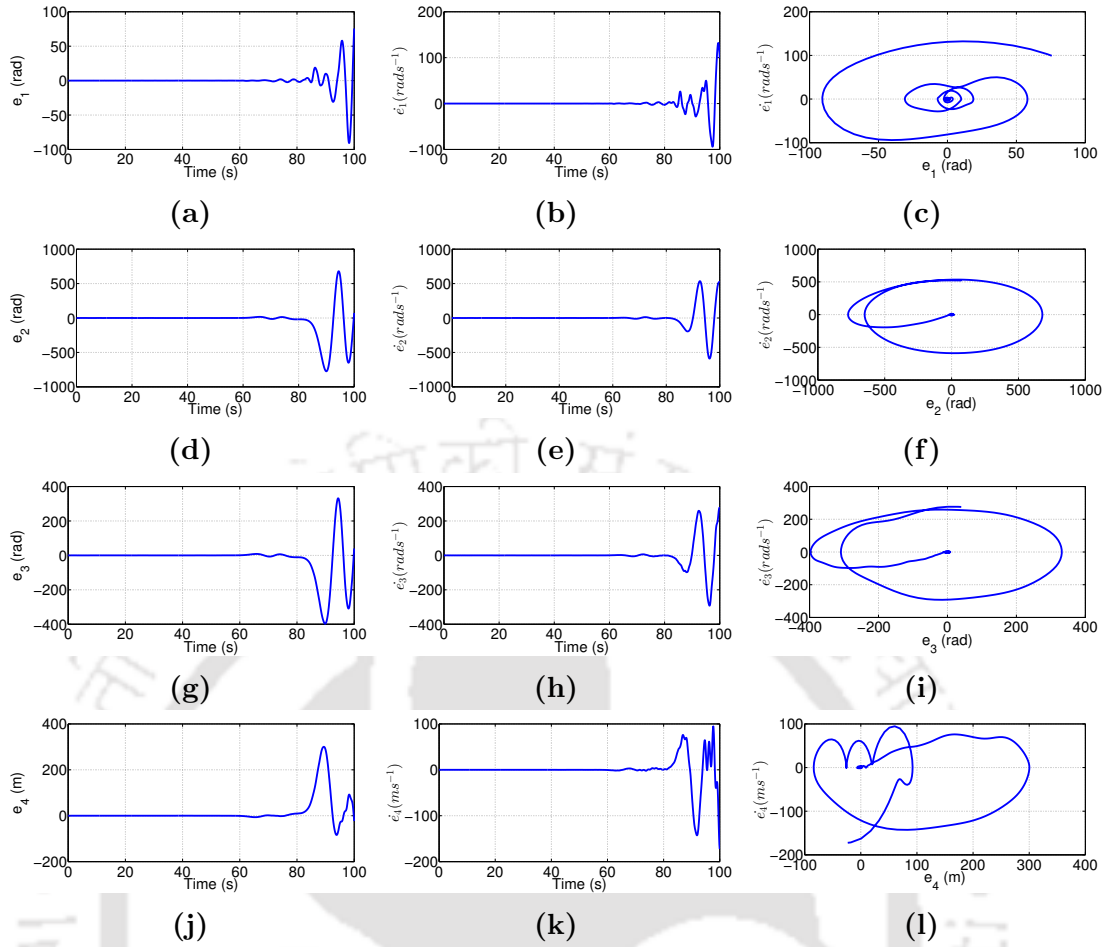


Figure 3.26: Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=180$, $K_v=0.5$ and $K_i=0.5$

Table 3.10: Changed properties of the RRRP robot

Quantity	Link 1	Link 2	Link 3	Link 4
Length (m)	1.1	0.977	0.412	0.933
Mass (kg)	12.876	10.1	8.72	9.45
Distance of centre of gravity of link i from the origin of basis i (m)	0.48	0.525	0.049	0.51
Radius (m)	0.054	0.053	0.043	0.048

be established using Floquet theory.

3.4.5 Comments on Floquet theory

This subsection presents a list of comments that can be made about the application of Floquet theory to tune controller gains for asymptotic stability, where the advantages and limitations of such an approach are highlighted. Future possible applications of Floquet theory are also discussed further in this subsection.

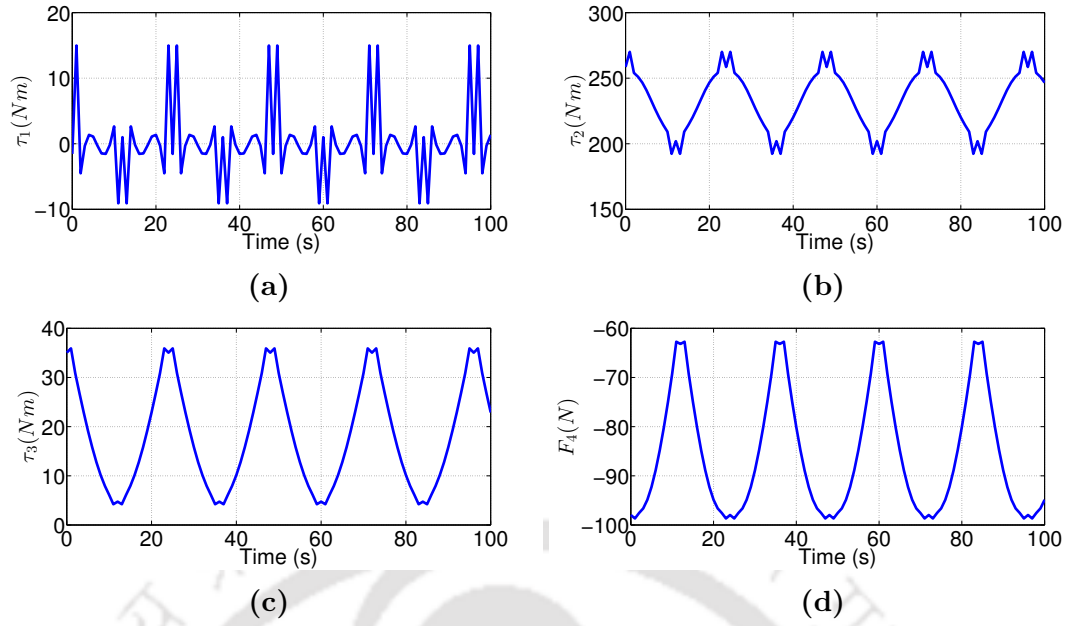


Figure 3.27: Nominal torque plots of the actuators in (a) joint 1, (b) joint 2, (c) joint 3 and (d) joint 4 of the RRRP robot

Table 3.11: Absolute percentage change of properties in Table 3.10 with respect to the properties in Table 3.8

Quantity	Link 1	Link 2	Link 3	Link 4
Length (m)	10	2.3	3	6.7
Mass (kg)	7.3	1	9	5.5
Distance of centre of gravity of link i from the origin of basis i (m)	4	5	2	2
Radius (m)	8	6	7.5	4

3.4.5.1 Advantages and Limitations of Floquet theory

1. Several tuning rules proposed in literature for stabilizing tracking errors of robot manipulators required, at the minimum, the bounds of the inertia matrix. References to such researches are given in subsection 1.3.8 of chapter 1 (see for example (Abdallah et al., 1991; Craig et al., 1987; Lewis et al., 2003; Sadegh and Horowitz, 1990; Spong et al., 2004) and (Cervantes and Alvarez-Ramirez, 2001)). But, in the present work, the Floquet theory is successfully applied to find feedback gains for asymptotically stabilizing tracking errors for an RRRP robot without requiring any such bounds. Furthermore, the application of Floquet theory (as is evident from the procedure given in subsection 3.4.3) can be made to any serial n -link manipulator, irrespective of (i) the number of links present, (ii) whether the motion of the robot is in two or three dimensions and (iii) whether the robot comprises revolute or prismatic joints.

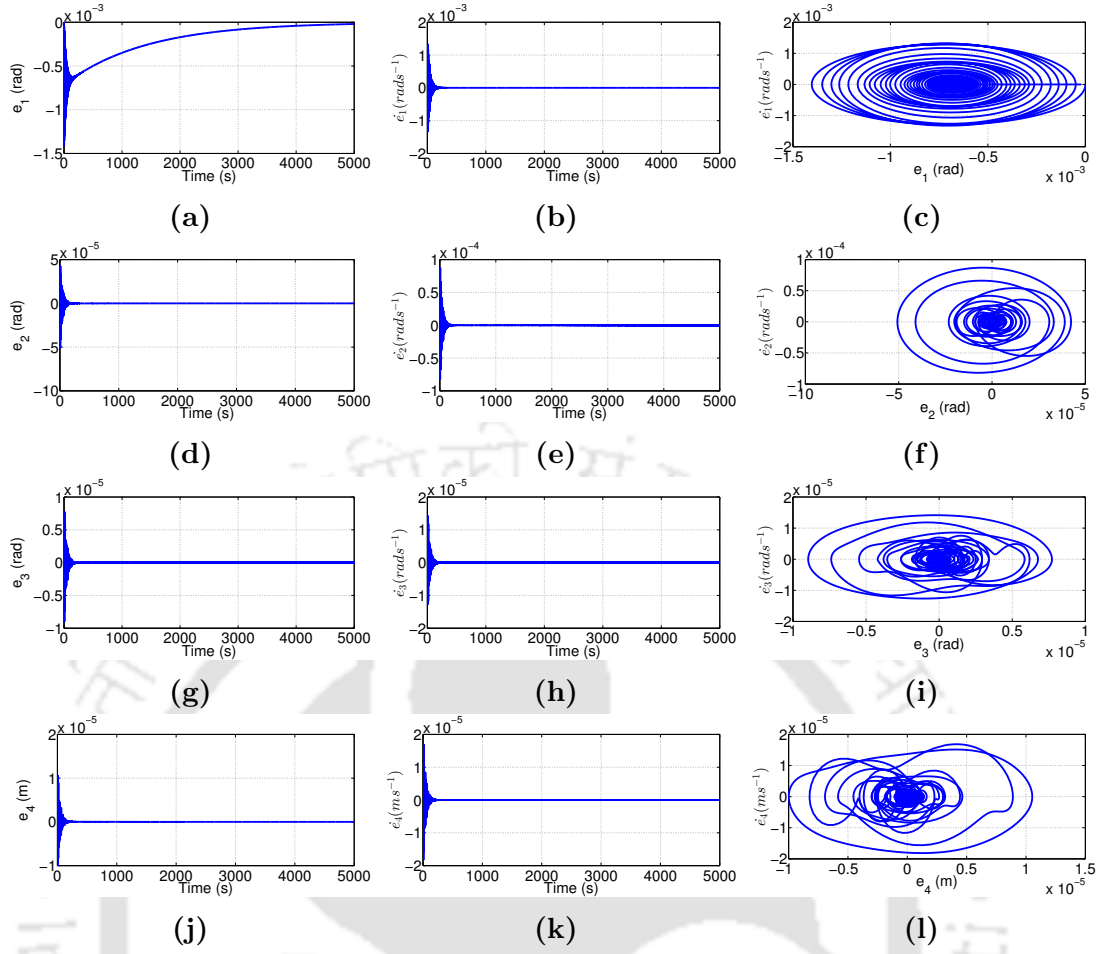


Figure 3.28: Time response of tracking error, its velocity and phase portrait corresponding to the joint variables (a), (b), (c) θ_1 ; (d), (e), (f) θ_2 ; (g), (h), (i) θ_3 and (j), (k), (l) d_4 for $K_p=350$, $K_v=4$ and $K_i=0.25$ for a different inertia of the robot as compared to the design inertia

2. For analyzing the stability of a system using Floquet theory, the Jacobian matrix $[J_n(t)]$ in Eq. 3.14 should be time periodic. Given that the matrix $[J_n(t)]$ comprises the desired trajectories, the desired trajectories themselves must be periodic for Floquet theory to be applied. For this reason, trajectory planning is specifically done to ensure that the desired trajectories are periodic. This is a limitation of Floquet theory, as it is not necessary that desired periodic trajectories can be obtained for every robot performing any task.
3. Floquet theory is useful for determining only local stability. Local stability implies stability about the vicinity of the chosen periodic orbit, in this case, the desired trajectories - i.e., the actual trajectory of the robot must start in the vicinity of the desired trajectory ($q(0) \approx q_d(0)$ and $\dot{q}(0) \approx \dot{q}_d(0)$). On the other hand, global stability does not require the actual trajectory to start in the vicinity of the desired trajectory. Hence, in the form presented in this work, Floquet theory cannot be used for global stability analysis.

4. Floquet theory is a linearized stability analysis - this can be observed from the fact that the derivation of Eq. 3.14 requires neglecting higher order error terms. Although this is a limitation, the usefulness of Floquet theory can be understood from the fact that the linearization carried out in this work is about a reference solution as opposed to an equilibrium point. This is of particular importance in robot control theory due to the fact that in literature, two types of control for robot manipulators have been studied (Spong et al., 2004) - (i) Set point control, which deals with studying stability about a desired point (not varying with time), and (ii) trajectory tracking, which deals with stability in tracking a desired time varying trajectory. Trajectory tracking is the harder problem in robot control theory. Given that Floquet theory deals with linearization about a reference trajectory as opposed to a desired point, it is fundamentally useful when dealing with trajectory tracking.

3.4.5.2 Future Possible applications of Floquet theory

One of the drawbacks of PID controllers is that they may not give optimal results in the presence of disturbances and parametric uncertainty in system parameters. The application of Floquet theory in the case of parametric uncertainty has been demonstrated in (Reddy and Ghosal, 2018), where the authors apply Floquet theory to a 2D planar robot in the presence of parametric uncertainties driven by an augmented PD controller. The authors in (Reddy and Ghosal, 2018) demonstrated that asymptotic tracking could be achieved only for small values of mismatch in model parameters. Similar analysis can be conducted for other types of controllers (apart from the augmented PD controller) and the relation between the mismatch in the model parameters and the ranges of controller gains for asymptotic stability can be obtained. However, the application of Floquet theory to cases involving disturbances is not straightforward. When disturbances are present, the robot equations given by Eq. 3.5 will include a disturbance vector (for example, $[B(t)]_{4 \times 1}$) on the right hand side. When the analysis conducted in subsection 3.4.3 is applied to such a case, there will be an inhomogeneous term in Eq. 3.14 in addition to the homogeneous term. Equation 3.14 would be replaced by $\dot{y} = [J_n(t)]y + [H(t)]$, where $[J_n(t)]$ is the homogeneous term and $[H(t)]$ is the inhomogeneous term (resulting from the disturbance vector). To analyze the stability in this case, the Extended Floquet theory (Slane and Tragesser, 2011) must be used. However, there are certain limitations of this approach - namely, that such a technique can guarantee only simple stability and not asymptotic stability. Moreover, this approach also requires the inhomogeneous term ($[H(t)]$, comprising the terms in the disturbance vector) to have the same time period as that of the homogeneous term ($[J_n(t)]$, comprising the desired trajectory terms). This implies that the time period of the terms in the disturbance vector must be

the same as the time period of the desired trajectories. In practice however, this cannot be guaranteed. For this reason, the case of disturbances requires further analysis. Details on the Extended Floquet theory can be found in reference ([Slane and Tragesser, 2011](#)).

3.5 Summary

This chapter presents two climbing mechanisms, one based on prismatic joint and the other based on four degrees of freedom revolute-revolute-revolute-prismatic (RRRP) serial chain manipulator. The prismatic joint based climbing mechanism can climb only vertical straight pipes whereas the RRRP climbing mechanism can climb both vertical straight and ninety degree bend pipes. As the pipe climbing robot has an inchworm motion while it climbs the pipe, the RRRP climbing mechanism changes its configuration between RRRP and PRRR configuration at each step of the motion of the robot. The joint angles corresponding to the end-effector's position for different motion types are obtained using adaptive neuro-fuzzy inference system (ANFIS). Finally, the torque acting at each joint of the RRRP climbing mechanism for its two configurations are evaluated. This dynamic analysis of the RRRP climbing mechanism would be helpful to fabricate a pipe climbing robot with the ability to move on vertical straight and ninety degree bend pipes.

In the later half of the chapter, the trajectory tracking of the joints of a RRRP pick and place robot driven by a PID control law is studied, the feedback gains of which are tuned using Floquet theory. As Floquet theory can only be applied to periodic systems, a method is also presented to generate a periodic trajectory for any serial robot undergoing a pick and place operation. The robustness of Floquet theory to change in inertia of the RRRP robot is also established in this chapter. The Floquet theory can also be applied to the RRRP climbing mechanism if the pipe climbing robot executes a repetitive motion.

Chapter 4

Development of a Pipe Climbing Robot

4.1 Introduction

This chapter discusses the fabrication, electronic components integration, performance and overall development of the pipe climbing robot. The materials used for fabricating the robot are given in section 4.2. The load carrying capacity of the gripper is discussed in section 4.3. The prototype of the pipe climbing robot is given in section 4.4. This section also discusses the robot's working, the electronic components used, the robot's performance based on payload to weight ratio, and energy consumption. Section 4.5 discusses the mode of operation of the robot for pipes of any dimensions.

4.2 Materials Used and Fabrication

The transparent plates in the gripper are made of perspex and are cut into the required dimensions using CO₂ laser cutting machine. The plates are of dimensions : $(300 \times 150 \times 8.5) \text{ mm}^3$. The inner cavity in the plates is of dimensions : $(100 \times 60 \times 8.5) \text{ mm}^3$. The beams have been cut from spring steel sheets of C-80 grade using wirecut electrical discharge machining (EDM). The machining process and the fabricated beams are shown in Fig. 4.1. The cams are made of mild steel and have been fabricated using wirecut EDM. After the fabrication, the cam profile has been smoothed using CNC milling machine. The fabricated cams are shown in Fig. 4.2a. The camshaft is also made of mild steel and has been fabricated using CNC lathe. The cams have been attached to the camshaft in the required positions using tungsten inert gas (TIG) welding, as shown in Fig. 4.2b. The supports for DC motors and stepper motors have been fabricated from mild steel bars. The lever is also made of mild steel bar but has been bent to the required shape by forging, as shown in Fig. 4.3.



(a)



(b)



(c)



(d)

Figure 4.1: (a) Cutting operation being carried out at the Wirecut EDM machine, (b) display panel of the Wirecut EDM machine, showing the completion of cutting, (c) fabricated beams for carrying out experiments to determine snapping load (discussed in chapter 2), and (d) fabricated beams to be fitted into the gripper



(a)



(b)

Figure 4.2: (a) Fabricated cams, and (b) cams welded to the camshaft

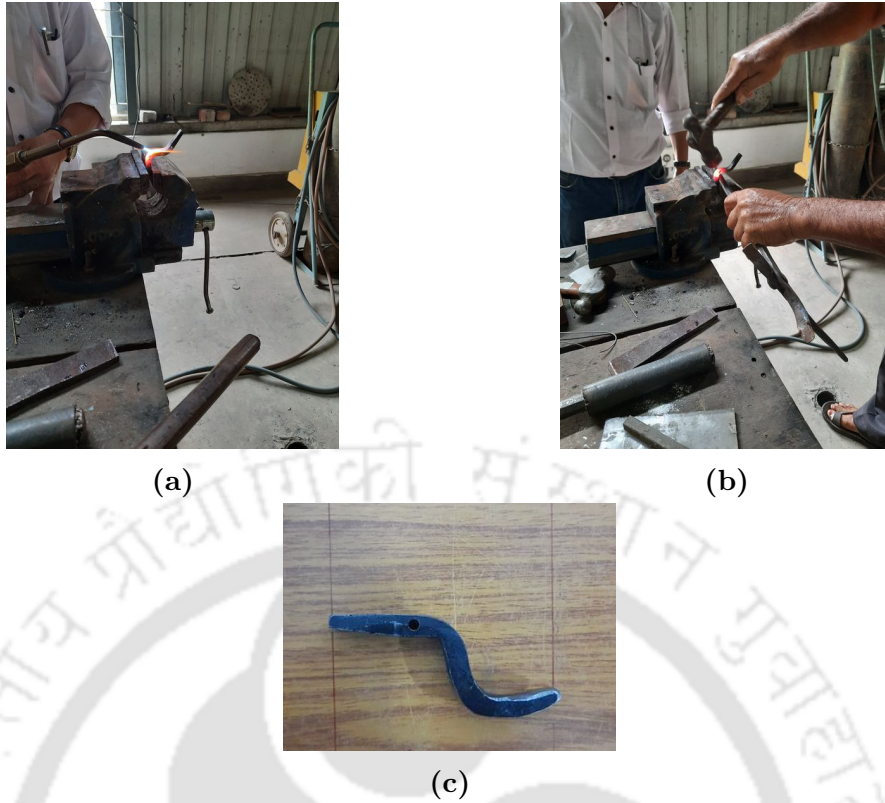
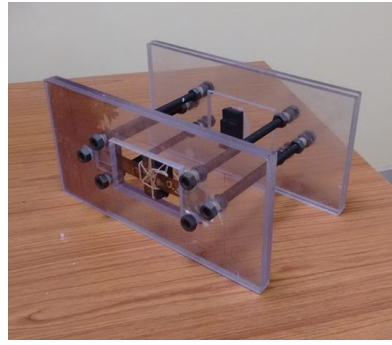


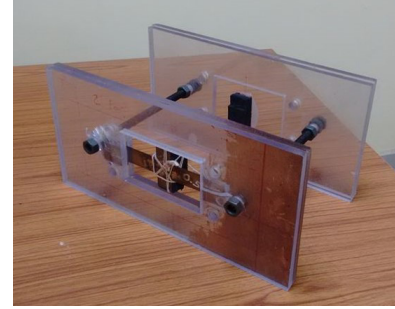
Figure 4.3: (a) A mild steel bar being heated using oxy-acetylene flame coming out of a weld torch, (b) the bar being hammered to the required shape of the lever, and (c) the fabricated lever

4.3 Load Carrying Capacity of the Gripper

Fig. 4.4 shows the prototype of the gripper. The gripper with six bolts, as shown in Fig. 4.4a, weighs 22.45 N. While carrying out experiments, it is found that the gripper with six bolts can carry an additional weight of 49.05 N. Thus, the overall load bearing capacity of the gripper with six bolts is 71.5 N and has a payload of 49.05 N. In order to increase the payload of the gripper, the weight of the gripper is reduced. This is done by reducing the number of bolts in the gripper. The gripper with two bolts, as shown in Fig. 4.4b, weighs 16.84 N and has an overall load bearing capacity of 36.46 N. The payload to weight ratio of the gripper with six bolts is 2.185 as compared to the gripper with two bolts, for which this value is 1.165. Also, the overall load bearing capacity of the former case is much higher than the latter. Hence, to increase the payload of the gripper without compromising its overall load bearing capacity, in the final prototype, two bolts with a nominal length of 200 mm are used as shown in Figs. 4.4b and 4.4c but the four holes in the plates associated with the bistable buckled beam are filled with bolts of nominal length 25 mm. The remaining four holes associated with the dummy plate are kept empty, as shown in Fig. 4.4c. The final prototype weighs 17.43 N and has an overall load bearing capacity of 71.5 N.



(a)



(b)



(c)



(d)

Figure 4.4: Prototype of the gripper with (a) 6 bolts, (b) 2 bolts, (c) mechanical drive system and (d) snapshot of the experiment for determining the load carrying capacity

After the design and development of the gripper, it is integrated with the mechanical drive system, as shown in Fig. 4.4c. There are also supports for the stepper motor at the two ends of the gripper. The gripper weighs 30.66 N and its overall load bearing capacity is 128.76 N. The increase in overall load bearing capacity of the gripper is due to the fact that camshaft in the gripped state also contributes to the gripping force, as shown in Fig. 4.4d. The payload to weight ratio of the gripper with the mechanical drive system is 3.2. Thus, the final prototype of the gripper along with the mechanical drive system can carry an additional load of 98.1 N.

4.4 Prototype of the Pipe Climbing Robot

The two grippers are integrated to form a pipe climbing robot, namely, Complibot, as shown in Fig. 4.5. Complibot has a motion similar to that of an inchworm. The two grippers are connected through two electrically actuated lead screws, which give a translational motion to the free gripper with respect to the fixed gripper. A CAD model of the climbing mechanism consisting of two electrically actuated lead screws is shown in Fig 4.6. Each lead screw is actuated using a stepper motor.

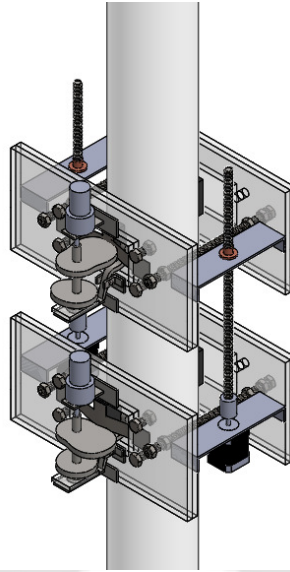


Figure 4.5: Isometric view of the 3-D CAD model of the pipe climbing robot with two grippers and a climbing mechanism

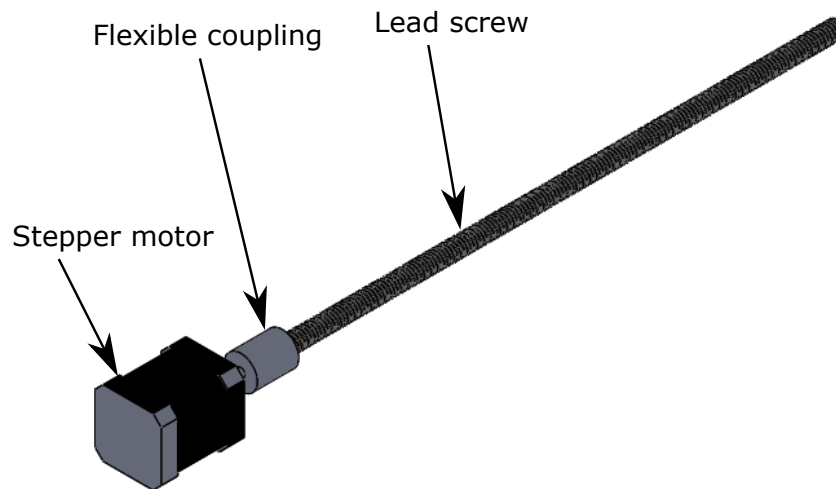


Figure 4.6: Isometric view of the 3-D CAD model of the climbing mechanism

4.4.1 Working

After assembling the prototype around the pipe, the lower gripper grips the pipe. First, the camshaft of the lower gripper rotates by an angle of ninety degrees and stops. The cam I pushes the bistable buckled beam from its OFF position to ON position, as is evident from the displacement diagram of cam I, as shown in Fig.

2.23b in chapter 2. The cam I continues to be in this position till the time the bistable buckled beam is in ON position. Next, the two stepper motors actuate the two lead screws synchronously, which push the upper gripper upward. The upper gripper remains free during all this time. After pushing the upper gripper to a pre-defined distance, the stepper motors stop. Then, the upper gripper grips the pipe. This is followed by lower gripper ungripping the pipe. While ungripping the pipe, the camshaft corresponding to the lower gripper which stopped after rotating ninety degrees completes the remaining two hundred seventy degrees and in doing so, cam II actuates the lever and brings the bistable buckled beam from its ON position to OFF position. Now, the upper gripper is fixed while the lower gripper is free. The two stepper motors rotate synchronously in the opposite sense this time, and hence the upper gripper pulls the lower gripper upward. Again, the lower gripper grips the pipe followed by the ungripping of the upper gripper. The stepper motors rotate and push the upper gripper upward with respect to the lower gripper. This process continues. The entire process would get reversed if the robot were to move in downward direction.

4.4.2 Actuators and Sensors Used

The pipe climbing robot uses a total of four actuators. Each gripper uses a DC motor to actuate the camshaft and there are two stepper motors which work synchronously to execute the translational motion of the robot. The robot uses NEMA 17 stepper motors which have a holding torque of 5.6 kg cm. Each stepper motor is driven through a TB6600 stepper motor driver, which controls the stepper motor's movement and speed. The DC motors used have a rated voltage and a rated speed of 12 V and 30 r.p.m., respectively. Both the DC motors are driven by two relays in a relay module. Each gripper also uses an infra-red (IR) obstacle sensor to control the position of cam I in the camshaft. The cam I in both the grippers stop after the camshaft rotates an angle of ninety degrees from the initial position. The angular position of the cams, the linear movement of one gripper with respect to the other gripper and the periodic motion of all the actuators, one after the other are controlled by a program written in Arduino software and fed to the Arduino Uno micro-controller board. A two button switch is used to control the upward and downward motion of the robot. A current sensor is also used to calculate the power consumed by the robot.

4.4.3 Demonstration

Figure 4.7 shows some snapshots of the movement of the robot on a vertical PVC pipe of 110 mm diameter. The robot works well and climbs up and down the pipe without any slip. This robot can also be used to climb other cylindrical objects like areca nut tree and electric poles. Table 4.1 compares the developed pipe climbing

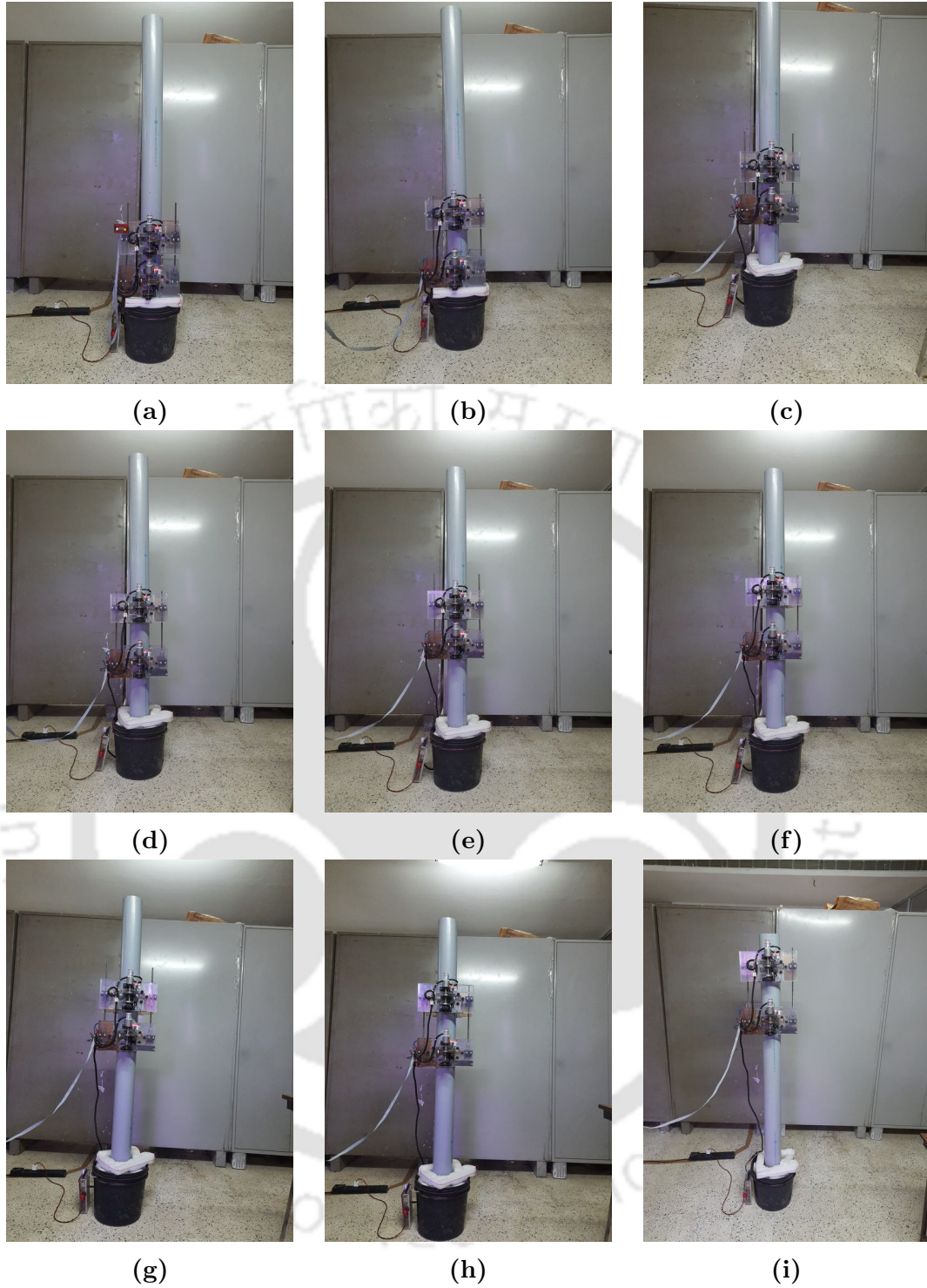


Figure 4.7: Snapshots of the movement of the robot on a vertical pipe

robot, Complibot, with some of the existing pipe climbing robots. The data for the existing pipe climbing robots in Table 4.1 has been taken from the data in Table 1.4.

From Table 4.1, it can be seen that Complibot has a payload to weight ratio of 0.52 and consumes an average power of 18.58 W. Thus, Complibot is a very efficient robot as it has a very high payload to weight ratio compared to the minimum

Table 4.1: Comparison with similar pipe climbing robots

Pipe climbing robots	Mass (kg)	Payload (kg)	Payload to weight ratio	Energy/Power	Velocity (m min ⁻¹)
Das et al. (2016)	20	—	—	—	2.18
Han et al. (2016)	30	10	0.33	—	10.8
Khan et al. (2020)	1.42	0.08	0.06	—	1.5
Tavakoli et al. (2011)	42	—	—	—	1
Lau et al. (2013)	3	—	—	—	0.23
Guan et al. (2016)	17.5	2.5	0.14	272.3 J (Inchworm gait)	—
Complibot	7.69	4	0.52	18.58 W	0.2

power it consumes.

4.5 Mode of Operation of the Robot

There are provisions in Complibot by which it can adapt to pipes of different diameters. To use and assemble the Complibot on a pipe, the following steps are to be followed-

- **Find out the pipe specifications**

At first, the pipe diameter, D_p , is to be found out. In most cases, the user would be knowing the pipe diameter, D_p , beforehand. However, it can be found out by measuring the circumference of the pipe with a measuring tape.

- **Calculate weight of the robot**

Next, the total weight of the robot or the total weight on the pipe, W , is to be calculated by combining the weights of gripper, climbing mechanism, payload, among others.

- **Selection of a proper beam and calibration**

With W known, the gripper should generate as much grip on the pipe that the friction force, F_f , generated is greater than the total weight W . This ensures a successful grip on the pipe. Thus, the gripping of pipe by the gripper depends on the condition-

$$F_f > W \quad (4.1)$$

The value of F_f depends on the following two factors-

- (a) The coefficient of friction, μ , between the rubber pads and the pipe.
- (b) The gripping force, F_g , exerted by the bistable buckled beam.

As stated before in chapter 2, the gripping force, F_g , that the bistable buckled beam exerts on the pipe depends on the width and thickness of the beam and the axial deflection, D_a , given to the unstressed beam. Also, emphasis is to be given to the material of the rubber pads. It is preferable to use pads made of silicone rubber. This is because the value of μ of silicone rubber with other surfaces is mostly greater than one, $\mu > 1$. This ensures a lesser gripping force to be exerted by the bistable buckled beam on the pipe and hence lesser size of the beam and smaller D_a .

The gripping force, F_g exerted by the buckled beam on the pipe can be calculated with the help of following formula-

$$F_g = \frac{F_f}{\mu} \quad (4.2)$$

where $F_f > W$. The snapping load of the mid-point of the buckled beam, L_s , is equivalent to F_g . Hence, with F_g calculated, the user can select a beam of a particular dimension and the amount of D_a the beam would be subjected to from the experimental data points of Tables 2.3 and 2.4, between D_a and L_s for different dimensions of the beam.

- **Assembly and mounting**

The gap between the plates for clamping the beam and the plate for affixing the rubber pad, g , as can be seen in Fig. 4.8, depends upon D_p and the vertical deflection of the mid-point of the beam from the mean position, D_v . The gap, g , can be calculated by using the following formula-

$$g = D_p + t_c + t_s + (D_v - t_p) \quad (4.3)$$

where t_c is the thickness of the rubber pad on the buckled beam, t_s is the thickness of the rubber pad which is affixed on the plate and t_p is the thickness of a plate, as shown in Fig. 4.8.

D_v depends on D_a given to the beam. Depending upon the D_a given to the unstressed straight beam, which depends upon the F_g the user requires, the D_v corresponding to the D_a can thus be obtained from the experimental data points of Tables 2.1 and 2.2. With this numerical data, g can be calculated and the assembly of the gripper can be done systematically.

It is to be noted that during assembly of the gripper, D_a can only be measured and not D_v as reaching out to the beam inside the gripper is difficult. Hence, D_v corresponding to a chosen D_a is to be obtained from Tables 2.1 and 2.2.

Next, the gripper is assembled by simultaneously assembling the plates by maintaining the gap, g . While assembly, the value of g is kept slightly less

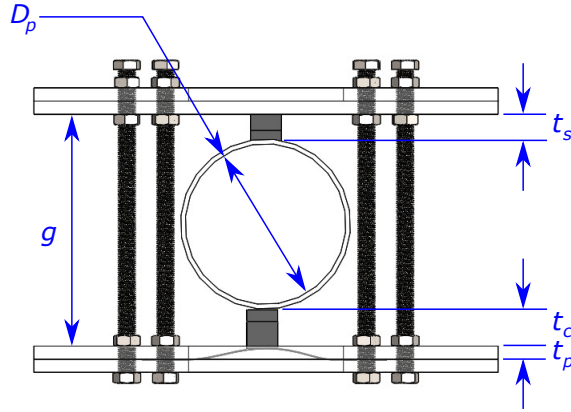


Figure 4.8: Top view of the gripper with labels

than the exact value. This is because if g is exact, the rubber pads would just touch the pipe and no gripping force would be generated.

- **Actuation**

After assembly and mounting, the unstressed straight beam has to be buckled once at the very beginning by axially loading the straight unstressed beam. For this, the three nuts on the outer side of the plates for clamping the beam, are loosened and the beam is given D_a of the calculated amount, depending on the user. This axial loading is done manually by the user. The beam being very thin gets buckled due to the axial loading. The three nuts which were unscrewed before, are tightened. The beam now remains in buckled state. The buckled beam can be toggled across the two stable equilibrium states, by using actuators. The design of two mechanical drive systems to automate the gripping has already been discussed in chapter 2.

4.6 Summary

This chapter presents the development of a compliant external pipe climbing robot with inchworm locomotion, namely, Complibot. The gripper designed previously in chapter 2 is fabricated and integrated with another gripper by two stepper motor driven lead screws to form Complibot. Experiments are carried out on the gripper alone to determine its maximum load carrying capacity. Same experiments are also carried out on Complibot during its motion on the pipe to determine its maximum load carrying capacity, payload, speed and energy consumed. It is found that Complibot has one of the best payload to weight ratios (0.52) with minimum energy consumption (18.7 W). The steps involved in using Complibot in pipes of different diameters are also discussed.

Chapter 5

Conclusion and Scope for Future Research

5.1 Introduction

In this chapter, the conclusion of the present research has been highlighted and scope for the future work is also explained. Section 5.2 discusses the general conclusions that can be drawn from this thesis. Specific conclusions are given in section 5.3 and the scopes for future research are given in section 5.4.

5.2 General Conclusions

In this thesis, a pipe climbing robot having inchworm locomotion is designed and developed. Pipes are widely used in industries and residential areas which require periodic inspection to prevent an accident. Hence, pipe climbing robots are being developed to cater to the needs of industries and residential areas. In this context, the present thesis has designed and developed a pipe climbing robot with a novel gripper design involving a bistable buckled beam. Two novel designs involving cams and a Scotch Yoke cum beam engine inspired mechanism are also studied to automate the gripping process of the gripper. Theoretical studies are also carried out on a novel revolute-revolute-revolute-prismatic (RRRP) climbing mechanism using a soft computing technique, namely, adaptive neuro-fuzzy inference system (ANFIS). The trajectory tracking of joint angles of an RRRP pick and place serial manipulator is also studied by using Floquet theory.

The pipe climbing robot with inchworm locomotion is preferred over other locomotion techniques as pipe climbing robots with inchworm locomotion have better load carrying capacity as compared to wheeled, legged and snake robots. Generally, any pipe climbing robot with inchworm locomotion has two grippers and a climbing mechanism, which connects the two grippers. The operation of a bistable buckled beam is chosen as the gripping mechanism in the grippers of the robot as

a bistable buckled beam has two stable equilibrium states in its range of motion and does not require any energy to maintain the two stable equilibrium states. A CAD model of the gripper is designed in Solidworks. Experimental and numerical studies are also carried out on the bistable buckled beam to determine the design parameters, snapping load and vertical deflection corresponding to a given axial deflection. The axial deflection to the beam is given once manually in the very beginning, due to which the straight beam buckles. After that, the buckled beam is toggled from one stable equilibrium state to the other stable equilibrium state and vice-versa.

To automate the actuation of the bistable buckled beam, two mechanical drive systems are modelled and designed. One of the drive systems is a Scotch Yoke cum beam engine inspired mechanism and the other drive system is a camshaft with two cams. The second drive system involving cams is chosen over the Scotch Yoke cum beam engine inspired mechanism as the second drive system has lesser number of parts than the beam engine inspired mechanism. Both the drive systems are modelled and their working is checked using animation, basic motion and motion analysis options in Solidworks.

After the gripper is designed, two climbing mechanisms are proposed. One is based on prismatic joint, for climbing straight vertical pipes and the other is based on RRRP serial manipulator, for climbing ninety degree bend pipes. The dynamic analysis of the RRRP climbing mechanism is carried out by planning the movement of the robot in a ninety degree bend pipe. While climbing the pipe, the climbing mechanism changes its configuration from RRRP to PRRR and vice-versa at each step. Then, ANFIS is used to solve the inverse kinematics. Lastly, the Euler-Lagrange equation of motion is used to obtain the torque acting at the joints of the robot.

The trajectory tracking at the joints of a RRRP serial pick and place robot, governed by proportional-integral-derivative control law is done by using Floquet theory which can only be applied to periodic systems. Hence, a periodic trajectory planning in joint space is carried out which makes the trajectory of any pick and place robot periodic.

After designing the gripper, two grippers are fabricated and are integrated with two stepper motor driven lead screws to form an inchworm type pipe climbing robot, Complibot. Experiments are carried out to find the maximum load carrying capacity of the gripper during static state and of the robot during dynamic state. The power consumption of the robot is also found out.

5.3 Specific Conclusions

The specific conclusions are given point wise in the following subsections.

5.3.1 Design of the Gripping Mechanism

- A bistable buckled beam of dimension - $(100 \times 20 \times 0.5)$ mm³ is used to provide a maximum gripping force of 45.78 N, when subjected to an axial deflection of 3 mm.
- The design parameters associated with the bistable buckled beam, (i) vertical displacement of the mid-point of the beam, D_v and (ii) snapping load of the beam when actuated at the mid-point, L_s for dimensions - $(100 \times 20 \times 0.5)$ mm³ are 10.5 mm and 45.78 N, respectively.
- To obtain a higher gripping force, one may use thicker beams and can also increase the axial deflection (pre-stress) given to the straight unstressed beam. However, it may be noted that it is difficult to control the pre-stress in beams, which are thicker than 0.5 mm. Also, the beam begins deforming plastically when given an axial deflection, greater than 3 mm.

5.3.2 Design of the Mechanical Drive Systems

- The bistable buckled beam is actuated using a mechanical drive system of camshaft and lever. The two cams in the camshaft have a prime circle radius of 25 mm. The lift for cam I is 30 mm whereas the lift for cam II is 10 mm. The offset distance for cam II is 20 mm.
- The profile of cam I in the camshaft is designed by a cycloidal motion function and it is assumed that it mates with a radial follower.
- The profile of cam II in the camshaft is designed by assuming it to mate with an offset follower. An eighth order polynomial function is used to design the cam profile.
- The bistable buckled beam can also be actuated using a drive system consisting of a novel Scotch Yoke cum beam engine inspired mechanism and a lever. In the proposed mechanism, the distance between the crank center and the pin is 7 mm and the length of the rocker is 47 mm.

5.3.3 Dynamic Analysis of the Climbing Mechanism

- A total of 15,059 data points and 7,733 data points are used to train the ANFIS models corresponding to RRRP configuration and PRRR configuration of the climbing mechanism, respectively.
- The ANFIS models corresponding to both the configurations are able to satisfactorily predict joint angles corresponding to different end-effector positions, with error lying within 10^{-1} m.

- To obtain the nominal torque of the joints of the RRRP climbing mechanism, the trajectory in joint space between two points is planned using the method of “modified linear function with parabolic blens”. The constant angular acceleration at the blends is taken as 0.1 rad s^{-2} for all the joints. The start, end and rest times are taken as 0 s, 12 s and 1 s, respectively, for all the joints and for all the motion types of the climbing mechanism.

5.3.4 Trajectory Tracking of the RRRP Pick and Place Robot

- A Fourier half range cosine series is used to get the periodic trajectories for the joints of the robot.
- Floquet theory is found to be robust to the change in inertia of the robot. Floquet theory is successfully used for accurate trajectory tracking of the joints when the inertia of the robot is changed randomly with maximum deviation of any link lying within 10 %.
- It is observed that for heavier links and for higher values of K_i , the region of stability exists only for higher values of K_p and K_v .
- The maximum overshoot for the error plots corresponding to the feedback gains of a stable region is found to be 10^{-3} .

5.3.5 Development of the Pipe Climbing Robot

- Complibot has a payload to weight ratio of 0.52, a power consumption of 18.58 W and has a speed of 0.202 m min^{-1} .
- Complibot has a high payload with minimum energy consumption and a good overall load bearing capacity as it uses a novel gripper with bistable buckled beam as the gripping mechanism. The proposed gripper, along with cams in static condition has a very high payload to weight ratio of 3.2.

5.4 Scope for Future Research

The possible extensions of the thesis, which one can carry out in the future are given in the following points.

- The weight of the robot is 7.69 kg and its overall load bearing capacity is 11.69 kg. The payload of the robot can be increased by removing excess material from the gripper and the cams. The topology optimization of the gripper may also be carried out to increase its payload without affecting its overall load bearing capacity.

- In the present work, a bistable buckled beam is used in the gripper to grip the pipe. In place of a bistable buckled beam, an as-fabricated bistable curved beam (Qiu et al., 2004) could also be used. The as-fabricated bistable curved beam can be optimized so that it has a very low switching point but a very high switch back point. This would ensure that the as-fabricated curved beam is able to exert a very high gripping force. A very low switching point would mean a very less amount of energy would be required for its switching. However, a very high energy would be required to bring the as-fabricated bistable curved beam back to its ungripped state.
- In the developed pipe climbing robot, two stepper motor driven lead-screws are used as the climbing mechanism. For the pipe climbing robot with an RRRP climbing mechanism, most of the load acts on one side of the gripper, giving rise to an unbalanced moment about the pipe. Hence, one may put balance weights on one side of the gripper, ensuring that the center of gravity lies at the center point of the gripper and the robot.
- Theoretical studies have been carried out for the RRRP climbing mechanism. So, based on these, one can fabricate and successfully demonstrate the pipe climbing robot on a ninety degree bend pipe with RRRP climbing mechanism.
- In the present work, ANFIS is used to obtain the joint angles from the given end-effector positions of the RRRP climbing mechanism. One can use ANFIS for real time trajectory planning in Cartesian space. ANFIS based controllers could also be developed for the RRRP climbing mechanism.
- Non-destructive testing equipment used for the inspection of pipes could be integrated with the developed pipe climbing robot.
- The concept of bistable buckled beam as a gripper in pipes could also be extended to the development of internal pipe climbing robots.

References

- Abbas, M., Narayan, J., and Dwivedy, S. K. (2019). Simulation analysis for trajectory tracking control of 5-DOFs robotic arm using ANFIS approach. In *5th International Conference on Computing, Communication, Control and Automation (ICCUBEA)*, pages 1–6.
- Abdallah, C., Dawson, D. M., Dorato, P., and Jamshidi, M. (1991). Survey of robust control for rigid robots. *IEEE Control Systems Magazine*, 11(2):24–30.
- Al-Fahaam, H., Nefti-Meziani, S., Theodoridis, T., and Davis, S. (2018). The design and mathematical model of a novel variable stiffness extensor-contractor pneumatic artificial muscle. *Soft Robotics*, 5(5):576–591.
- Almonacid, M., Saltaren, R. J., Aracil, R., and Reinoso, O. (2003). Motion planning of a climbing parallel robot. *IEEE Transactions on Robotics and Automation*, 19(3):485–489.
- Andò, B., Baglio, S., Bulsara, A., and Marletta, V. (2014). A bistable buckled beam based approach for vibrational energy harvesting. *Sensors and Actuators A: Physical*, 211:153–161.
- Aoyagi, R., Homma, Y., and Ito, K. (2017). Six-legged robot capable of climbing various columnar objects. In *International Conference on Advanced Mechatronic Systems (ICAMechS)*, pages 24–29.
- Aracil, R., Saltarén, R., Almonacid, M., Azorín, J. M., and Sabater, J. M. (2000). Climbing parallel robots morphologies. *IFAC Proceedings Volumes*, 33(27):471–476.
- Aracil, R., Saltarén, R., and Reinoso, O. (2003). Parallel robots for autonomous climbing along tubular structures. *Robotics and Autonomous Systems*, 42(2):125–134.
- Ayala, H. V. H. and dos Santos Coelho, L. (2012). Tuning of PID controller based on a multiobjective genetic algorithm applied to a robotic manipulator. *Expert Systems with Applications*, 39(10):8968–8974.

- Baghani, A., Ahmadabadi, M., and Harati, A. (2005). Kinematics modeling of a wheel-based pole climbing robot (UT-PCR). In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 2099–2104.
- Balakuntala, M. V., Palathingal, S., and Ananthasuresh, G. (2021). A passive universal grasping mechanism based on an everting shell. In *Mechanism and Machine Science*, pages 601–608.
- Baumgartner, R., Kogler, A., Stadlbauer, J. M., Foo, C. C., Kaltseis, R., Baumgartner, M., Mao, G., Keplinger, C., Koh, S. J. A., Arnold, N., et al. (2020). A lesson from plants: high-speed soft robotic actuators. *Advanced Science*, 7(5):1903391.
- Buragohain, M. and Mahanta, C. (2008). A novel approach for ANFIS modelling based on full factorial design. *Applied Soft Computing*, 8(1):609–625.
- Burden, R. L. and Faires, J. D. (2011). *Numerical Analysis*. Brooks/Cole, Cengage Learning.
- Carabin, G., Emanuelli, D., Gallo, R., Mazzetto, F., and Vidoni, R. (2020). Development of a climbing-robot for spruce pruning: preliminary design and first results. In *Symposium on Robot Design, Dynamics and Control*, pages 100–108.
- Cazottes, P., Fernandes, A., Pouget, J., and Hafez, M. (2009). Bistable buckled beam: modeling of actuating force and experimental validations. *ASME Journal of Mechanical Design*, 131(10):101001.
- Cervantes, I. and Alvarez-Ramirez, J. (2001). On the PID tracking control of robot manipulators. *Systems and Control Letters*, 42(1):37–46.
- Chang, P.-L., Chi, I.-T., Tran, N. D. K., and Wang, D.-A. (2020). Design and modeling of a compliant gripper with parallel movement of jaws. *Mechanism and Machine Theory*, 152:103942.
- Charlot, B., Sun, W., Yamashita, K., Fujita, H., and Toshiyoshi, H. (2008). Bistable nanowire for micromechanical memory. *Journal of Micromechanics and Microengineering*, 18(4):045005.
- Chen, G., Gou, Y., and Zhang, A. (2011). Synthesis of compliant multistable mechanisms through use of a single bistable mechanism. *ASME Journal of Mechanical Design*, 133(8):081007.
- Choi, A. J., Yang, H.-H., and Han, J.-H. (2021). Study on robust aerial docking mechanism with deep learning based drogue detection and docking. *Mechanical Systems and Signal Processing*, 154:107579.

- Cohen, G. and Coon, G. (1953). Theoretical consideration of retarded control. *Trans. ASME*, 75:827–834.
- Cottone, F., Gammaitoni, L., Vocca, H., Ferrari, M., and Ferrari, V. (2012). Piezoelectric buckled beams for random vibration energy harvesting. *Smart Materials and Structures*, 21(3):035021.
- Craig, J. J., Hsu, P., and Sastry, S. S. (1987). Adaptive control of mechanical manipulators. *The International Journal of Robotics Research*, 6(2):16–28.
- Das, M., Agrawal, A., Sonone, A., Gupta, R., Upadhyay, D., Rao, Y., and Javed, A. (2016). Developing a bioinspired pole climbing robot. In *International Conference on Robotics: Current Trends and Future Challenges (RCTFC)*, pages 1–6.
- Daynes, S., Potter, K., and Weaver, P. (2008). Bistable prestressed buckled laminates. *Composites Science and Technology*, 68(15-16):3431–3437.
- Diaconu, C., Weaver, P., and Mattioni, F. (2007). Solutions for morphing airfoil sections using bi-stable laminated composite structures. In *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, page 1719.
- Estier, T., Crausaz, Y., Merminod, B., Lauria, M., Piguet, R., and Siegwart, R. (2000). An innovative space rover with extended climbing abilities. In *Robotics 2000*, pages 333–339.
- Faber, J. A., Udani, J. P., Riley, K. S., Studart, A. R., and Arrieta, A. F. (2020). Dome-patterned metamaterial sheets. *Advanced Science*, 7(22):2001955.
- Faizal, M. N., Othman, W., and Hassan, S. S. (2015). Development of pole-like tree climbing robot. In *IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, pages 224–229.
- Fan, J., Yang, C., Chen, Y., Wang, H., Huang, Z., Shou, Z., Jiang, P., and Wei, Q. (2018). An underwater robot with self-adaption mechanism for cleaning steel pipes with variable diameters. *Industrial Robot: An International Journal*, 45(2):193–205.
- Fauroux, J.-C. and Morillon, J. (2010a). Design of a climbing robot for cylindro-conic poles based on rolling self-locking. In *Mobile Robotics: Solutions and Challenges*, pages 447–454.
- Fauroux, J.-C. and Morillon, J. (2010b). Design of a climbing robot for cylindro-conic poles based on rolling self-locking. *Industrial Robot: An International Journal*, 37(3):287–292.

- Fengyu, X., Jinlong, H., and Bei, W. (2015). The obstacle-climbing capability of a pole-climbing robot. In *34th Chinese Control Conference (CCC)*, pages 5863–5868.
- Follador, M., Conn, A., and Rossiter, J. (2015). Bistable minimum energy structures (BiMES) for binary robotics. *Smart Materials and Structures*, 24(6):065037.
- Fu, K. S., Gonzalez, R., and Lee, C. G. (1987). *Robotics: Control Sensing. Vis.* Tata McGraw-Hill Education.
- Gao, H. (2020). Wheel based pole climbing structure built for replacing manpower in hazardous environments and creating a platform for telegraph pole deicing and reconstruction. In *Journal of Physics: Conference Series*, volume 1549, page 052017.
- Ghorbel, F., Srinivasan, B., and Spong, M. W. (1998). On the uniform boundedness of the inertia matrix of serial robot manipulators. *Journal of Robotic Systems*, 15(1):17–28.
- Goldman, G. and Hong, D. (2008). Considerations for finding the optimal design parameters for a novel pole climbing robot. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 43260, pages 859–866.
- Gray, J. (1946). The mechanism of locomotion in snakes. *Journal of Experimental Biology*, 23(2):101–120.
- Grosan, C., Abraham, A., and Tigan, S. (2006). Engineering drug design using a multi-input multi-output neuro-fuzzy system. In *Eighth International Symposium on Symbolic and Numeric Algorithms for Scientific Computing*, pages 365–371.
- Guan, Y., Jiang, L., Zhang, X., and Zhang, H. (2009). Climbing gaits of a modular biped climbing robot. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pages 532–537.
- Guan, Y., Jiang, L., Zhu, H., Wu, W., Zhou, X., Zhang, H., and Zhang, X. (2016). Climbot: A bio-inspired modular biped climbing robotsystem development, climbing gaits, and experiments. *ASME Journal of Mechanisms and Robotics*, 8(2).
- Guan, Y., Jiang, L., Zhu, H., Zhou, X., Cai, C., Wu, W., Li, Z., Zhang, H., and Zhang, X. (2011). Climbot: A modular bio-inspired biped climbing robot. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1473–1478.

- Hafez, M., Lichter, M. D., and Dubowsky, S. (2003). Optimized binary modular reconfigurable robotic devices. *IEEE/ASME Transactions on Mechatronics*, 8(1):18–25.
- Han, S., Ahn, J., and Moon, H. (2016). Remotely controlled prehensile locomotion of a two-module 3D pipe-climbing robot. *Journal of Mechanical Science and Technology*, 30(4):1875–1882.
- Han, S. C., An, J., and Moon, H. (2013). A remotely controlled out-pipe climbing robot. In *10th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, pages 126–126.
- Hao, G. and Kong, X. (2012). Conceptual design and modelling of a self-adaptive compliant parallel gripper for high-precision manipulation. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 45035, pages 161–167.
- Hao, G., Mullins, J., and Cronin, K. (2017). Simplified modelling and development of a bi-directionally adjustable constant-force compliant gripper. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 231(11):2110–2123.
- Haynes, G. C., Khripin, A., Lynch, G., Amory, J., Saunders, A., Rizzi, A. A., and Koditschek, D. E. (2009). Rapid pole climbing with a quadrupedal robot. In *IEEE International Conference on Robotics and Automation*, pages 2767–2772.
- Howell, L. L., Rao, S., and Midha, A. (1994). Reliability-based optimal design of a bistable compliant mechanism. *ASME Journal of Mechanical Design*, 116(4):1115–1121.
- Huang, H.-W. and Yang, Y.-J. (2012). A MEMS bistable device with push-on–push-off capability. *Journal of Microelectromechanical Systems*, 22(1):7–9.
- Huang, W., Jin, H., Ge, M., and Zhao, J. (2020). A new pressure-adsorption climbing robot realized through ducted fan. In *International Conference on Artificial Intelligence and Information Systems (ICAIS)*, pages 643–646.
- Imajo, N., Takada, Y., and Kashinoki, M. (2015). Development and evaluation of compact robot imitating a hermit crab for inspecting the outer surface of pipes. *Journal of Robotics*. Volume : 2015, Article ID : 312780.
- Ito, K., Aoyagi, R., and Homma, Y. (2019). TAOYAKA-III: a six-legged robot capable of climbing various columnar objects. *Journal of Robotics and Mechatronics*, 31(1):78–87.

- Ito, K., Homma, Y., and Rossiter, J. (2020). The soft multi-legged robot inspired by octopus: climbing various columnar objects. *Advanced Robotics*, 34(17):1096–1109.
- Ito, K. and Ninomiya, Y. (2021). TAOYAKA V: a multi-legged robot, successfully combining walking and climbing mechanisms. *Artificial Life and Robotics*, 26(1):97–102.
- Jang, J.-S. R., Sun, C.-T., and Mizutani, E. (2004). *Neuro-Fuzzy and Soft Computing-A Computational Approach to Learning and Machine Intelligence*. Pearson Education(Singapore) Pte. Ltd., Indian Branch, Delhi.
- Jayasundara, I., Mudugamuwa, A., Baokun, H., Perera, K., and Amarasinghe, Y. (2020). Design and development of a novel external pipe crawling robot ex-piro. In *5th International Conference on Robotics and Automation Engineering (ICRAE)*, pages 121–125.
- Jensen, B., Howell, L., and Salmon, L. (1999). Design of two-link, in-plane, bistable compliant micro-mechanisms. *ASME Journal of Mechanical Design*, 121(3):416–423.
- Jiang, Y., Chen, D., Zhang, H., Giraud, F., and Paik, J. (2020). Multimodal pipe-climbing robot with origami clutches and soft modular legs. *Bioinspiration & Biomimetics*, 15(2):026002.
- Jitosho, R., Choi, K., Foris, A., and Mazumdar, A. (2019). Exploiting bistability for high force density reflexive gripping. In *International Conference on Robotics and Automation (ICRA)*, pages 1241–1247.
- Kamagaluh, B., Kumar, J. S., and Virk, G. S. (2012). Design of multi-terrain climbing robot for petrochemical applications. In *Adaptive Mobile Robotics*, pages 639–646.
- Kamegawa, T., Harada, T., and Gofuku, A. (2009). Realization of cylinder climbing locomotion with helical form by a snake robot with passive wheels. In *IEEE International Conference on Robotics and Automation*, pages 3067–3072.
- Kasac, J., Novakovic, B., Majetic, D., and Brezak, D. (2004). Global asymptotic stabilization of robot manipulators with mixed revolute and prismatic joints. *IFAC Proceedings Volumes*, 37(13):1461–1466.
- Kasac, J., Novakovic, B., Majetic, D., and Brezak, D. (2006). Global positioning of robot manipulators with mixed revolute and prismatic joints. *IEEE Transactions on Automatic Control*, 51(6):1035–1040.

- Khalid, Z. B., Ullah, M. H., Ahmed, R., Choudhury, Z. H., Kaish, I., and Rhaman, M. K. (2015). Electrical pole climbing robot: For wiring and repairing distribution lines. In *18th International Conference on Computer and Information Technology (ICCIT)*, pages 368–372.
- Khan, H. (2021). Efficient design and analysis of battery switching stations for the collaborative wireless network of mobile robots. In *International Conference on Artificial Intelligence (ICAI)*, pages 198–202.
- Khan, M. B., Chuthong, T., Do, C. D., Thor, M., Billeschou, P., Larsen, J. C., and Manoonpong, P. (2020). iCrawl: An inchworm-inspired crawling robot. *IEEE Access*, 8:200655–200668.
- Khan, S. and Prabhu, S. (2018). Design and fabrication of wheeled pole climbing robot with high payload capacity. In *2nd International Conference on Advances in Mechanical Engineering*, pages 1–7.
- Kim, J.-H., Lee, J.-C., and Choi, Y.-R. (2012). Vision-based pipe grasping scheme for a pole climbing robot. In *International Symposium on Optomechatronic Technologies (ISOT)*, pages 1–2. IEEE.
- Kim, J.-H., Lee, J.-C., and Choi, Y.-R. (2018). PiROB: Vision-based pipe-climbing robot for spray-pipe inspection in nuclear plants. *International Journal of Advanced Robotic Systems*, 15(6):1729881418817974.
- Kim, J.-H., Lee, J.-C., Choi, Y.-R., and Lee, S. (2016). Automatic grasping of a pole climbing robot using a visual camera with laser line beams. In *MATEC Web of Conferences*, volume 42, page 03005.
- Kim, S.-W., Koh, J.-S., Cho, M., and Cho, K.-J. (2010). Towards a bio-mimetic flytrap robot based on a snap-through mechanism. In *3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, pages 534–539.
- Kreyszig, E. (1999). *Advanced Engineering Mathematics, 8-th edition*. John Wiley and Sons.
- Kumar, V., Nakra, B., and Mittal, A. (2011). A review on classical and fuzzy pid controllers. *International Journal of Intelligent Control and Systems*, 16(3):170–181.
- Lankalapalli, S. and Ghosal, A. (1997). Chaos in robot control equations. *International Journal of Bifurcation and Chaos*, 7(03):707–720.
- Lau, S., Othman, W., and Bakar, E. A. (2013). Development of slider-crank based pole climbing robot. In *IEEE International Conference on Control System, Computing and Engineering*, pages 471–476.

- Lee, S. H. (2013). Design of the out-pipe type pipe climbing robot. *International Journal of Precision Engineering and Manufacturing*, 14(9):1559–1563.
- Lerner, E., Zhang, H., and Zhao, J. (2020). Design and experimentation of a variable stiffness bistable gripper. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 9925–9931.
- Lewis, F. L., Dawson, D. M., and Abdallah, C. T. (2003). *Robot Manipulator Control: Theory and Practice*. CRC Press.
- Lipkin, K., Brown, I., Peck, A., Choset, H., Rembisz, J., Gianfortoni, P., and Naaktgeboren, A. (2007). Differentiable and piecewise differentiable gaits for snake robots. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1864–1869.
- Liu, C.-H., Huang, G.-F., and Chen, T.-L. (2017). An evolutionary soft-add topology optimization method for synthesis of compliant mechanisms with maximum output displacement. *ASME Journal of Mechanisms and Robotics*, 9(5).
- Liu, W., Badel, A., Formosa, F., Wu, Y., and Agbossou, A. (2013). Novel piezoelectric bistable oscillator architecture for wideband vibration energy harvesting. *Smart Materials and Structures*, 22(3):035013.
- Liu, Y., Kim, H., and Seo, T. (2016a). AnyClimb: A new wall-climbing robotic platform for various curvatures. *IEEE/ASME Transactions on Mechatronics*, 21(4):1812–1821.
- Liu, Y., Lee, D., Kim, H., and Seo, T. (2015). Compliant wall-climbing robotic platform for various curvatures. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 532–537.
- Liu, Y. and Xu, Q. (2016). Design and analysis of a micro-gripper with constant force mechanism. In *12th World Congress on Intelligent Control and Automation (WCICA)*, pages 2142–2147.
- Liu, Y., Zhang, Y., and Xu, Q. (2016b). Design and control of a novel compliant constant-force gripper based on buckled fixed-guided beams. *IEEE/ASME Transactions on Mechatronics*, 22(1):476–486.
- Ma, G., Liu, X., Pagilla, P. R., and Ge, S. S. (2019). Tracking of periodic trajectories for switched systems under time-varying asynchronous switching. *ASME Journal of Dynamic Systems, Measurement, and Control*, 141(8):084502.
- Maempel, J., Koch, T., Koehring, S., Obermaier, A., and Witte, H. (2009). Concept of a modular climbing robot. In *IEEE Symposium on Industrial Electronics & Applications*, volume 2, pages 789–794.

- Mahdavi, S., Noohi, E., and Ahmadabadi, M. N. (2007). Basic movements of a nonholonomic wheel-based pole climbing robot. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pages 1–6.
- Mampel, J., Gerlach, K., Schilling, C., and Witte, H. (2009). A modular robot climbing on pipe-like structures. In *4th International Conference on Autonomous Robots and Agents*, pages 87–91.
- Masters, N. D. and Howell, L. L. (2003). A self-retracting fully compliant bistable micromechanism. *Journal of Microelectromechanical Systems*, 12(3):273–280.
- Mavanthoor, A. and Midha, A. (2006). Bistable compliant four-bar mechanisms with a single torsional spring. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 42568, pages 151–157.
- Mishra, D., Agrawal, K., Yadav, R., and Srivastava, R. (2018). Design of out pipe crawler for oil refinery based on analysis & classification of locomotion and adhesion techniques. In *5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, pages 1–7.
- Mittal, R. and Nagrath, I. (2003). *Robotics and Control*. Tata McGraw-Hill.
- Mukhtar, M., Khudher, D., and Kalganova, T. (2021). A control structure for ambidextrous robot arm based on multiple adaptive neuro-fuzzy inference system. *IET Control Theory & Applications*, 15(11):1518–1532.
- Mustapa, M., Othman, W., Bakar, E. A., and Othman, A. (2018). Development of pole-like tree spiral climbing robot. In *Intelligent Manufacturing & Mechatronics*, pages 285–293.
- Nanda, S. R., Kulkarni, V., and Sahoo, N. (2016). Design of artificial neuro-fuzzy based methodology for six component force balance. *Procedia Engineering*, 144:528–536.
- Nanda, S. R., Kulkarni, V., Sahoo, N., and Menezes, V. (2019). An innovative approach for prediction of aerodynamic coefficients in shock tunnel testing with soft computing techniques. *Measurement*, 134:773–780.
- Narayan, J. and Singla, A. (2017). ANFIS based kinematic analysis of a 4-DOFs SCARA robot. In *4th International Conference on Signal Processing, Computing and Control (ISPCC)*, pages 205–211.
- Narayan, J., Singla, E., Soni, S., and Singla, A. (2018). Adaptive neuro-fuzzy inference system-based path planning of 5-degrees-of-freedom spatial manipulator for medical applications. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 232(7):726–732.

- Ngo, T.-H., Tran, H.-V., Nguyen, T.-A., Dao, T.-P., and Wang, D.-A. (2018). Design and kinetostatic modeling of a compliant gripper for grasp and autonomous release of objects. *Advanced Robotics*, 32(14):717–735.
- Nguyen, A. K., Russell, A., Naclerio, N., Vuong, V., Huang, H., Chui, K., and Hawkes, E. W. (2020). A tri-stable soft robotic finger capable of pinch and wrap grasps. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 9028–9034.
- Nguyen, T.-A. and Wang, D.-A. (2016). A gripper based on a compliant bistable mechanism for gripping and active release of objects. In *International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS)*, pages 1–4.
- Noohi, E., Mahdavi, S. S., Baghani, A., and Ahmadabadi, M. N. (2010). Wheel-based climbing robot: modeling and control. *Advanced Robotics*, 24(8-9):1313–1343.
- Norton, R. L. and Han, J. (1999). *Design of Machinery*. McGraw-Hill New York.
- Palathingal, S. and Ananthasuresh, G. (2016). Design of bistable pinned-pinned arches with torsion springs by determining critical points. In *Mechanism and Machine Science*, pages 677–688.
- Palathingal, S. and Ananthasuresh, G. (2017). Design of bistable arches by determining critical points in the force-displacement characteristic. *Mechanism and Machine Theory*, 117:175–188.
- Palathingal, S. and Ananthasuresh, G. (2018). A bilateral relationship between stable profiles of pinned–pinned bistable shallow arches. *International Journal of Solids and Structures*, 143:183–193.
- Park, S. and Hah, D. (2008). Pre-shaped buckled-beam actuators: theory and experiments. *Sensors and Actuators A: Physical*, 148(1):186–192.
- Pluimers, P. J., Tolou, N., Jensen, B. D., Howell, L. L., and Herder, J. L. (2012). A compliant on/off connection mechanism for preloading statically balanced compliant mechanisms. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 45035, pages 373–377.
- Polchankajorn, P. and Maneewarn, T. (2011a). Development of a helical climbing modular snake robot. In *IEEE International Conference on Robotics and Automation*, pages 197–202.

- Polchankajorn, P. and Maneewarn, T. (2011b). Effective parameters for helical pole climbing of the wheel-based modular snake robot. In *The 5th International Conference on Automation, Robotics and Applications*, pages 232–237.
- Pontecorvo, M. E., Barbarino, S., Murray, G. J., and Gandhi, F. S. (2013). Bistable arches for morphing applications. *Journal of Intelligent Material Systems and Structures*, 24(3):274–286.
- Pratihari, D. K. (2013). *Soft Computing: Fundamentals and Applications*. Alpha Science International Limited.
- Pratihari, D. K. (2017). *Fundamentals of Robotics: Manipulators, Wheeled and Legged Robots*. Alpha Science International Limited.
- Qiaoling, D., Xinpo, L., Yankai, W., and Sinan, L. (2020). The obstacle-surmounting analysis of a pole-climbing robot. *International Journal of Advanced Robotic Systems*, 17(6):1729881420979146.
- Qiaoling, D., Yan, L., and Sinan, L. (2019). Design of a micro pole-climbing robot. *International Journal of Advanced Robotic Systems*, 16(3):1729881419852813.
- Qiu, J., Lang, J. H., and Slocum, A. H. (2004). A curved-beam bistable mechanism. *Journal of Microelectromechanical Systems*, 13(2):137–146.
- Ramesh, P., Nanda, S. R., Kulkarni, V., and Dwivedy, S. K. (2019). Application of neural-networks and neuro-fuzzy systems for the prediction of short-duration forces acting on the blunt bodies. *Soft Computing*, 23(14):5725–5738.
- Rao, R. V., Savsani, V. J., and Vakharia, D. (2011). Teaching-learning-based optimization: a novel method for constrained mechanical design optimization problems. *Computer-Aided Design*, 43(3):303–315.
- Reddy, B. S. and Ghosal, A. (2018). Robustness analysis of a simple and augmented proportional plus derivative controller in trajectory following robots using the floquet theory. *ASME Journal of Computational and Nonlinear Dynamics*, 13(7):074501.
- Refaai, M. R. A. (2021). Using multiple adaptive neuro-fuzzy inference system to solve inverse kinematics of SCARA robot. In *18th International Multi-Conference on Systems, Signals & Devices (SSD)*, pages 154–159.
- Ripin, Z. M., Soon, T. B., Abdullah, A., and Samad, Z. (2000). Development of a low-cost modular pole climbing robot. In *TENCON Proceedings. Intelligent Systems and Technologies for the New Millennium (Cat. No. 00CH37119)*, volume 1, pages 196–200.

- Rojas, S., Boston, D. M., and Arrieta, A. F. (2019). Actuation simplification for grippers based on bioinspired spring origami. In *Bioinspiration, Biomimetics, and Bioreplication IX*, volume 10965, page 109650O.
- Rollinson, D. and Choset, H. (2013). Gait-based compliant control for snake robots. In *IEEE International Conference on Robotics and Automation*, pages 5138–5143.
- Roodenburg, D., Spronck, J., Van der Zant, H., and Venstra, W. (2009). Buckling beam micromechanical memory with on-chip readout. *Applied Physics Letters*, 94(18):183501.
- Rothmund, P., Ainla, A., Belding, L., Preston, D. J., Kurihara, S., Suo, Z., and Whitesides, G. M. (2018). A soft, bistable valve for autonomous control of soft actuators. *Science Robotics*, 3(16).
- Sadd, M. H. (2009). *Elasticity: Theory, Applications, and Numerics*. Academic Press.
- Sadegh, N. and Horowitz, R. (1990). Stability and robustness analysis of a class of adaptive controllers for robotic manipulators. *The International Journal of Robotics Research*, 9(3):74–92.
- Sadeghi, A., Moradi, H., and Ahmadabadi, M. N. (2008). Analysis, simulation and implementation of a human inspired pole climbing robot. In *Advances In Mobile Robotics*, pages 247–254.
- Sadeghi, A., Moradi, H., and Ahmadabadi, M. N. (2012). Analysis, simulation, and implementation of a human-inspired pole climbing robot. *Robotica*, 30(2):279–287.
- Sadeqi, A., Moradi, H., and Ahmadabadi, M. N. (2008). A human-inspired pole climbing robot. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4199–4199.
- Saha, S. K. (2014). *Introduction to Robotics*. Tata McGraw-Hill Education.
- Şahin, M. and Erol, R. (2017). A comparative study of neural networks and anfis for forecasting attendance rate of soccer games. *Mathematical and Computational Applications*, 22(4):43.
- Saltarén, R., Aracil, R., Reinoso, O., and Scarano, M. A. (2005). Climbing parallel robot: A computational and experimental study of its performance around structural nodes. *IEEE Transactions on Robotics*, 21(6):1056–1066.
- Saltarén, R., Aracil, R., Sabater, J., Reinoso, O., and Jimenez, L. (1999). Modelling, simulation and conception of parallel climbing robots for construction

- and service. In *2nd Int. Workshop & Conf. on Climbing & Walking Robots (CLAWAR)*.
- Sano, S., Ohara, K., Ashizawa, S., Ichikawa, A., Suzuki, S., Omichi, T., and Fukuda, T. (2017). Development of wall climbing robot using passive joint and vacuum pad on rough surface. In *International Symposium on Micro-NanoMechatronics and Human Science (MHS)*, pages 1–3.
- Sarojini, D., Lassche, T., Herder, J., and Ananthasuresh, G. (2016). Statically balanced compliant two-port bistable mechanism. *Mechanism and Machine Theory*, 102:1–13.
- Scholtes, D., Seelecke, S., Rizzello, G., and Motzki, P. (2020). Design of a compliant industrial gripper driven by a bistable shape memory alloy actuator. In *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*.
- Schultz, M. and Hyer, M. (2004). A morphing concept based on unsymmetric composite laminates and piezoceramic mfc actuators. In *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*, page 1806.
- Sebastian, B., Ray, D. N., and Majumder, S. (2015). Design and analysis of a tree climbing robot. In *Proceedings of the 2015 Conference on Advances In Robotics*, pages 1–7.
- Sharma, R., Rana, K., and Kumar, V. (2014). Statistical analysis of ga based pid controller optimization for robotic manipulator. In *International Conference on Issues and Challenges in Intelligent Computing Techniques (ICICT)*, pages 713–718.
- Shin, D., Na, S. Y., Kim, J. Y., and Jung, J. H. (2010). Detection and classification of pipelines for mobile monitoring robots. In *The 2nd International Conference on Computer and Automation Engineering (ICCAE)*, volume 2, pages 139–143.
- Simiteses, G. and Hodges, D. H. (2006). *Fundamentals of Structural Stability*. Butterworth-Heinemann.
- Singh, G., Patiballa, S., Zhang, X., and Krishnan, G. (2019). A pipe-climbing soft robot. In *International Conference on Robotics and Automation (ICRA)*, pages 8450–8456.
- Singh, P. and Ananthasuresh, G. (2012). A compact and compliant external pipe-crawling robot. *IEEE Transactions on Robotics*, 29(1):251–260.
- Singh, V. P. (1999). *Theory of Machines*. Dhanpat Rai and Co. (Pvt.) Ltd. Delhi.

- Sivanandam, S. and Deepa, S. (2007). *Principles of Soft Computing*. John Wiley & Sons.
- Slane, J. and Tragesser, S. (2011). Analysis of periodic nonautonomous inhomogeneous systems. *Nonlinear Dynamics and Systems Theory*, 11(2):183–198.
- Slotine, J.-J. E., Li, W., et al. (1991). *Applied Nonlinear Control*, volume 199. Prentice hall Englewood Cliffs, NJ.
- Spong, M. W., Hutchinson, S., and Vidyasagar, M. (2004). Forward kinematics: the denavit-hartenberg convention. *Robot Dynamics and Control, 2nd ed.; John Wiley & Sons: New York, NY, USA*, pages 57–82.
- Staveniuter, R. A., Birglen, L., and Herder, J. L. (2017). A planar underactuated grasper with adjustable compliance. *Mechanism and Machine Theory*, 112:295–306.
- Sun, J., Tighe, B., and Zhao, J. (2020). Tuning the energy landscape of soft robots for fast and strong motion. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 10082–10088.
- Suzuki, M., Yukawa, T., Satoh, Y., and Okano, H. (2006). Mechanisms of autonomous pipe-surface inspection robot with magnetic elements. In *IEEE International Conference on Systems, Man and Cybernetics*, volume 4, pages 3286–3291.
- Takeda, M. and Shimoyama, I. (2019). Analysis of the vertical driving performance of multiple connected pipe-climbing microrobots with magnetic wheels. *Micromachines*, 10(8):524.
- Takemori, T., Tanaka, M., and Matsuno, F. (2016). Gait design of a snake robot by connecting simple shapes. In *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 189–194.
- Tandy, E. H. (1954). Inspection of petroleum refinery equipment. *Corrosion*, 10(5):160–164.
- Tavakoli, M., Lopes, P., Sgrigna, L., and Viegas, C. (2015). Motion control of an omnidirectional climbing robot based on dead reckoning method. *Mechatronics*, 30:94–106.
- Tavakoli, M., Marjovi, A., Marques, L., and de Almeida, A. T. (2008). 3DCLIMBER: A climbing robot for inspection of 3D human made structures. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4130–4135.

- Tavakoli, M., Marques, L., and de Almeida, A. T. (2010). Development of an industrial pipeline inspection robot. *Industrial Robot: An International Journal*, 37(3):309–322.
- Tavakoli, M., Marques, L., et al. (2011). 3DCLIMBER: Climbing and manipulation over 3D structures. *Mechatronics*, 21(1):48–62.
- Tavakoli, M. and Viegas, C. (2014). Analysis and application of dual-row omnidirectional wheels for climbing robots. *Mechatronics*, 24(5):436–448.
- Tavakoli, M., Viegas, C., Marques, L., Pires, J. N., and De Almeida, A. T. (2013). OmniClimbers: Omni-directional magnetic wheeled climbing robots for inspection of ferromagnetic structures. *Robotics and Autonomous Systems*, 61(9):997–1007.
- Tavakoli, M., Zakerzadeh, M. R., Vossoughi, G., and Bagheri, S. (2005). A hybrid pole climbing and manipulating robot with minimum dofs for construction and service applications. *Industrial Robot: An International Journal*, 32(2):171–178.
- Thomas, O., Lazarus, A., and Touzé, C. (2010). A harmonic-based method for computing the stability of periodic oscillations of non-linear structural systems. In *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 883–892.
- Thomas, S., Almanza, M., Civet, Y., and Perriard, Y. (2018). Actuation displacement analysis of a self-switching shape memory alloy buckled beam. In *21st International Conference on Electrical Machines and Systems (ICEMS)*, pages 1771–1776.
- Thuruthel, T. G., Abidi, S. H., Cianchetti, M., Laschi, C., and Falotico, E. (2019). A bistable soft gripper with mechanically embedded sensing and actuation for fast grasping. In *29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pages 1049–1054.
- Uicker, J. J., Pennock, G. R., Shigley, J. E., and McCarthy, J. M. (2003). *Theory of Machines and Mechanisms*. Oxford University Press New York.
- Vangbo, M. (1998). An analytical analysis of a compressed bistable buckled beam. *Sensors and Actuators A: Physical*, 69(3):212–216.
- Vossoughi, G., Bagheri, S., Tavakoli, M., Zakerzadeh, M., and Hosseinzadeh, M. (2004). Design, modeling and kinematics analysis of a novel serial/parallel pole climbing and manipulating robot. In *Engineering Systems Design and Analysis*, volume 4174, pages 399–408.

- Wang, H., Yang, C., Deng, X., and Fan, J. (2016). A simple modeling method and trajectory planning for a car-like climbing robot used to strip coating from the outer surface of pipes underwater. In *Assistive Robotics: Proceedings of the 18th International Conference on CLAWAR*, pages 704–712.
- Wang, X., Khara, A., and Chen, C. (2020). A soft pneumatic bistable reinforced actuator bioinspired by venus flytrap with enhanced grasping capability. *Bioinspiration & Biomimetics*, 15(5):056017.
- Wang, Y., Gupta, U., Parulekar, N., and Zhu, J. (2019). A soft gripper of fast speed and low energy consumption. *Science China Technological Sciences*, 62(1):31–38.
- Welsch, F., Kirsch, S.-M., Motzki, P., Schmidt, M., and Seelecke, S. (2018). Vacuum gripper system based on bistable sma actuation. In *Smart Materials, Adaptive Structures and Intelligent Systems*, volume 51944, page V001T04A014.
- Wright, C., Johnson, A., Peck, A., McCord, Z., Naaktgeboren, A., Gianfortoni, P., Gonzalez-Rivero, M., Hatton, R., and Choset, H. (2007). Design of a modular snake robot. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2609–2614.
- Wu, P. (1989). Erosion/corrosion-induced pipe wall thinning in us nuclear power plants. Technical report, US Nuclear Regulatory Commission (NRC), Washington, DC (United States).
- Xie, D., Liu, J., Kang, R., and Zuo, S. (2020). Fully 3D-printed modular pipe-climbing robot. *IEEE Robotics and Automation Letters*, 6(2):462–469.
- Xu, Q. (2017). Design of a constant-force microgripper mechanism for biological micromanipulation. In *12th International Conference on Nano/Micro Engineered and Molecular Systems (NEMS)*, pages 418–421.
- Yang, S. and Xu, Q. (2017). Design and simulation of a passive-type constant-force mems microgripper. In *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 1100–1105.
- Yang, X.-S. (2012). Flower pollination algorithm for global optimization. In *International Conference on Unconventional Computing and Natural Computation*, pages 240–249.
- Yao, J., Gao, S., Jiang, G., Hill, T. L., Yu, H., and Shao, D. (2015). Screw theory based motion analysis for an inchworm-like climbing robot. *Robotica*, 33(8):1704.

- Yaqub, S., Ali, A., Usman, M., Zuhaib, K. M., Khan, A. M., An, B., Moon, H., Lee, J.-Y., and Han, C. (2019). A spiral curve gait design for a modular snake robot moving on a pipe. *International Journal of Control, Automation and Systems*, 17(10):2565–2573.
- Yukawa, T., Suzuki, M., Satoh, Y., and Okano, H. (2006a). Design of magnetic wheels in pipe inspection robot. In *IEEE International Conference on Systems, Man and Cybernetics*, volume 1, pages 235–240.
- Yukawa, T., Suzuki, M., Satoh, Y., and Okano, H. (2006b). Magnetic part design of pipe-surface inspection robot. In *32nd Annual Conference on IEEE Industrial Electronics (IECON)*, pages 3957–3962.
- Zhang, H., Lerner, E., Cheng, B., and Zhao, J. (2020). Compliant bistable grippers enable passive perching for micro aerial vehicles. *IEEE/ASME Transactions on Mechatronics*. (Early Access).
- Zhang, H., Sun, J., and Zhao, J. (2019a). Compliant bistable gripper for aerial perching and grasping. In *International Conference on Robotics and Automation (ICRA)*, pages 1248–1253.
- Zhang, Z., Li, X., Yu, X., Chai, H., Li, Y., Wu, H., and Jiang, S. (2019b). Magnetic actuation bionic robotic gripper with bistable morphing structure. *Composite Structures*, 229:111422.
- Zhou, Y., Zhang, Y., Ni, F., and Liu, H. (2017). A spring-like pipe climbing gait for the snake robot. In *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 1886–1891.
- Ziegler, J. G. and Nichols, N. B. (1993). Optimum settings for automatic controllers. *ASME Journal of Dynamic Systems, Measurement, and Control*, 115(2B):220–222.
- Zimmer, L., Welsch, F., Kirsch, S.-M., Rizzello, G., Seelecke, S., and Motzki, P. (2020). Adaptive material handling system based on shape memory alloy actuators. In *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*.

Appendix A

Experimental Data Points between D_v and D_a , and L_s and D_a

A.1 Trial I

Table A.1: Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness (Trial I)

D_a (mm)	D_v (mm)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	6.5	6	8	6
2	9	9	9	9
3	11	11	11	11.5
4	12.5	12	12.5	12.5
5	14	14	13.5	14

Table A.2: Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness (Trial I)

D_a (mm)	D_v (mm)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	6	6	5.5	5
2	8	9.5	9	8.5
3	10	11	11.5	11
4	12	13	12.5	12
5	13	14	14	13.5

Table A.3: Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness (Trial I)

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	1.4715	2.4525	5.886	7.848
2	1.962	4.4145	7.848	12.2625
3	2.4525	5.886	9.81	16.1865
4	3.4335	7.3575	11.2815	19.1295
5	3.924	7.848	13.2435	20.601

Table A.4: Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness (Trial I)

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	7.848	10.791	16.677	20.601
2	11.2815	24.525	28.449	34.335
3	16.677	37.278	41.202	46.107
4	23.0535	44.6355	50.031	51.012
5	27.468	52.974	57.879	59.841

A.2 Trial II

Table A.5: Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness (Trial II)

D_a (mm)	D_v (mm)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	6.5	7	6	8
2	8.5	9.5	9	9
3	10.5	11	11	11
4	12	12.5	12.5	13
5	13	14	14.5	14.5

Table A.6: Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness (Trial II)

D_a (mm)	D_v (mm)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	7	7	7	5.5
2	9.5	9	9	8.5
3	11	11	10.5	10.5
4	12.5	12.5	13	11.5
5	14.5	14	13	13

Table A.7: Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness (Trial II)

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	0.981	2.943	5.886	8.3385
2	1.4715	4.4145	8.3385	12.2625
3	1.962	6.3765	10.791	16.1865
4	2.4525	7.3575	11.2815	18.1485
5	3.4335	8.3385	12.753	19.62

Table A.8: Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness (Trial II)

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	8.3385	11.772	18.1485	21.582
2	12.2625	24.525	27.468	35.316
3	16.677	37.7685	41.202	46.107
4	23.0535	44.145	49.5405	51.993
5	28.449	53.4645	58.3695	60.822

A.3 Trial III

Table A.9: Variation of D_v with D_a for various widths of the beam having 0.3 mm thickness (Trial III)

D_a (mm)	D_v (mm)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	6	6	6.5	6.5
2	9	9	9.5	9.5
3	10	10.5	11	11.5
4	12.5	13	13	13.5
5	13.5	14	14	14.5

Table A.10: Variation of D_v with D_a for various widths of the beam having 0.5 mm thickness (Trial III)

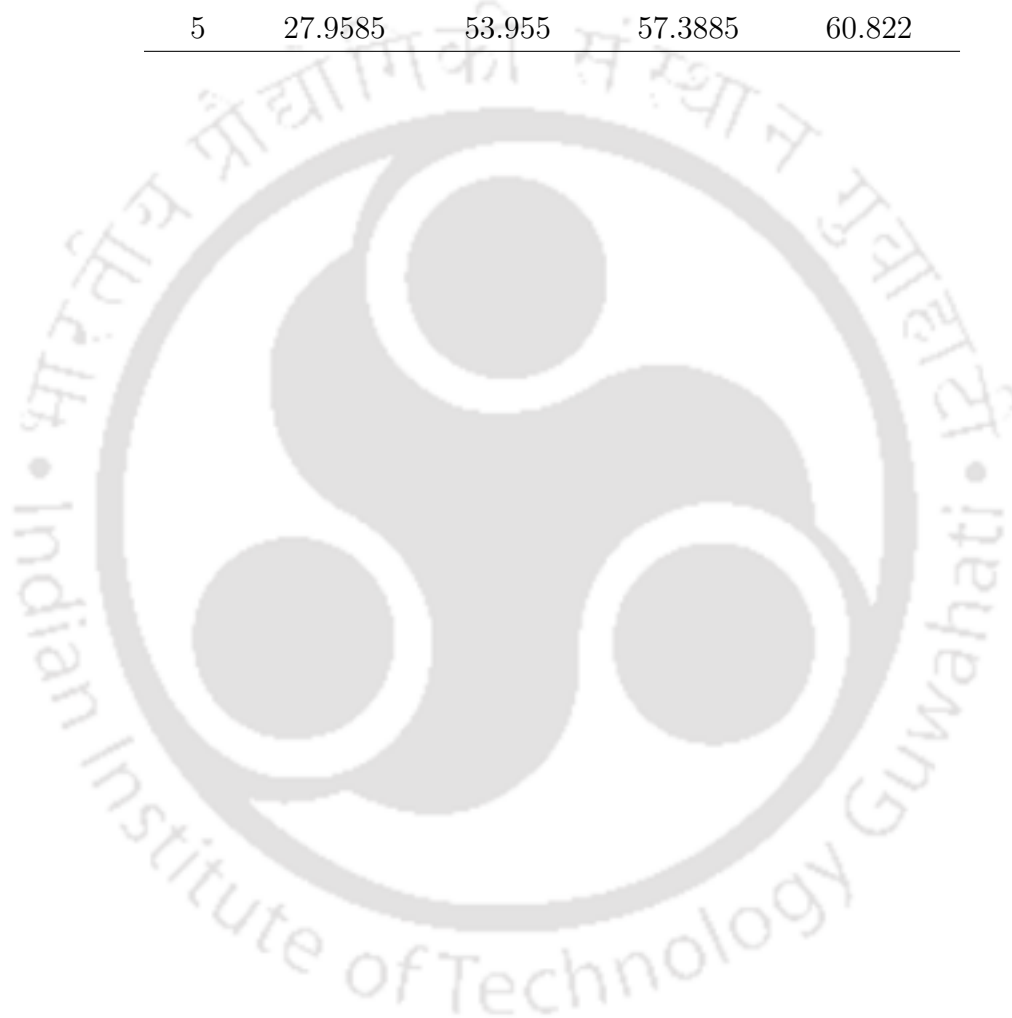
D_a (mm)	D_v (mm)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	7	6	7	5.5
2	9.5	9.5	10	8.5
3	11.5	10	11.5	10
4	13	11.5	13	12
5	14.5	13	14	13

Table A.11: Variation of L_s with D_a for various widths of the beam having 0.3 mm thickness (Trial III)

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	0.981	2.943	5.3955	8.3385
2	1.4715	4.4145	7.848	11.2815
3	2.4525	5.886	9.81	16.1865
4	2.943	7.848	11.772	18.1485
5	3.924	8.829	13.2435	20.1105

Table A.12: Variation of L_s with D_a for various widths of the beam having 0.5 mm thickness (Trial III)

D_a (mm)	L_s (N)			
	E			
	$b = 5$ mm	$b = 10$ mm	$b = 15$ mm	$b = 20$ mm
1	8.829	11.772	18.1485	20.601
2	12.2625	24.525	27.9585	35.316
3	15.696	38.259	40.221	45.126
4	22.563	44.145	50.5215	51.5025
5	27.9585	53.955	57.3885	60.822



Appendix B

Algorithm for Generating the Training Data Set for ANFIS

Algorithm 1: Generation of training data set for RRRP configuration for joint variable θ_2

```
1  $l_1 = 1$ 
2  $l_2 = 1$ 
3  $\theta_1 = 0$ 
4  $j=0$ ;
5 for  $\theta_2 = (-\pi/2) : (5 * \pi/180) : (\pi/2)$  do
6   for  $\theta_3 = 0 : (5 * \pi/180) : \pi$  do
7     for  $d_4 = 0.2 : 0.03 : 0.5$  do
8        $j=j+1$ 
9        $p_x=0$ 
10       $p_z=0$ 
11       $p_x = \cos(\theta_1)(l_2 \cos(\theta_2) + d_4 \sin(\theta_2 + \theta_3))$ 
12       $p_z = -l_1 - d_4 \cos(\theta_2 + \theta_3) + l_2 \sin(\theta_2)$ 
13       $px(j, 1) = p_x$ 
14       $pz(j, 1) = p_z$ 
15       $theta2rec(j, 1) = \theta_2$ ;
16    end
17  end
18 end
19 trainingdataset=[ $px, pz, theta2rec$ ]
20 Plot the ( $px, pz$ ) to get the RRRP workspace
```

Algorithm 2: Generation of training data set for PRRR configuration for joint variable Θ_2

```
1  $L_2 = 1$ 
2  $L_3 = 1$ 
3  $\Theta_4 = 0$ 
4  $j=0$ ;
5 for  $D_1 = 0.2 : 0.03 : 0.5$  do
6   for  $\Theta_2 = (pi/2) : (5 * pi/180) : (pi)$  do
7     for  $\Theta_3 = (-pi/2) : (-5 * pi/180) : ((-3 * pi)/2)$  do
8        $j=j+1$ 
9        $p_Y=0$ 
10       $p_Z=0$ 
11       $p_Y = -L_2 \cos(\Theta_2) + L_3 \sin(\Theta_2 + \Theta_3)$ 
12       $p_Z = -D_1 - L_3 \cos(\Theta_2 + \Theta_3) - L_2 \sin(\Theta_2)$ 
13       $pY(j, 1) = p_Y$ 
14       $pZ(j, 1) = p_Z$ 
15       $Theta2rec(j, 1) = \Theta_2$ ;
16    end
17  end
18 end
19 Trainingdataset=[ $pY, pZ, Theta2rec$ ]
20 Plot the ( $pY, pZ$ ) to get the PRRR workspace
```

Appendix C

Trajectory Planning Using Modified Linear Function with Parabolic Blends

Case I :- When $q_s < q_g$,

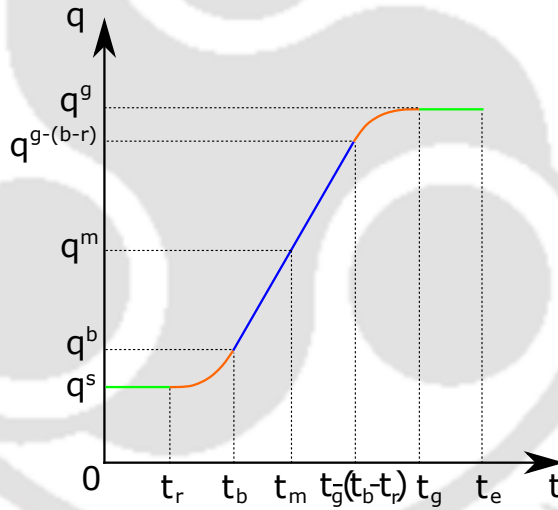


Figure C.1: Trajectory of modified linear function with parabolic blends

In Fig. C.1, q_s is the start position and q_g is the end position. t_s , t_e , t_r and t_b are the start, end, rest and blend times, respectively. $\ddot{q}^c$ is the acceleration at the blends. From Fig. C.1,

$$q^m = \frac{q^s + q^g}{2} \quad (C.1)$$

$$t_m = \frac{t_g - t_r}{2} + t_r \quad (C.2)$$

$$q^b = q^s + \frac{1}{2}\ddot{q}^c(t_b - t_r)^2 \quad (C.3)$$

$$\ddot{q}^c(t_b - t_r) = \frac{q^m - q^b}{t_m - t_b} \quad (\text{C.4})$$

Combining Eqs. C.1, C.2, C.3 and C.4,

$$\begin{aligned} \ddot{q}^c(t_b - t_r) &= \frac{\left(\frac{q^g + q^s}{2}\right) - \{q^s + \frac{1}{2}\ddot{q}^c(t_b - t_r)^2\}}{\left(\frac{t_g - t_r}{2}\right) + t_r - t_b} \\ \Rightarrow \ddot{q}^c t_b^2 - \ddot{q}^c(t_r + t_g)t_b + \ddot{q}^c t_r t_g + q^g - q^s &= 0 \\ \Rightarrow t_b &= \frac{t_r + t_g}{2} - \frac{1}{2} \sqrt{\frac{\ddot{q}^c(t_r + t_g)^2 - 4\{\ddot{q}^c t_r t_g + (q^g - q^s)\}}{\ddot{q}^c}} \end{aligned} \quad (\text{C.5})$$

From Eq. C.5, the constraint to be satisfied is -

$$\begin{aligned} \ddot{q}^c(t_r + t_g)^2 - 4\{\ddot{q}^c t_r t_g + (q^g - q^s)\} &\geq 0 \\ \Rightarrow \ddot{q}^c\{(t_g + t_r)^2 - 4t_r t_g\} &\geq 4(q_g - q_s) \\ \Rightarrow \ddot{q}^c &\geq \frac{4(q_g - q_s)}{(t_g - t_r)^2} \end{aligned} \quad (\text{C.6})$$

Path 1 (Rest period) :- $0 \leq t < t_r$

$$\begin{aligned} q &= q^s \\ \dot{q} &= 0 \\ \ddot{q} &= 0 \end{aligned} \quad (\text{C.7})$$

Path 2 (Parabolic blend) :- $t_r \leq t \leq t_b$

$$\begin{aligned} q &= a_0 + a_1 t + a_2 t^2 \\ \dot{q} &= a_1 + 2a_2 t \\ \ddot{q} &= 2a_2 \end{aligned}$$

The constraints are :-

$$\begin{aligned} q^r &= q^s, \dot{q}^r = 0, \ddot{q}^r = \ddot{q}^c \\ q^b &= q^s + \frac{1}{2}\ddot{q}^c(t_b - t_r)^2, \dot{q}^b = \ddot{q}^c(t_b - t_r), \ddot{q}^b = \ddot{q}^c \end{aligned}$$

Solving for a_0 , a_1 and a_2 by using the constraints,

$$\ddot{q}^r = 2a_2 = \ddot{q}^c$$

$$\Rightarrow a_2 = \frac{\ddot{q}^c}{2}$$

$$\dot{q}^r = a_1 + 2a_2 t_r = 0$$

$$\Rightarrow a_1 = -\ddot{q}^c t_r$$

$$q^r = a_0 + a_1 t_r + a_2 t_r^2 = q^s$$

$$\Rightarrow q^s = a_0 - \ddot{q}^c t_r^2 + \frac{\ddot{q}^c}{2} t_r^2$$

$$\Rightarrow a_0 = q^s + \frac{1}{2} \ddot{q}^c t_r^2$$

By putting the values of a_0 , a_1 and a_2 in parabolic blend equations, the final equations are :-

$$q = q^s + \frac{1}{2} \ddot{q}^c (t - t_r)^2$$

$$\dot{q} = \ddot{q}^c (t - t_r)$$

$$\ddot{q} = \ddot{q}^c$$
(C.8)

Path 3 (Linear function) :- $t_b < t \leq t_g - (t_b - t_r)$

$$q = a_0 + a_1 t$$

$$\dot{q} = a_1$$

$$\ddot{q} = 0$$

The constraints are :-

$$q^b = q^s + \frac{1}{2} \ddot{q}^c (t_b - t_r)^2, \dot{q}^b = \ddot{q}^c (t_b - t_r), \ddot{q}^b = \ddot{q}^c$$

$$q^{g-(b-r)} = q^b + \ddot{q}^c (t_b - t_r) (t_g - 2t_b + t_r)$$

$$\dot{q}^{g-(b-r)} = \ddot{q}^c (t_b - t_r)$$

$$\ddot{q}^{g-(b-r)} = -\ddot{q}^c$$

Solving for a_0 and a_1 ,

$$a_1 = \ddot{q}^c(t_b - t_r)$$

$$a_0 = q^s + \frac{1}{2}\ddot{q}^c(t_b - t_r)^2 - \ddot{q}^c(t_b - t_r)t_b$$

The final equations are :-

$$q = q^s + \frac{1}{2}\ddot{q}^c(t_b - t_r)^2 - \ddot{q}^c(t_b - t_r)t_b + \ddot{q}^c(t_b - t_r)t$$

$$\dot{q} = \ddot{q}^c(t_b - t_r)$$

$$\ddot{q} = 0$$
(C.9)

Path 4 (Parabolic blend) :- $t_g - (t_b - t_r) < t \leq t_g$

$$q = a_0 + a_1t + a_2t^2$$

$$\dot{q} = a_1 + a_2t$$

$$\ddot{q} = 2a_2$$

The constraints are :-

$$q^{g-(b-r)} = q^s + \frac{1}{2}\ddot{q}^c(t_b - t_r)^2 + \ddot{q}^c(t_b - t_r)(t_g - 2t_b + t_r)$$

$$\dot{q}^{g-(b-r)} = \ddot{q}^c(t_b - t_r)$$

$$\ddot{q}^{g-(b-r)} = -\ddot{q}^c$$

$$q^g = q^g, \dot{q}^g = 0, \ddot{q}^g = -\ddot{q}^c$$

Solving for a_0 , a_1 and a_2 ,

$$a_2 = -\frac{\ddot{q}^c}{2}, a_1 = \ddot{q}^c t_g, a_0 = q^g - \frac{1}{2}\ddot{q}^c t_g^2$$

The final equations are :-

$$q = q^g - \frac{1}{2}\ddot{q}^c(t_g - t)^2$$

$$\dot{q} = \ddot{q}^c(t_g - t)$$

$$\ddot{q} = -\ddot{q}^c$$
(C.10)

Path 5 (Rest period) :- $t_g < t \leq t_e$

$$\begin{aligned} q &= q^g \\ \dot{q} &= 0 \\ \ddot{q} &= 0 \end{aligned} \quad (C.11)$$

Case II :- When $q_s > q_g$,

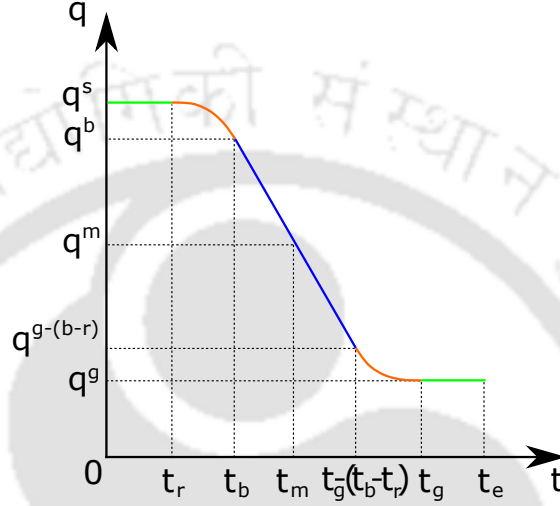


Figure C.2: Trajectory of modified linear function with parabolic blends when $q_s > q_g$

The equation of the trajectory when $q_s > q_g$, as shown in Fig. C.2 can also be derived in a way similar to case I where $q_s < q_g$. The blend time and the constraint on acceleration for the present case are given as-

$$t_b = \frac{t_r + t_g}{2} - \frac{1}{2} \sqrt{\frac{\ddot{q}^c(t_r + t_g)^2 - 4\{\ddot{q}^c t_r t_g + (q^s - q^g)\}}{\ddot{q}^c}} \quad (C.12)$$

$$\ddot{q}^c \geq \frac{4(q_s - q_g)}{(t_g - t_r)^2} \quad (C.13)$$

The equation of the trajectory and its first and double derivative with respect to time are as follows :-

Path 1 (Rest period) :- $0 \leq t < t_r$

$$\begin{aligned} q &= q^s \\ \dot{q} &= 0 \\ \ddot{q} &= 0 \end{aligned} \quad (C.14)$$

Path 2 (Parabolic blend) :- $t_r \leq t \leq t_b$

$$\begin{aligned} q &= q^s - \frac{1}{2}\ddot{q}^c(t - t_r)^2 \\ \dot{q} &= -\ddot{q}^c(t - t_r) \\ \ddot{q} &= -\ddot{q}^c \end{aligned} \tag{C.15}$$

Path 3 (Linear function) :- $t_b < t \leq t_g - (t_b - t_r)$

$$\begin{aligned} q &= q^s - \frac{1}{2}\ddot{q}^c(t_b - t_r)^2 + \ddot{q}^c(t_b - t_r)t_b - \ddot{q}^c(t_b - t_r)t \\ \dot{q} &= -\ddot{q}^c(t_b - t_r) \\ \ddot{q} &= 0 \end{aligned} \tag{C.16}$$

Path 4 (Parabolic blend) :- $t_g - (t_b - t_r) < t \leq t_g$

$$\begin{aligned} q &= q^g + \frac{1}{2}\ddot{q}^c(t_g - t)^2 \\ \dot{q} &= -\ddot{q}^c(t_g - t) \\ \ddot{q} &= \ddot{q}^c \end{aligned} \tag{C.17}$$

Path 5 (Rest period) :- $t_g < t \leq t_e$

$$\begin{aligned} q &= q^g \\ \dot{q} &= 0 \\ \ddot{q} &= 0 \end{aligned} \tag{C.18}$$

It may be noted that Eqs. C.12 to C.18 are almost similar to Eqs. C.5 to C.11 except a few sign changes.

Appendix D

Coefficients of Mass matrix, Coriolis vector and Gravity vector

$$\begin{aligned} M_{11} = & \frac{1}{2}(-4d_4^2m_4 \cos(2(\theta_2 + \theta_3)) + 4d_4^2m_4 + 8d_4l_2m_4 \sin(2\theta_2 + \theta_3) + 8d_4l_2m_4 \sin(\theta_3) \\ & + 8d_4l_{c4}m_4 \cos(2(\theta_2 + \theta_3)) - 8d_4l_{c4}m_4 + 8d_4m_4o \sin(2(\theta_2 + \theta_3)) + \cos(2\theta_2) \\ & (-I_{12} + I_{22} + l_2(l_2(m_2 + 4(m_3 + m_4)) - 2l_{c2}m_2)) + I_{12} - 4I_{13} \cos(2(\theta_2 + \theta_3)) \\ & + 4I_{13} - 4I_{14} \cos(2(\theta_2 + \theta_3)) + 4I_{14} + 2I_{21} + I_{22} + 4I_{33} \cos(2(\theta_2 + \theta_3)) + 4I_{33} \\ & + 4I_{34} \cos(2(\theta_2 + \theta_3)) + 4I_{34} + l_2^2m_2 + 4l_2^2m_3 + 4l_2^2m_4 - 2l_2l_{c2}m_2 - 8l_2l_{c3}m_3 \\ & \sin(2\theta_2 + \theta_3) - 8l_2l_{c3}m_3 \sin(\theta_3) - 8l_2l_{c4}m_4 \sin(2\theta_2 + \theta_3) - 8l_2l_{c4}m_4 \sin(\theta_3) \\ & + 8l_2o \cos(\theta_3)(m_3 + m_4) + 8l_2m_3o \cos(2\theta_2 + \theta_3) + 8l_2m_4o \cos(2\theta_2 + \theta_3) \\ & - 8l_{c3}m_3o \sin(2(\theta_2 + \theta_3)) - 8l_{c4}m_4o \sin(2(\theta_2 + \theta_3)) + 4m_3o^2 \cos(2(\theta_2 + \theta_3)) \\ & + 4m_3o^2 + 4m_4o^2 \cos(2(\theta_2 + \theta_3)) + 4m_4o^2) \end{aligned}$$

$$M_{12} = 0$$

$$M_{13} = 0$$

$$M_{14} = 0$$

$$\begin{aligned} M_{22} = & 4d_4^2m_4 - 8l_2 \sin(\theta_3)(-d_4m_4 + l_{c3}m_3 + l_{c4}m_4) - 8d_4l_{c4}m_4 + 4I_{23} + 4I_{24} + I_{32} \\ & + l_2^2m_2 + 4l_2^2m_3 + 4l_2^2m_4 - 2l_2l_{c2}m_2 + 8l_2o \cos(\theta_3)(m_3 + m_4) + 4m_3o^2 + 4m_4o^2 \end{aligned}$$

$$\begin{aligned} M_{23} = & d_4^2m_4 - l_2 \sin(\theta_3)(-d_4m_4 + l_{c3}m_3 + l_{c4}m_4) - 2d_4l_{c4}m_4 + I_{23} + I_{24} \\ & + l_2o \cos(\theta_3)(m_3 + m_4) + m_3o^2 + m_4o^2 \end{aligned}$$

$$M_{24} = -m_4(l_2 \cos(\theta_3) + o)$$

$$M_{33} = d_4^2m_4 - 2d_4l_{c4}m_4 + I_{23} + I_{24} + m_3o^2 + m_4o^2$$

$$M_{34} = -m_4o$$

$$M_{44} = m_4$$

$$\begin{aligned}
C_1 = & \dot{\theta}_1(-\dot{\theta}_2(d_4^2(-m_4) \sin(2(\theta_2 + \theta_3)) + 2l_2 \cos(2\theta_2 + \theta_3)(-d_4m_4 + 4l_{c3}m_3 + l_{c4}m_4) \\
& + 2o \cos(2(\theta_2 + \theta_3))(m_4(l_{c4} - d_4) + 4l_{c3}m_3) + 2d_4l_{c4}m_4 \sin(2(\theta_2 + \theta_3)) \\
& - I_{12} \sin(2\theta_2) - 4I_{13} \sin(2(\theta_2 + \theta_3)) - I_{14} \sin(2(\theta_2 + \theta_3)) + I_{22} \sin(2\theta_2) \\
& + 4I_{33} \sin(2(\theta_2 + \theta_3)) + I_{34} \sin(2(\theta_2 + \theta_3)) + l_2^2m_2 \sin(2\theta_2) + 4l_2^2m_3 \sin(2\theta_2) \\
& + l_2^2m_4 \sin(2\theta_2) - 2l_2l_{c2}m_2 \sin(2\theta_2) + 8l_2m_3o \sin(2\theta_2 + \theta_3) + 2l_2m_4o \sin(2\theta_2 + \theta_3) \\
& + 4m_3o^2 \sin(2(\theta_2 + \theta_3)) + m_4o^2 \sin(2(\theta_2 + \theta_3))) - \dot{\theta}_3(d_4^2(-m_4) \sin(2(\theta_2 + \theta_3)) \\
& + l_2 \cos(\theta_3)(m_4(l_{c4} - d_4) + l_{c3}m_3) - d_4l_2m_4 \cos(2\theta_2 + \theta_3) + 2o \cos(2(\theta_2 + \theta_3)) \\
& (-d_4m_4 + l_{c3}m_3 + l_{c4}m_4) + 2d_4l_{c4}m_4 \sin(2(\theta_2 + \theta_3)) - I_{13} \sin(2(\theta_2 + \theta_3)) \\
& - I_{14} \sin(2(\theta_2 + \theta_3)) + I_{33} \sin(2(\theta_2 + \theta_3)) + I_{34} \sin(2(\theta_2 + \theta_3)) + l_2l_{c3}m_3 \\
& \cos(2\theta_2 + \theta_3) + l_2l_{c4}m_4 \cos(2\theta_2 + \theta_3) + l_2m_3o \sin(2\theta_2 + \theta_3) + l_2m_3o \sin(\theta_3) \\
& + l_2m_4o \sin(2\theta_2 + \theta_3) + l_2m_4o \sin(\theta_3) + m_3o^2 \sin(2(\theta_2 + \theta_3)) + m_4o^2 \\
& \sin(2(\theta_2 + \theta_3))) + 2\dot{d}_4m_4 \sin(\theta_2 + \theta_3)((d_4 - l_{c4}) \sin(\theta_2 + \theta_3) + l_2 \cos(\theta_2) \\
& + o \cos(\theta_2 + \theta_3))) \\
C_2 = & \frac{1}{2}\dot{\theta}_1^2(d_4^2(-m_4) \sin(2(\theta_2 + \theta_3)) + 2l_2 \cos(2\theta_2 + \theta_3)(-d_4m_4 + 4l_{c3}m_3 + l_{c4}m_4) \\
& + 2o \cos(2(\theta_2 + \theta_3))(m_4(l_{c4} - d_4) + 4l_{c3}m_3) + 2d_4l_{c4}m_4 \sin(2(\theta_2 + \theta_3)) \\
& - I_{12} \sin(2\theta_2) - 4I_{13} \sin(2(\theta_2 + \theta_3)) - I_{14} \sin(2(\theta_2 + \theta_3)) + I_{22} \sin(2\theta_2) \\
& + 4I_{33} \sin(2(\theta_2 + \theta_3)) + I_{34} \sin(2(\theta_2 + \theta_3)) + l_2^2m_2 \sin(2\theta_2) + 4l_2^2m_3 \sin(2\theta_2) \\
& + l_2^2m_4 \sin(2\theta_2) - 2l_2l_{c2}m_2 \sin(2\theta_2) + 8l_2m_3o \sin(2\theta_2 + \theta_3) \\
& + 2l_2m_4o \sin(2\theta_2 + \theta_3) + 4m_3o^2 \sin(2(\theta_2 + \theta_3)) + m_4o^2 \sin(2(\theta_2 + \theta_3))) \\
& - \dot{\theta}_3l_2(2\dot{\theta}_2 + \dot{\theta}_3)(\cos(\theta_3)(m_4(l_{c4} - d_4) + l_{c3}m_3) + o \sin(\theta_3)(m_3 + m_4)) \\
& + 2\dot{d}_4m_4(\dot{\theta}_2 + \dot{\theta}_3)(d_4 + l_2 \sin(\theta_3) - l_{c4}) \\
C_3 = & \frac{1}{2}\dot{\theta}_1^2(d_4^2(-m_4) \sin(2(\theta_2 + \theta_3)) + l_2 \cos(\theta_3)(m_4(l_{c4} - d_4) + l_{c3}m_3) \\
& - d_4l_2m_4 \cos(2\theta_2 + \theta_3) + 2o \cos(2(\theta_2 + \theta_3))(-d_4m_4 + l_{c3}m_3 + l_{c4}m_4) \\
& + 2d_4l_{c4}m_4 \sin(2(\theta_2 + \theta_3)) - I_{13} \sin(2(\theta_2 + \theta_3)) - I_{14} \sin(2(\theta_2 + \theta_3)) \\
& + I_{33} \sin(2(\theta_2 + \theta_3)) + I_{34} \sin(2(\theta_2 + \theta_3)) + l_2l_{c3}m_3 \cos(2\theta_2 + \theta_3) \\
& + l_2l_{c4}m_4 \cos(2\theta_2 + \theta_3) + l_2m_3o \sin(2\theta_2 + \theta_3) + l_2m_3o \sin(\theta_3) \\
& + l_2m_4o \sin(2\theta_2 + \theta_3) + l_2m_4o \sin(\theta_3) + m_3o^2 \sin(2(\theta_2 + \theta_3)) \\
& + m_4o^2 \sin(2(\theta_2 + \theta_3))) + \dot{\theta}_2^2l_2(\cos(\theta_3)(m_4(l_{c4} - d_4) + l_{c3}m_3) \\
& + o \sin(\theta_3)(m_3 + m_4)) + 2\dot{d}_4m_4(d_4 - l_{c4})(\dot{\theta}_2 + \dot{\theta}_3) \\
C_4 = & \dot{\theta}_1^2(-m_4) \sin(\theta_2 + \theta_3)((d_4 - l_{c4}) \sin(\theta_2 + \theta_3) + l_2 \cos(\theta_2) + o \cos(\theta_2 + \theta_3)) \\
& - m_4(\dot{\theta}_2^2(d_4 + l_2 \sin(\theta_3) - l_{c4}) + 2\dot{\theta}_2\dot{\theta}_3(d_4 - l_{c4}) + \dot{\theta}_3^2(d_4 - l_{c4}))
\end{aligned}$$

$$\begin{aligned}
G_1 &= 0 \\
G_2 &= g(-\sin(\theta_2 + \theta_3)(-d_4m_4 + l_{c3}m_3 + l_{c4}m_4) + \cos(\theta_2) \\
&\quad (l_2(m_2 + m_3 + m_4) - l_{c2}m_2) + o(m_3 + m_4) \cos(\theta_2 + \theta_3)) \\
G_3 &= g(o(m_3 + m_4) \cos(\theta_2 + \theta_3) - \sin(\theta_2 + \theta_3) \\
&\quad (m_4(l_{c4} - d_4) + l_{c3}m_3)) \\
G_4 &= -gm_4 \cos(\theta_2 + \theta_3)
\end{aligned}$$

wherein $\theta_1, \theta_2, \theta_3$ and d_4 are the joint variables, m_1, m_2, m_3 and m_4 are the masses of links 1,2,3 and 4 respectively, l_1 and l_2 are the lengths of links 1 and 2 respectively. l_{ci} where i varies from 1,2,3,4 is the distance of centre of gravity of link i from the i^{th} coordinate frame. I_{1j} where j varies from 1,2,3,4 is the mass moment of inertia of link j about the principal $x-axis$ at the origin of coordinate frame j . Similarly, I_{2j} and I_{3j} are the mass moments of inertia of link j about the principal $y-axis$ and the principal $z-axis$ respectively at the origin of coordinate frame j . These mass moments of inertia can be calculated from the values of Table 3.8. o is equal to 0.2 m, as can be seen in Fig. 3.20.

Appendix E

Algorithm for carrying out numerical search to generate K_p versus K_v map

Algorithm 3: Stability analysis using Floquet theory

```
1  $K_i = 0.5$ 
2  $X(0) = I$ 
3  $T = 24$ 
4 for  $K_p = 0 : 1 : 500$  do
5   for  $K_v = 0 : 0.1 : 5$  do
6     Solve the differential equation  $\frac{dX}{dt} = [J_n(t)]X$  over the time period
        $T$  subjected to initial conditions  $X(0) = I$ 
7     Store the monodromy matrix  $X$  in a cell array
8   end
9 end
10 for  $K_p = 0 : 1 : 500$  do
11   for  $K_v = 0 : 0.1 : 5$  do
12     if the absolute values of all the eigen values of the monodromy
       matrix are less than 1 then
13       | the  $(K_p, K_v)$  point is a stable point
14     else
15       | the  $(K_p, K_v)$  point is an unstable point
16     end
17   end
18 end
19 Plot the  $(K_p, K_v)$  map for stable region
```

Publications

Patents

- **Dutta, S. K.**, Reddy A. N., Reddy, B. S., Dwivedy S. K. (2020). Bistable compliant gripper for pipe climbing robot. *Indian Patent*, Application Number : 202031037108
(Status : Published, first examination report awaited)

Journals

- **Dutta, S. K.**, Reddy, B. S., Dwivedy S. K. (2021). Tuning proportional-integral-derivative gains of a 3-D RRRP pick and place robot for asymptotic trajectory tracking. *ASME Journal of Dynamic Systems, Measurement and Control*, 143(4):041001
(DOI : 10.1115/1.4048585)
- **Dutta, S. K.**, Reddy, B. S., Dwivedy S. K. (2021). Complibot : A compliant external pipe climbing robot. *Extreme Mechanics Letters*
(Status : Under review)
- **Dutta, S. K.**, Reddy, B. S., Narayan, J., Dwivedy S. K. (2021). Dynamic analysis of a RRRP climbing mechanism using neuro-fuzzy system. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*
(Status : Under review)
- **Dutta, S. K.**, Reddy, B. S., Dwivedy S. K. (2021). Design and development of external pipe climbing robots : a critical survey. *Mechatronics*
(Status : Under preparation)

Book Chapters

- **Dutta, S. K.**, Reddy, A. N., Dwivedy S. K. (2020). A study of direct and inverse problems in force sensing of elastic bodies. In *Emerging Trends in Mechanical Engineering*, pages 347–355
(DOI : 10.1007/978-981-32-9931-3_34)

- **Dutta, S. K.**, Balathil, J. K., Reddy P. A., Reddy A. N. (2021). Design of a torque controller with application to a single degree of freedom haptic device. In *Advances in Mechanical Processing and Design*, pages 551–559 (DOI : 10.1007/978-981-15-7779-6_50)
- **Dutta, S. K.**, Reddy, B. S., Dwivedy S. K. (2022). Design of a two degrees of freedom actuator for rehabilitation robotic applications. In *Machines, Mechanism and Robotics*, pages 1189–1196 (DOI : 10.1007/978-981-16-0550-5_113)

Conference Papers

- **Dutta, S. K.**, Reddy, B. S., Dwivedy S. K., Design of a novel mechanism for actuation of a bistable buckled beam. In *5th International and 20th National Conference on Machines and Mechanisms*, December 2021, Jabalpur, India. (Status : Accepted for oral presentation)



About the Author

Mr. Saurav Kumar Dutta was born in Duliajan, a small industrial town in Dibrugarh district in the state of Assam, in India on June 8, 1993 to Ms. Mithu Dutta and Mr. Samir Kumar Dutta. He attended Kendriya Vidyalaya Duliajan and passed Class 10th, the All India Senior Secondary School Examination (AISSE), in May 2009 by securing 93.8 %. From the same school, he passed Class 12th, the All India Senior School Certificate Examination (AISSCE), in Science stream in May 2011 by securing 82.4 %. After completing his studies in school, he attended GIMT Guwahati to pursue mechanical engineering. Here, he obtained his Bachelor of Engineering (B.E.) degree with Honours in July 2015 by securing 82.4 % from Gauhati University, India. In July of the same year, he joined the Mechanical Engineering Department of Indian Institute of Technology Guwahati as a direct PhD student and since then, he has been working towards his PhD degree. His research interests include solid mechanics, dynamics, kinematics, compliant mechanisms, finite element methods and the application of these subjects in the field of robotics.