Fuzzy Controller for Continuum Robots

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NUST-2011-MS-CS-010

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A thesis submitted in partial fulfillment of the requirements for the degree of
Masters of Science in Computer Science (MSCS)
In
School of Electrical Engineering and Computer Science (SEECS)
National University of Sciences and Technology (NUST)
H-12, Islamabad (44000), Pakistan

(July 2015)

Approval

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Abstract

Continuum robots are very dexterous to be used in different applications. Such applications range from the minimal invasive surgery and endoscopic examination to metal welding in congested environment such as oil pipes. Both continuum and serpentine robots are mimicking the motion of biologically inspired continuum fashion motion of animal kingdom, by bending through continuous arcs.

Continuum robots could produce motion by pneumatic actuators which are actually gas or fluid filled with certain degree of freedom. Such robots could produce motion in every direction in a continuous fashion without axial rotation.

Following the orientation of surface, continuum robots trace out some angular displacement values with the outside force by bending down in a certain direction. We have to compensate for the degree of bending by producing deformation in the opposite direction, without making a penetration into the delicate parts of the body. In our research main focus is on designing a fuzzy controller which is responsible for aligning the continuous motion when it leads through certain closed regions. When robotize medical device are inserted inside human then end effector is effected by external force, which could be blood perturbation in our case. Both Fuzzy controller and PID controller is compensating for the bending produced in the tip position of end effector, and keep in erectile position to avoid any blockage of blood. It is demonstrated that for safety critical applications, fuzzy controller's performs better than the conventional PID controller.

Certificate of Originality

I hereby declare that this submission is my own work to the best of my knowledge. It contains no materials previously published or written by any other person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at National University of Sciences & Technology (NUST) School of Electrical Engineering & Computer Science (SEECS) or any other education institute, except where due acknowledgment is made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistic is acknowledged. I also verified the originality of contents through plagiarism software.

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Acknowledgements

First of all, I would like to express my endless gratitude to ALLAH almighty (SWT) for his abundant blessings. After that I am sincerely grateful to my supervisor Dr. Sohail Iqbal for his priceless guidance, encouragements, devotion and patience. He molded my thoughts to the right directions and provided technical excellence to complete my thesis. He has been inspirational for me throughout this thesis.

I am also very grateful to my guidance and evaluation committee members including Dr. Ammar Hasan, Dr. Kashif Rajpoot and Dr. Peter Charles Bloodsworth for their precious time, valuable suggestions, invaluably constructive criticism, and for their truthful and illuminating views to enhance our research work. I would also like to thanks all my friends and colleagues for their guidance, encouragements, and continuous support.

Last but not least, I would like to say a big thanks to my parents and my family for their endless love, kindness and encouragements. Without their prayers and continuous support, it would not have been possible to accomplish this milestone.

Dedicated to my parents

For their endless love, kindness and encouragements

And my supervisor (Dr. Sohail Iqbal)

For his priceless guidance, encouragements and devotion

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List of Abbreviations

Abbreviation	**Description**
DOF	Degree of Freedom
FLC	Fuzzy Logic Controller
PV	Process Variable
SP	Set Point
PAM	Pneumatic artificial muscle
NOTES	Natural Orifice Transluminal Endoscopic Surgery
MIS	Minimally Invasive Surgery
HTW	High temperature Winkler gasification

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Chapter 1

Introduction

In certain industries, health departments and nuclear vicinities human outreach is not possible mainly because of poisonous and hazardous materials producing. The replacement of electromechanical devices and some small instruments becomes pretty important by attaining greater degree of precision and accuracy. This research is revolving around continuum robotics, with the sole purpose of having improved navigation and whole body grasp of objects.

With diversified applications, continuum robots have specifically made a good contribution in the medical domain. Most of the medical instrumentation such colonscope and catheters have been robotized for carrying out medical inspection and procedures. The successful completion of our work also encompass robotizing those devices by designing a fuzzy controller for it. These controllers can be controlled without the direct intervention of humans and could work in such dangerous areas, without posing any threat to human lives. In surgical procedures the robotize devices are acting intelligently by traversing through narrow unstructured region, without coming in contact with the soft tissues of interior wall, and thus human safety.

Talking specifically about medical field doctors fail to diagnose diseases in certain delicate parts i.e. small and large intestines. To meet this partially solved matter of grave concern and intense nature our whole focus in this research is to robotize medical devices such as colonoscopies, catheters and laparoscopic shafts by designing fuzzy controllers for the continuum robots.

Beside medical field this fuzzy controller can be scaled up to other areas as well where human outreach is not possible i.e. nuclear vicinity and chemical plants. Precision and accuracy is of utmost importance when dealing with the above mentioned tasks.

1.1. Continuum Robots

There are different kinds of robots; classification is based upon the presence of joints and their interconnectivity [11]. There are innumerable ways of designing robots, molding every single one according to the requirements. Discrete robots are human arm inspired and are suitable for heavy mechanics where lifting heavy objects is of paramount importance. For miniature or small level tasks, some other attributes play a vital role to get the job done.

Within discrete robots it could further branch out to serpentine robots, where joints are closely attached in a way producing movement in continuous fashion. Their movement and the path it traced out resembles with snake movement. Discretization of joints ensures the firm grasp of objects, by whirling around the regular and irregular geometry.

Continuum robots are joint-less robots and do not contain rotational joints [11]. It bends in any direction, and reach out places where human intervention is not possible. Their movement resembles that of snake, tentacles or tongue of animal kingdom.

There are several forms of continuum robots based on the organization of actuators, notably extrinsic, intrinsic and hybrid. Intrinsic are further classified into intrinsic planar and intrinsic spatial. Intrinsic planar are liquid filled or gas filled, which underwent bending in a single plane through the heating of gas or liquid. Structure and layout is not uniformly across the axial line, the stiffness varies across the sides, ensuring the bending on one side, due to strain variation [3-13]. Intrinsic spatial- the basis construction of intrinsic spatial robot constitutes of fluid filled actuators with the supporting structure.

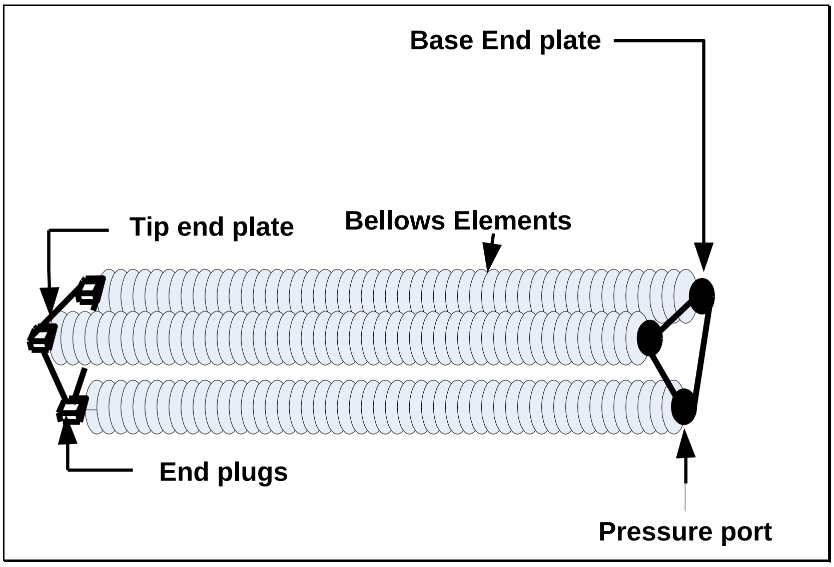


Figure 1.1 Spatial Bellows Actuator © **G.** Robinson, J.B.C. Davies May 1999

The three bellows attach by whirling around a support tie which is used to serve different but useful purposes, to produce axial bending rather than radial expansion also to align them in fixed position and also to stop them from being expanded away from each other. Due to variation of heating the bellows gets, it produces three degrees of bending. When the strain energy overcomes the heating energy, the bellows comes to its original position.

Apart from the supporting tie used in the above figure, Suzumori et al. used nylon fibers to resist radial expansion, as such expansion don’t produces considerable axial expansion. The construction is called flexible micro actuator or FMA [12].

Davies gives the construction of convoluted bellows to ensure the considerable degree of bending is produced along axial line that radial expansion [22-23]. Convoluted design was mainly aim to overcome the possible drawbacks associated with supporting tie or nylon fiber to be specific. This compliant grasping is used for handling irregular geometrical objects, also reducing the likelihood of damage when comes in contact with manipulator. Amadeus mainly focused on the end-effector of robot working in submarine environment [5-24].

Robinson et al. do mentioned the limitation, stringent design and future research challenges for designing end-effector to navigate in narrow unstructured environment, where human intervention and outreach is not possible [24].

Kallio et al. put an effort for designing micro manipulator arm and used three small size nickel bellow for it. Bending and expansion of bellows were successfully transferred along the micro manipulators, resembling that of continuum robot [6].

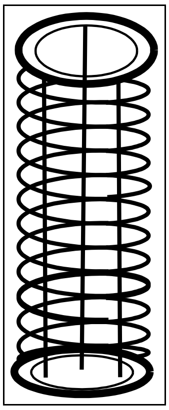


Figure 1.2 Extrinsic Actuator © **G.** Robinson, J.B.C. Davies May 1999

Extrinsic actuators- convoluted spring with three antagonistic tendons is used to produce bending in every direction, increasing the freedom of movement. The convoluted structure carries two plates on either side with pair or triads of tendon enclosing inside it [15, 7].

Hybrid actuators are amalgam of intrinsic and extrinsic, similar more or less to extrinsic except that convoluted springs are replaced by redundant bellows. Hybrid consist of two sets of triad tendons, one set is keeping the shape of proximal halfway intact, while the other is trying to control the form of distal portion. Flexible robot or continuum robot is suitable for navigating in unstructured and congested environment, as discrete robot cannot conform to the adaptiveness of unstructured environment.

Discrete robot has limited degree of freedom, while continuum mechanism theoretically has infinite degree of freedom, increasing maneuverability. PAM (Pneumatic artificial muscle) is too noteworthy which is actually following continuum mechanism [11].

Continuum robot is necessary when it comes to human robot interaction as part of safety requirement, which is also of paramount importance in service robot domain [12]. PAM therefore undergoes motion in a continuum fashion, fulfilling the need for safety requirement. Variable stiffness is observed across the layout in PAM, defining the boundary condition for force.

1.2. Minimally Invasive Surgery (MIS)

To ensure patient safety Minimally Invasive Surgery (MIS) is of utmost importance, and it has caught a lot of attention from the early 2000s. MIS is the recent example of technology advancement, which helps in excision of tumor outgrowth, reducing patient trauma, shortened hospitalization with narrow incisions and improved diagnostic accuracy. Surgery in the heart, throat and aorta are examples of surgical applications in the medical domain. Despite of so many advantages it contains drawbacks including reducing the efficiency of human in working environment, and also controlling miniature robotize devices. Robotic design for compliant motion inside unstructured region often poses problems in terms of navigation, and inflicts limitation on their structural features. With many applications continuum robot is mainly designed for carrying out minimally invasive surgeries. Continuum robots are termed as joint-less robots and don’t contain any rigid link or rotational joint, and underwent bending through continuous bending along its structure. Some problems could be associated with the continuum design: optimization of design, sensing ability, kinematic design and modelling and their bending control in real time.

With such degree of freedom continuum robots have the ability to navigate through complex, comprising of enhanced maneuverability. Traversing through congested and unconventional environments, make them the most important robot for carrying out surgical procedures, without posing any danger to patient. Continuum robot in MIS involves use of laproscopic devices, and auto control and manipulation of instruments. Robotize devices are used for excision of tumor outgrowth and other masses with minimal scrapping.

1.3. Overview of thesis

Brief overviews of the rest of chapters are as follows

Chapter 2, Covers a brief introduction of the continuum robots involving motivation, development phases, classification of continuum Robot, Trunk cable Kinematics and computation of curvature and other arc parameters for continuum robot.

Chapter 3 explains fuzzy logic and fuzzy rules for controlled continuum end effector, while navigating through narrow unconventional environments. It also the application of fuzzy logic in power plants for optimizing the throughput of gas produced from different varieties of coal.

Chapter 4 explains the modelling of Continuum robot end effector based on the inverted pendulum model. It also explains the proposed solution for compensating the bending while being exerted by the external force. The results are validated through simulations of Fuzzy logic Controller and PID controller. Such controllers were meant to damp the vibration produced at the tip position of end effector.

Chapter 5 describes Simulation results for continuum robot end effector modelling, and the results produced with Fuzzy controllers and PID controllers in the presence of white noise. It also explains the comparison of the results through analysis.

Chapter 6 concludes thesis with possible directions of research.

CHAPTER 2

CONTINUUM ROBOTS

2.1. Motivation

Continuum robots due to its structural design can operate in non-structured and congested environments. Due to limited outreach & intervention of humans in the medical domain and nuclear vicinities, robot designers think of flexible structure with unlimited degree of freedom attaining the desire and high degree of precision. Continuously bending structure, ability to bend and navigate, possibly unstructured and deformable surroundings is termed as continuum robot. Flexible structure poses no threat, as it cannot traverse through soft tissues when comes in contact with the walls inside human body.

Other type of robot, the conventional or traditional robot, consists of series of rigid links with limited degree of freedom, operable only in structured and spacious environments. Without moving and changing the gait along the body structure, it reaches out limited points on the plane. Forward kinematics has been devised for different types of robots, typically fluid filled pneumatic actuators [13], concentric tube robots [14], cable-actuated robots [15] and magnetic catheters [16]. Constant curvature concept is mainly used in miniatures or micro robots, not applicable for deflections in large robots [17].

As discussed continuum robot application could not be limit only to medical domain and nuclear vicinities, but it has wider application, i.e. cleansing and welding of submarines ships, and also in rescue efforts for saving human lives stuck underneath the debris [2]. Most of the researches have been done on robotizing medical equipment’s catheters, endoscopes, lathroscope, which on success would have the ability to turn around the corners while navigating through unstructured regions, without having prior knowledge of inside environment.

The robotic surgical procedures carry out inside the human body allows end effector to extend it to the location, inaccessible on the part of human intervention. Techniques notably minimally invasive surgery and Natural Orifice Transluminal Endoscopic Surgery (NOTES) embarks and revolutionizing new beginning in the medical field. The insertion of robotize device or surgical slaves used in the above mentioned techniques, traverse through without making in contact with the soft tissues. Such miniature interacts with the structure carefully

while being subject to the assembly of unfamiliar contact positions along the robot structure in a length wise manner [18].

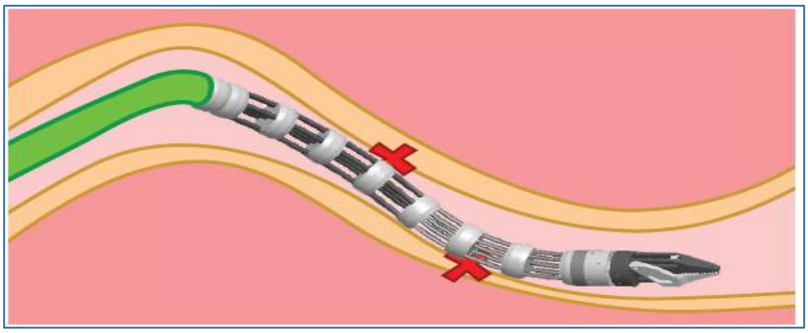


Figure 2.1 multiple contacts at unknown locations during compliant insertion of surgical instrumentation

© Roger E. Goldman, Andrea Bajo, Nabil Simaan

Safe interaction can be achieved through passive compliance structure without the need for further sensing and complex control, for guided path traversal. Mentioned structure is flexible and could bend with the contact force; therefore for external environmental interaction it does not require any explicit force for compliant control. Passive compliance is implemented in cable drive [19]-[20], shape memory alloy actuator (SMA) [21]-[22] and pneumatic drive structure [23]-[24]. Such implementation is promising in deploying the tasks with utmost safety but do have certain disadvantages in terms of MIS procedures. Due to the limited magnitude of forces it could not perform tasks such retracting soft tissues and blunt dissection. Research in the continuum structure revolves around the compliant uncertainty and modelling difficulties due to the unpredictable bending of tip position [25].

2.2. Development phases of continuum robots

2.2.1.Origin & Design

With the structural improvement and increasing degree of compliant interaction need for continuum robot is felt. Studying the design features and translating them into somewhat continuum structure take place in the late 1960s. Such robots are biologically inspired structures such as elephant trunk or backbone of a snake, whose locomotion, dexterity and navigation through cluttered and congested environments marks their distinguish features. Example includes ORM, which is made of pneumatically controlled bellows.

The transition from serpentine to continuum robot is mainly on the basis of navigation purposes. Weaknesses of Continuum robots include that it could not be scale up or molded into uplifting heavy objects, hard to understand the kinematics and also it results in the abandonment of encouraging research projects that initiated in the late 1960s.

Within the robotics domain the main research and development continued covering the hyper-redundant and continuum robots. Hirose contributed a lot through his pioneer work, and develop many different and innovative designs, originating the structural features from the biological systems. Much of his work is published in Hirose (1993). His work pave the way for new big and long lasting transition in robotics domain, setting up the tone for the researchers and inclining them towards the continuum aspects of robots. At that point of time some industrial continuum robot manipulators and end effectors were also developed which includes Spine robot, a spray painting robot (Developed by Davidson and Larson in 1985), some efforts were also put to mimic the locomotion and kinematics of biologically inspired animals, which includes elephant like trunk manipulators (Morecki et al. developed it in 1987; and Wilson et al. in 1993).

2.2.2.Modelling

To further enhance the navigational precision need for modelling continuum robot kinematics is felt in 1990s, which includes the contribution of Chirikjian and Burdick by presenting a modal approach. This approach was based on the theoretical foundation of continuum robots to approximate the layout, design and shape using a mathematical curve. The path traced out by such curve was model in terms of mathematical equations.

In 1995 two pioneer scientists Ivanescu and Stoian model the kinematics, locomotion and traceability of continuum robot mechanics. Diversity of application were spawn from the origination of continuum robot modelling, which notably includes both commercial (Antonelli and Immega in 1995) and hypothetical research (Robinson & Davies in 1999).

Great progress in the modelling, design and application has been observed in the first period of the 21st Century. Joint effort of Gravagne and Walker et.al has established a theoretical framework for the analysis of continuum robot in back 2002 and 2003. More sophisticated models of continuum robot were introduced through the application of beam theoretical concepts and simplifying the modelling through constant curvature approximation.

2.2.3. Multisection Forward kinematics

Continuum robot are required to touch every coordinate on the plane, this ability is present in multisection continuum robots. Multisection robots provide sufficient number of DOF for task requirements. Single section continuums provide 2 to 3 DOF. To provide more degree of freedom more sections are required in order to touch every single point on the plane without axial rotation. Apart from number of sections actuator length can also limit it to relatively small size workspace. Greater the radius of curvature less be will the curvature and hence less points of contact will be exposed from the point of attachment. For full arm grasp and working in congested and cluttered environment often one section is dedicated to the task. All of these factors are the motivation for the need of multisection continuum robot.

Despite of so many advantages, multisection robot provides complexity in mapping as mentioned in figure 2.2 In general the outputs generated as a result of forward kinematics for robot independent design are straightforward and can be used to generalize for multisection case. Each section could be seen as constituting transformation.

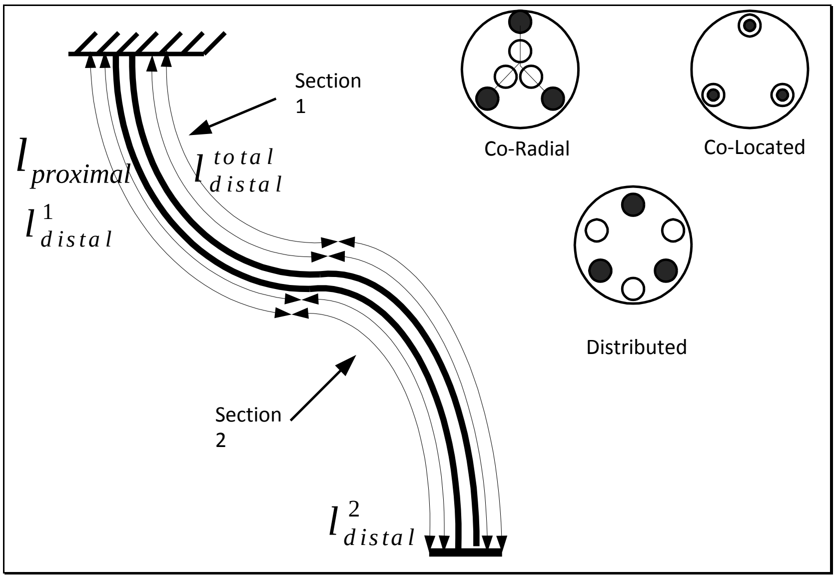


Figure 2.2 A two-section robot illustrates the ''tangle/untangle'' process ©Robert J. Webster, Bryan A. Jones

Thus the overall structure and design represents that all the extensions leading to multiple segments or sections require a thorough analysis, which encompasses push rods and cables. As mentioned in figure 2.2, co-located actuators as shown above offer a direct method to find distal actuator length as the summation of wholly co-located proximal actuators. Robot designed by Xu and Simaan (2008) shows that distal part or the portion near robot tip position is lies inside the proximal part. Considerable amount of movement is observed in the distal that slightly change the proximal part, thus providing a uniform structural compliance over the outside layer. Arc parameters such curvature, length of curvature and orientation helps in determining the length of distal actuator.

2.2.4. Inverse kinematics

For redundant and continuum robots inverse kinematics is very thought-provoking mechanism. Inverse mapping that is present between robotic task space and configuration space is computed for constant curvature continuum robot. As a result of this arc parameters for every single section of continuum robot is computed. Computed Arc parameters relate to the tip position of the robot, which usually of paramount importance during investigation and inspection purposes in the unstructured region. In 2009 Neppalli et al. specified a closed-form model geometric method for both single and multi-sections continuum robots, in which each section is modelled using straight rigid links and spherical joint. This model helps in solving the problem of inverse kinematics before changing again back to arc parameters. This approach can be scale up and valid for the complete solution space of discretize joint robot and can be easily applied to robot constituting several joints. However this solution is not applicable on limited actuator lengths.

The inverse mapping varies for each kind of continuum robot. Inverse mapping needs to model and specify both arc parameters and actuator parameters, which then interchangeably goes from arc to actuator parameters. Amongst them Bevel piloted inverse kinematics are the most direct, since ϕ for respective section describes the total axial rotation required after each and every forward transformation along the preceding segment. For certain design of continuum robots like concentric tube robots inverse kinematics pose complexity, given ϕ, κ and s in their workspace. In order to simplify this case, one can underwent work doing in the backward direction from the distal section, where ϕ_n is equal to the rotation angle along the axis it comprises.

In 2008 Xu and Simaan were of the view that single section inverse mappings required modelling of both arc parameters and actuator parameters to touch some desired points on the plane, which also comprise derivations for push rod-actuated robots. The same mapping applies on single section cable and pneumatically actuated robots. Later on with some more research covering the same problem, Jones and Walker provide “tangle/untangle” algorithm, with a pre job of producing a logical derivation of workplace for these robots. This algorithm was presented for multi section cable actuated robot with actuators specified equally spaced about the lower base of the trunk.

The whole focus of the above algorithm is on the arc parameters i.e. constant curvature kinematics and don’t cover gravitational loading or friction which is useful for continuum robot design. Frictional force could cause linear bending in the flexible push rod design. Luckily, this can be controlled by compensation that uses redundant actuation in single-section and multiple-section cases (Xu and Simaan 2006 &2009). Likewise, some continuum robot designs go through substantial axial compression due to actuator forces, requiring a careful observation in focus of the system to measure cable lengths which resemble to required arc parameters (Camarillo et al. 2009a).

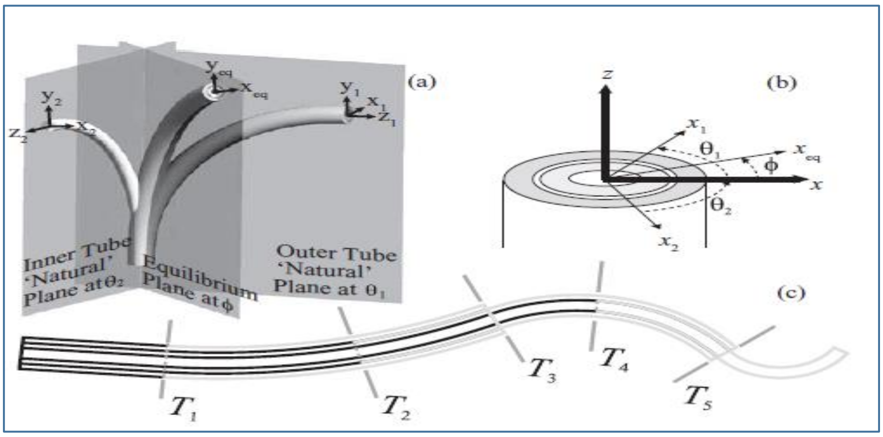


Figure 2.3 (a) Two precurved tubes are placed concentrically and rotated axially about their base point, the resultant shape it subtends are circular arcs (b) cross sectional area showing individual and equilibrium frames (c) Cannula comprises of 2n such sections for n tubes: ©Robert J. Webster, Bryan A. Jones

2.3. Classification of continuum Robot

With broad categories continuum robot could be further branch out into different classes based on the design and integration of different components with a different traceability curve. Curve depends mainly on the number of sections and the distance between the successive joints. Such classification is based on the location of mechanical actuators (Davies and Robinson et.al 1999), degree of freedom, bending, deformation capability and extensibility.

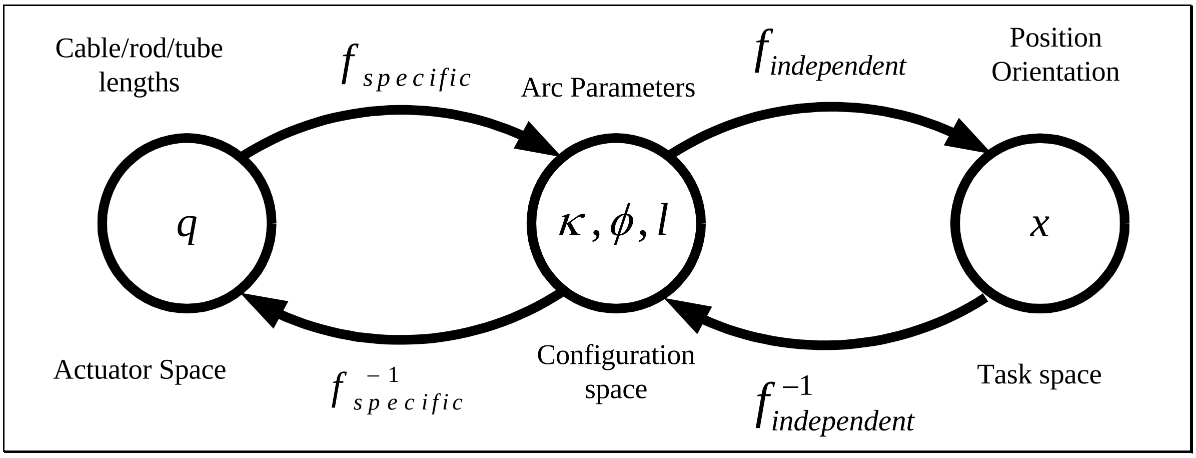


Figure 2.4: Three spaces and mappings define the kinematics of constant curvature robot © Robert J. Webster, Bryan A. Jones

Trivedi et.al in 2008 presents a review of soft robotics contrast rigid, hyper-redundant and hard continuum. He presents a study of robots which are mimicking motion of a subset of animal kingdom, including robotize starfish, worms, trunks and other continuum robotic manipulators, which were closely related to it in terms of kinematics and locomotion in their related environment. The purpose is not to draw a line between the hyper-redundant and continuum robots, but it is the diversity of architecture, applications and design that would be applied in terms of constant curvature, forward and inverse kinematics. In this case we omit any hyper-redundant type robot that don't exhibit constant curvature, due to the large attach links or where traceability curve is not a perfect approximation. Backbone bending exhibit either continuous or discrete and some design may contain flexible one. There are many designing strategies for actuators; some are designed to enhance payload capability while others are for navigation and inspection purposes.

2.4. Trunk Cable Kinematics

In spite of many applications demonstrated by large set of robots, less effort have been applied in modelling orientation and kinematics of these robots. For example all the previous efforts do not pay any heed towards end effector orientation and their positional kinematics. The uncertain coordinates end effector may come across while navigating through unstructured regions. The coordinates points traced in a plane or space should be represented through mathematical equation, to provide a reference formulation for the future modelling of continuum robots. The uncertainties in tracing may vary, which is actually originated from different architectures in robot modelling.

Hirose designed a serpentine robot which bear a resemblance to the kinematics of snake in 2-Dimensional environment [34] . However it does not encompass the spatial kinematics of the many snakes like continuum robot they designed. Chirikjian and Burdick link the general traceability curve to the degree of freedom it possesses [35], [36], [37]. To further simplify the model and for better implementation and analysis, the model is decompose to arrive at a reduced and contour degree of freedom, for better modelling of the curve which is traced by robot. Modern approaches rely on approximating the shape of the curve, which spawns may model complexities in terms of kinematics difficulties [38]. To scale it up to high degree of freedom, a different method is devised to measure the kinematics of manipulator with high DOF using standard D-H methods [28]. This approach is only valid and applicable for spherical and rigid links and do not work for revolute joints. The author of [26] chooses a continuously bending of circular which resembles navigational locomotion of joint-less continuum like robots, due to the several forces equally exerted on the curve surface [32].

However the model in [26] contains 3 flaws, firstly it assumes rigid or inextensible backbone which is not mimicking a constant curvature along the external surface; secondly it does not compute the positional loci and orientation of the end effector due to some assumption taken in the model, thirdly it is restricted to some specific design [26].

This simplification results in reduction in classes of shapes and kinematics, which in turn has bracketed their applications. In order to achieve the performance, the structure of continuum robot is related with the actuator length. The shape and orientation of continuum end effector can be controlled through relaxation and bending to the actuator length. This mechanism of contraction and relaxation requires a kinematic model which relates shapes as per different inputs to the actuator. This particular section presents an overview of new kinematic model, comprising three tendons, 120 degree apart from each other in the configuration such as Air-octor trunks &octarm. This model is different from other models in terms of number of tendons [39][26] , the previous were tailored to 4-tendons and therefore could not scale up to other structures. Likewise this model of three tendons could be extend to trimsole sensor [27], Hirose's elastic case kinematics [33], and various other miniatures or robotize device such endoscopes [29], [30], [31] by determining trunk lengths which is based on constant curvature.

2.4.1. Transformation from cable length to trunk curvature

Three cable length l_1, l_2 and l_3 in a section of the design, the constant distance d which is represented as d from the center of trunk to the site of cables, and n demonstrates number of segments in this trunk section. Trunk variables s, κ and φ gives the positional location of the tip of end effector. The case should be responsible to produce bending along the longitudinal axis without producing radial contraction. The three cables are present around the trunks which are equidistant from each other making an angle of 120 degree with respect to each other. In this the curvature is assumed to be uniform along each section of the trunk of continuum robot. Pneumatic pressure is used to achieve the required result by imparting equally distributed bending forces.

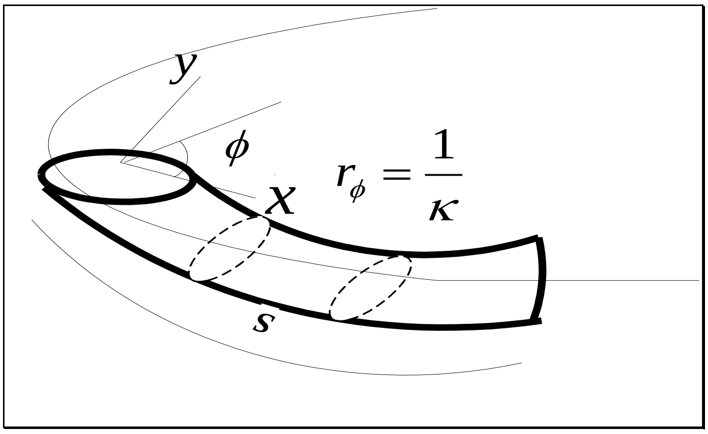


Figure 2.5: trunk variables: the variables give the orientation in the xy plane © Bryan A. Jones

The main aim is to compute the trunk variables which are actually done in three steps. Firstly the radius of curvature r_1, r_2 and r_3 due to l_1, l_2 and l_3 are computed. Secondly from these distances the maximum curvature kappa (κ) extracted. Thirdly from this kappa κ the trunk length *s* is derived.

2.4.2. Computation of κ_i, the per cable curvature

Consider figure 2.6, three cables connecting two segments are place equidistant from each other at an angle of 120 degree. Plane H is placed on the trunk where cable1 is attaching it and is at vertically right angle to other two cables. Plane H determines that three cables which are parallel to each other are placed at equal interval along the circumference of circle of trunk.

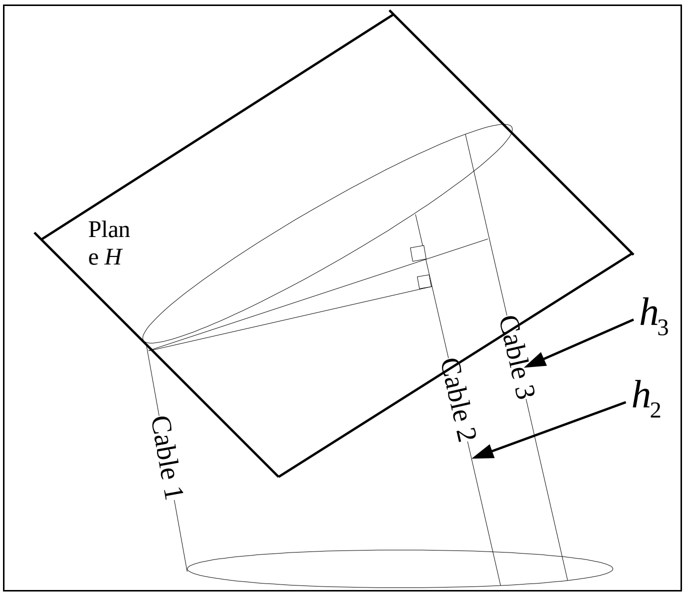


Fig 2.6: Bent segment in a section of the trunk © Bryan A. Jones

The 2nd plane as shown in figure 2.6 can be moved here and there to include any arbitrary point, such as the attachment point of the cable 1 to the trunk. Inserting the plane vertical to the trunk region, it decomposes into two triangles. The figure can be added up with another triangle originates from the center of circle to the adjoining point of cable 1, which shows the hypotenuse of all three triangles. ʜᴗc which is height from the center of circle is used to compute the curvature. To compute the value of ʜᴗc, we need to find the value of h_2 and h_3 the height of cable 2 and cable 3 respectively.

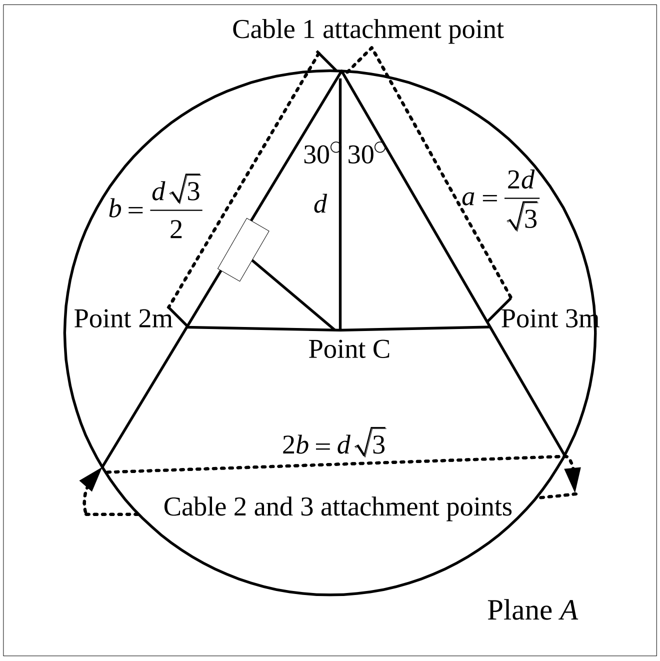


Figure 2.7: top down view of trunk © Bryan A. Jones

Although it has not been shown in figure 2.6 but a second plane also exist which is perpendicular to 2 and 3 and which comprises the connection point of cable 1 at the lower part of trunk segment. The cable 2 and cable 3 length $2h_2$ and $2h_3$ exceeds l_1 of cable1 are equally divided between the height measures from above the top plane and below the bottom plane. l_2 and l_3 can be expressed in terms of h_2 and h_3 respectively as for n-segment trunk section

$$\frac{l_2}{n} = \frac{l_1}{n} + 2h_2 \qquad (2.1)$$

$$\frac{l_3}{n} = \frac{l_1}{n} + 2h_3 \qquad (2.2)$$

Therefore from equation 2.1 & 2.2 we can derive

$$h_2 = \frac{l_2 - l_1}{2n} \qquad (2.4)$$

$$h_3 = \frac{l_3 - l_1}{2n} \qquad (2.5)$$

H_1=0 because the cable passes at the attachment of cable1 to find ʜᴗc refer to figure 2.7.

From the figure 2.7 we know that

$$\cos(30^\circ) = \frac{d}{a} \quad \text{(2.6)}$$

$$\cos(30^\circ) = \frac{b}{d} \quad \text{(2.7)}$$

As we know $\cos(30^\circ) = \frac{\sqrt{3}}{2}$

So putting $\cos(30^\circ) = \frac{\sqrt{3}}{2}$ in equation 2.6 and 2.7 we get

$$a = \frac{2d}{\sqrt{3}} \quad \text{(2.8)}$$

$$b = \frac{d\sqrt{3}}{2} \quad \text{(2.9)}$$

Here “b” is the half distance between cable 1 and cable 2, when the triangle is inscribed inside the circle. The full distance is

$$2b = d\sqrt{3} \quad \text{(2.10)}$$

Rotating plane at an angle of 90 degree along the dotted line produce figure 2.8 which is shown as

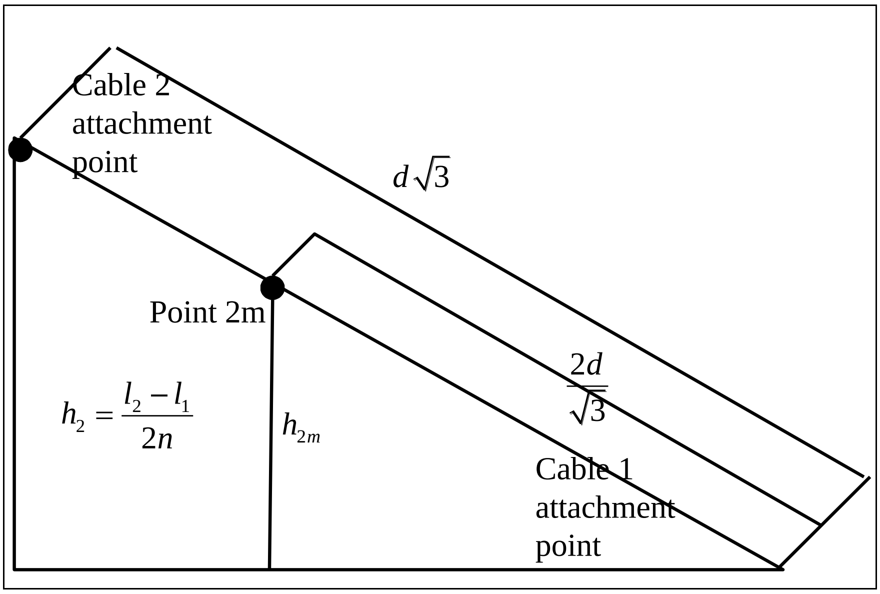


Figure 2.8: Height of point 1 and point 2 above plane© Bryan A. Jones

From the figure 2.8 we deduce that the length of larger and shorter side hypotenuse are $d\sqrt{3}$ and $\frac{2d}{\sqrt{3}}$ respectively. The height of point 2m h_{2m} can be found from similar triangle relation that is given as

$$\frac{h_2}{h_{2m1}} = \frac{d\sqrt{3}}{\frac{2d}{\sqrt{3}}} \qquad (2.11)$$

Substituting and solving for h_{2m1} in equation (2.11) give as

$$h_{2m1} = \frac{l_2 - l_1}{3n} \qquad (2.12)$$

Using the same for the point 3*m* we get

$$h_{3m1} = \frac{l_3 - l_1}{3n} \qquad (2.13)$$

To find h_c must be the average of point 2m and 3m which is given as

$$h_c = \frac{l_3 + l_2 - 2l_1}{6n} \qquad (2.14)$$

h_c shifts to negative at some orientation where the double of l_1 is greater than sum of l_2 & l_3 which is shown as

$$2l_1 > l_2 + l_3$$

It is assumed that the curvature is same for all the *n* number of sections in the segment of continuum structure. Therefore the curvature does not vary from every section but it remains constant along every section it constitutes. Curvature of section can be written as

$$\kappa = \frac{1}{r_\phi} \qquad (2.15)$$

Here r_ϕ is the radius of the circle traced as an arc of the trunk section. Consider an imaginary cable of length $\frac{l_c}{n}$ which is demonstrated in figure 2.9, this cable is assumed to be leading from top to bottom from center of cross section of trunk region. As mentioned in below figure 2.9 where two isosceles sides of triangle with length $r_\phi = \frac{1}{\kappa}$ and $\frac{l_c}{n}$ make an angle of β degrees. Plane *A* as depicted above in figure 2.7 containing the circle which constitute the upper top part of the trunk region in the structure, the corner of the triangle are present in this plane. Talking about the polar coordinates this corner can be treated as the vector $\kappa \prec \phi$ in plane *A*.

κ_l could be measured by introducing a new plane β as shown in figure which is perpendicular at right angle to plane *A* having $\frac{l_c}{n}$ and $\frac{l_\phi}{n}$, so the new plane now comprises of l_1 & $\frac{l_c}{n}$. As shown in figure 2.9 depicts the contents of plane β after rotation, which consist of an isosceles type of triangle with sides r_1 and $\frac{l_c}{n}$. Similar to equation 2.1 and 2.2, the length $\frac{l_c}{n}$ could be split into $\frac{l_1}{n}$ and h_c which are the length of cable 1 and the height this imaginary cable spreads above the plane anchored by l_1, it can be shown as

$$\frac{l_c}{n} = \frac{l_1}{n} + 2h_c \qquad (2.16)$$

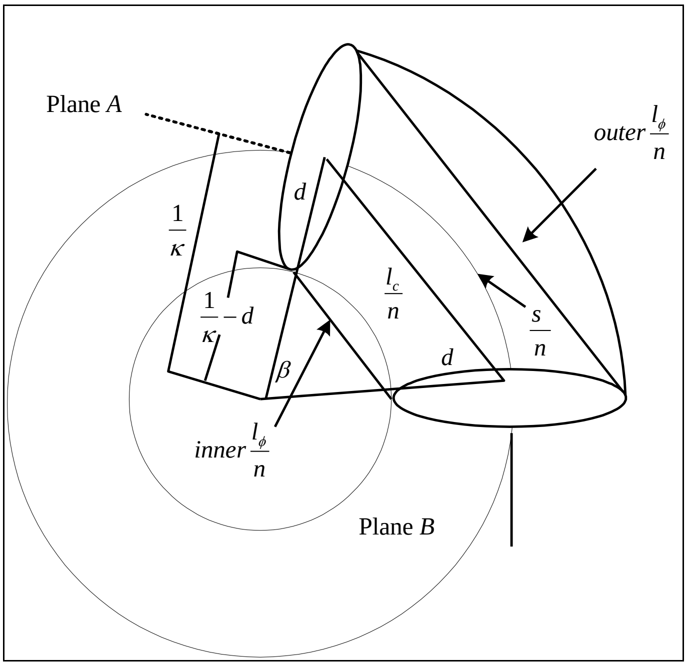


Figure 2.9: Geometry of bent trunk segment© Bryan A. Jones

By comparing and relating this to the smaller triangle in figure 2.8 produce

$$\frac{h_c}{d} = \frac{h_c + \frac{l_1}{2n}}{r_1} \qquad (2.17)$$

Replacing in equation 2.14 yields

$$r_1 = \frac{d(l_1 + l_2 + l_3)}{l_3 + l_2 - 2l_1} \qquad (2.18)$$

Noting $\kappa = \frac{1}{r_\phi}$ from equation (2.15) yields

$$\kappa_1 = \frac{l_3 + l_2 - 2l_1}{d(l_1 + l_2 + l_3)} \qquad (2.19)$$

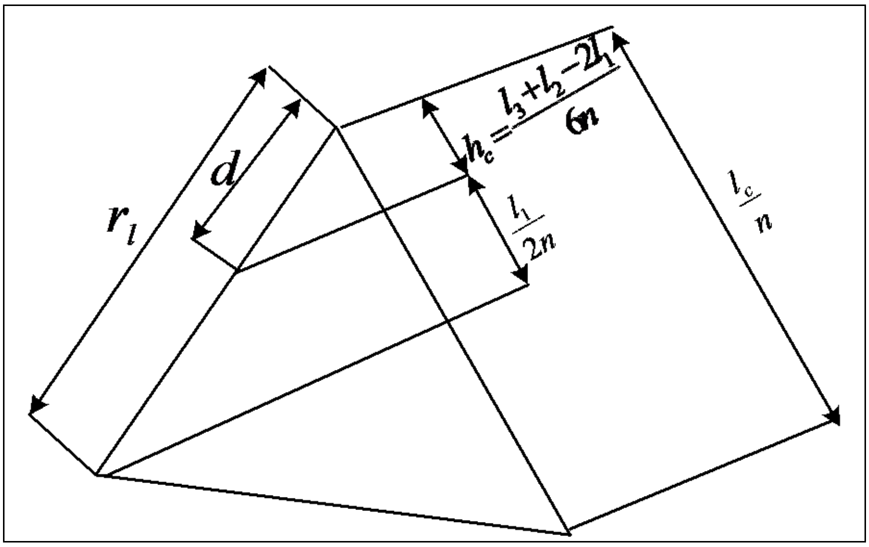


Figure 2.10: Determination of r_l © Bryan A. Jones

κ_2 and κ_3 are similarly produced as

$$\kappa_2 = \frac{l_3 + l_1 - 2l_2}{d(l_1 + l_2 + l_3)} \qquad (2.20)$$

$$\kappa_3 = \frac{l_2 + l_1 - 2l_3}{d(l_1 + l_2 + l_3)} \qquad (2.21)$$

This is how curvatures are computed for continuum robot modelling

2.5. Applications

As discussed earlier, diversification and flexibility of continuum robot offers due to variety of structural deformations, a number of applications could be associated with it. Such applications includes nuclear decontamination, nuclear reactor repair, for performing surgical procedures, for welding purposes, for locating body stuck underneath the debris, undersea manipulation and inspection of unstructured regions i.e. pipes etc.

A good shift of contribution has been made toward commonly used routine medical miniature devices. Examples include medical tool such as catheters arthroscopes & colonoscopes which can mimic Robot kinematics in a continuum fashion. Efforts have been made to robotize such manually operated devices which includes flexible needles (Webster et.al 2006a), arthroscope (by Dario et.al 2000), laser manipulators (Harada et.al 2007). Surgical dexterity of continuum end effector refers to the ability to navigate through unstructured regions without making contact with the inside delicate tissues, which also in turn ensures human safety. These devices are straight but bending ability has been incorporated inside it.

2.6. Conclusion

Continuum robot contributed a lot in the robotic community, by having diversified set of applications ranging from medical domain to carrying out tasks in nuclear vicinities, where human intervention is not possible. In the motivation section, we explained the inspiration and need behind continuum robot development. In the development discuss different phases of continuum robot development, also explains inverse and forward kinematics that how arc parameters are translated into actuator parameters to meet certain points on the plane.

In this chapter continuum robots have been clearly distinguished from the traditional robot in terms of their modelling and dexterity in unstructured, unconventional and cluttered environments. Of many the most general model which explains the structure and shape of continuum robot involve numerical integration and termed as forward kinematics. It is also explains the significance closed form piece wise constant curvature approximation.

This chapter also addresses trunk orientation, positional kinematics approximation in terms of arc parameters. Controlling the shape and position of the end effector requires a kinematic model which is changing continuously with actuator inputs including both extension and bending. Fuzzy logic approach is used with a set of IF-THEN rules to compensate the deflection from the position. These rules are fine-tuned which results in better result. Controlling parameters of PID are sometimes represented as Fuzzy output variables, in order for doing a comparative analysis between these controllers.

CHAPTER 3

FUZZY LOGIC AND ITS APPLICATIONS

3.1. Fuzzy Logic

Fuzzy logic refers to the infinite possibilities between binary values. It deals with approximate values, rather than exact and fixed. Unlike binary values i.e. 0 and 1 fuzzy logic variables also encompasses infinite range of values between them. Fuzzy logic has a large range of truth values, which can take both partial truth and partial false values [40]. Moreover when fuzzy rules are used these values are managed by specific member functions [41].

Lofti A. Zadeh has great contribution in fuzzy mathematics, known for proposing fuzzy related concepts: fuzzy algorithm, fuzzy semantics, fuzzy languages, fuzzy control and fuzzy systems. The term "fuzzy logic" was also introduced by him in 1965. [42][43] Fuzzy logic has diverse application in many fields, could be scale up to many several different control fields from control theory to artificial intelligence and many more. Fuzzy logic research is traced back to 1920s, which in that time was known as infinite-valued logic [44]. Two towering scientist Lukasiewvicz and Tarski laid the foundation of such logic, which after sometime was extended by Al-Zadeh.

3.1.1. Fuzzy Logic for Robot position control problem

Position control for continuum robots is very crucial while navigating through unstructured environments. With flexible structure the end effector of continuum robot is bending in either direction by external force. With variety of applications of robot control, mostly deal with control of tip position or manipulator. For discrete as well as continuum robots position control of robot arms and end effector respectively in free space is of utmost importance [55][56]. In some cases robotic tasks involve contacts with the environment, while in safe navigation avoiding contacts is required. In the latter case a safe traversing mechanism should be devised to avoid coming in contacts with the walls of the surrounding environment. The scrapping of the walls could be resulted if the end effector coming in contact with the soft tissues of the walls. Controlling mechanism should be devised to control the tip movement during of inspection or navigation, to avoid any contact with the interior walls of arteries or veins. Robot interaction with environment is termed as constrained & controlled motion tasks, because robot kinematics is limited by the surrounding environment through which it is interacting. Apart from the position control, forces exerted at the robot end-effector also need to be checked and controlled [57][58][59][60][61][62] [63][64] .

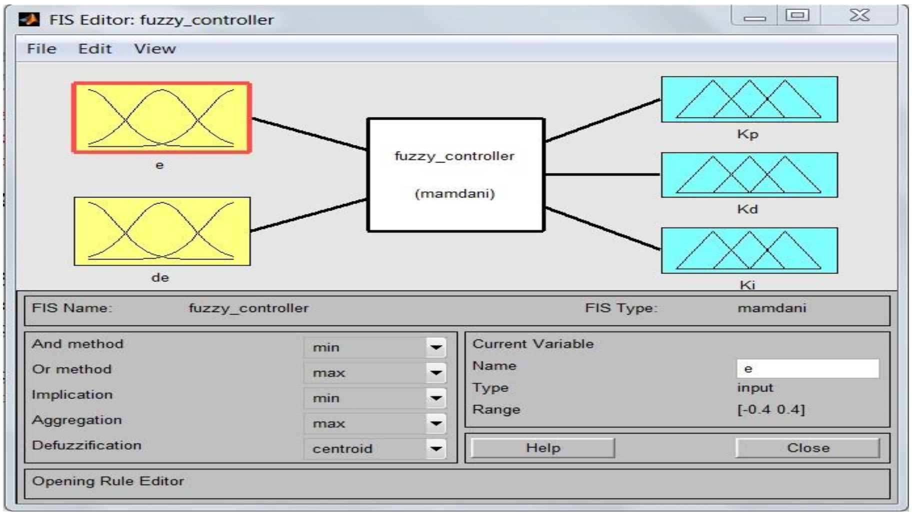
Different controlling mechanisms are used for constrained motion tasks each one has its own limitations in terms of carrying different tasks in different frame of reference. Main challenge for implementing PID controlling mechanism, is to get the dynamic variables changing instantly related to varying environmental workspace, parameters like friction and impedance are nonlinear, with varying time and space. Quick and real time adaptation can be achieved, since the step signal is feed indicating the exertion of desired force and helping avoiding any damage to the environment and robot. Certain parameters like contact geometry and navigational speed are prone to change varying from one task to another, dynamics and structural features of the surroundings may also be uncertain.

A need for adaptive fuzzy control was felt due to changing environmental dynamics and parameters. Fuzzy logic has diversified applications, ranging from consumer goods such as camcorders, cameras, microwave oven and washing machine to industrial process control, medical robotize instrumentation and decision support system.

3.1.2. Example of Fuzzy Logic rules for Controlled Robot end effector

Below figure 3.1 is showing fuzzy input and output variables. Fuzzy logic is used for mapping an input space i.e. error and derivative of error which are represented as “e” and “de” to an output space which are represented as Kp, Kd and Ki. Such mapping is done through a list of if-then declarations called rules as shown below. Only 7-rules are shown out of 49 rules, all the rules are executed in parallel, and order of rules is not important. Rules encompasses variables both input and output and the adjectives that explains those variables which are defined. Before building a system that translates rules, all the terms and the adjectives should be clearly defined before using them. Both the input and output variables are defined with 7 and 3 membership functions respectively, which are shown in figure 3.2 and 3.3.

1. *If (e is NB) and (de is NB) then (*K_P *is P)(*K_D *is N)(*K_I *is P)*
2. *If (e is NM) and (de is NB) then (*K_P *is Z)(*K_D *is P)(*K_I *is Z)*
3. *If (e is NS) and (de is NB) then (*K_P *is N)(*K_D *is P)(*K_I *is N)*
4. *If (e is ZE) and (de is NB) then (*K_P *is N)(*K_D *is N)(*K_I *is N)*
5. *If (e is PS) and (de is NB) then (*K_P *is N)(*K_D *is P)(*K_I *is N)*
6. *If (e is PM) and (de is NB) then (*K_P *is Z)(*K_D *is P)(*K_I *is Z)*
7. *If (e is PB) and (de is NB) then (*K_P *is P)(*K_D *is N)(*K_I *is P)*



FIS Name: fuzzy_controller
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: e
Type: input
Range: [-0.4 0.4]
Opening Rule Editor

Figure 3.1 Fuzzy Input and Out variables for continuum robot end effector

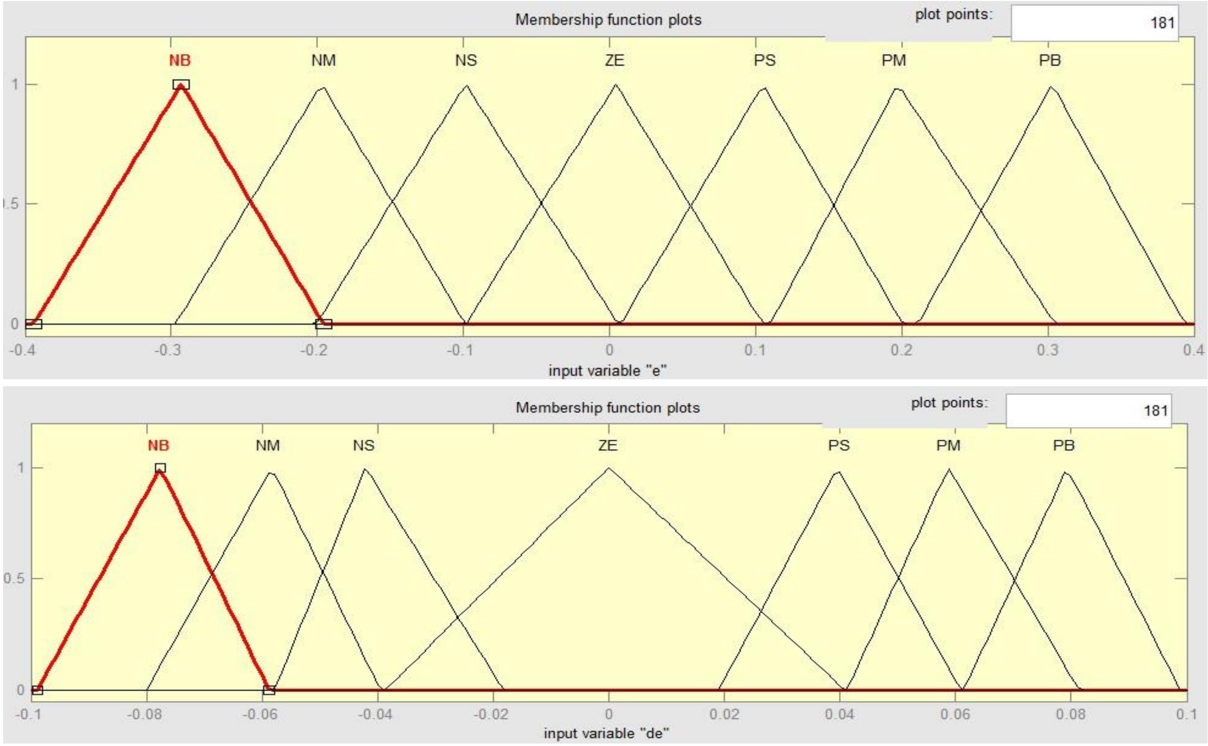


Figure 3.2 Membership function for e and de

The set containing the membership function NM in both input variables e and de lies some part in the set containing membership function NB. So in this for certain values which lie in both sets containing NB and NM of input and output variables e and de, then in this case 49 rules are fired one after another based on continuously changing position of the end effector. While traversing, one rule triggered the rest of rules one by one. The rules are dynamically triggered based on the position and bending of end-effector.

PID control parameters Proportional Integral and derivative terms are shown in terms of output variables carrying out three membership functions each as shown in figure 3.3.

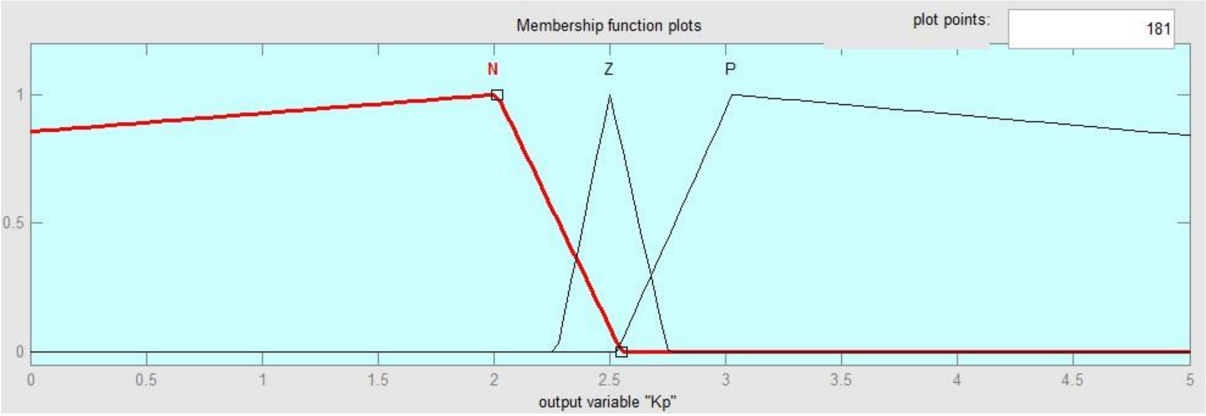


Figure 3.3 Membership function for Kp

Such changes have been made for the comparative analysis of Conventional PID controller and fuzzy controller based on MIMO system.

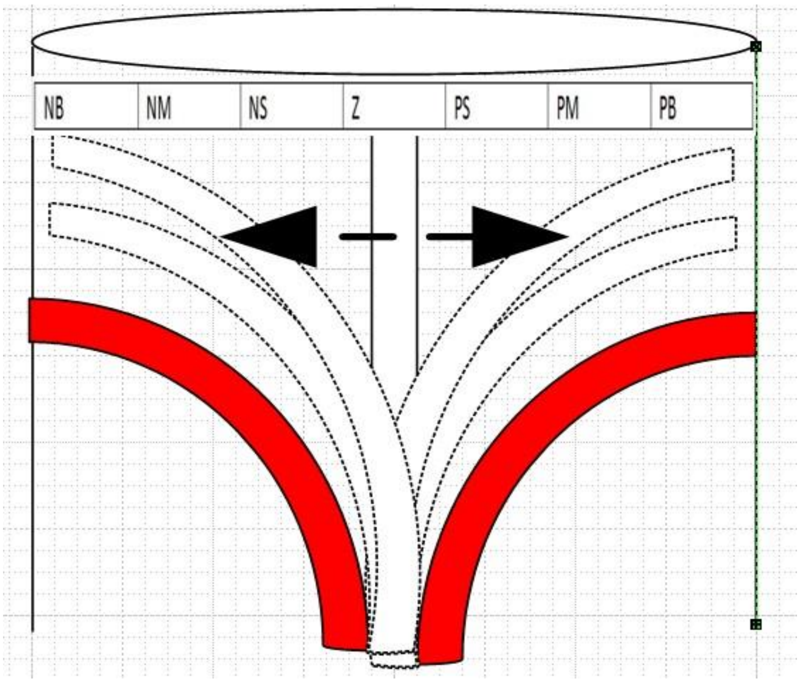


Figure 3.4 End effector deviations about their mean position

End effector deviation has been shown along their mean position which has been shown as Z membership function for both input variables. While navigating through unstructured region the external disturbance set the end effector on vibration, during the course of vibration the fuzzy rules comes into play, and helping to minimize the vibration. Fuzzy rules provide the flexibility of tuning the rules for better merging to the mean position.

Fuzzy controller is used for damping the vibration which mainly depends on the feedback control but feedforward has also been used based on the requirement and system methodology [65,66]. Mamadani and Sugeno are the two control systems that are used for vibration control and damping. People who mainly deal with the latter system accomplish a modal control called fuzzy modal control [67,68]. Such control is based on the concept of incorporating a parallel fuzzy control and where each one of them is linked with a modal, and the input leading to each controller is harmonized with such control system.

In Mamdani controller, the inputs consist of the velocity parametric value, and displacement or in some cases acceleration, which is derived from the velocity [69]. Due to some lapses and problems, FLC originated which has taken its inspiration from conventional PID controller, [69], neural networks [71] [72], and genetic algorithms [70] [73]. It has achieved and grabbed many accomplishments but it is lagging behind in terms of lacking synthesis techniques which is the main requirement for control system, around which whole functionality revolves.

As known, fuzzy controller is a nonlinear controller which required the tuning of more parameters in terms of rules than to tune than with a PID controller. These tuning parameters have a substantial undesirable impact on the controlled system. Therefore there is a dire need of parametric study in terms of tuning, that how it influence the system in terms of damping the vibration.

Application of Fuzzy logic overview

3.2. Fuzzy Logic in Power Plants

Fuzzy logic is used in power plants to ensure the maximum possible extraction of gas depending on the nature of coal produced. Such extractions of gas produced are the optimize amount produced. Fuzzy logic increase and improve the throughput, control quality and also the adaptation to different coal qualities.

3.2.1. Fuzzy Logic Supervisory Control for Coal Power Plant

Rheinbraun one of the pioneering scientist develop HTW (high temperature Winkler gasification) system, which is used to extract synthetic gas from brown coal. The only challenging it poses to control the amount of gas generated, conventional methods were used for the exact measurement of gas produced.

A stable operating point was defined for running the process which was done through control engineering. However developments were essential to use the winkler gasisfication process in a coal power industry with unified or combined coal gasification processes:

- More accurate control of gas quantity under variations of the coal quality
- More vigorous control in cases of load variation taking place quickly
- Automating supervisory process for controlling the extraction of gas from coal

Due to some discrepancies in the existing system, a fuzzy logic system was implemented to improve the throughput, control quality and also the compliance and adaption to different coal parameters. The extraction was made set to the nature and kind of coal. Some coals produced were enriched with gas while other did not produce much. Fuzzy logic makes sure that the gas production should be in accordance with the quality of coal, ruling out the bad part of the gas.

Figure 3.5 HTW plant in Berrenrath, Germany ©S.N. SIVANANDAM

3.2.2. Fuzzy control for supervising gas quality and quantity

Two tasks have been chosen for supervising gas quality and quantity

a. Regulating gas throughput

Fuzzy logic quickly responds to the fluctuation in the gas amount and keeps at certain set point. The safety of system is making sure by rapid response of the system to avoid any loss and damage. The set point could fluctuate between 70 percent and 100 percent based on partial and full load respectively. This variation erupted due to difference in coal quality, which could be humidity varied amount, ash content etc.

Fuzzy logic is used to cater with such challenges. Due to their usage in non-linear system it could compute the variation in all the coal parameters, and give the efficient and optimize way of retrieving gas amount. The amount of gas depends on quality of coal produced and not because of the lack of functionality and delayed response of fuzzy logic.

b. Process Stabilization

The process stabilization keeps several process parameters like Temperature, height & density and composition of the produced gas in the ideal range.

The reactor load affects the optimum of these process parameters. The position of the optimum also relies on the coal quality. The following parameters were used to outline the worth of the process:

Above mentioned process parameters could be badly impacted by the reactor load. The position of optimum range could be tweak around based on the coal quality, so that quality and quantity should go side by side. Following parameters and their variation gives any idea about how to stabilize the process

- Temperature in the reactor region prior of any production of gas
- Height and density of the fluid bed
- Compositional content of the gas (CO, CH_4, H_2)

When plastic and coal are mixed then due to their different heat capacities, process stabilization is difficult to manipulate, as this addition of plastic results in different process condition. Traces of plastic could be easily detected with the application of fuzzy logic controller by taking into consideration the process conditions.

3.2.3. Fuzzy Logic Control Design

Several control mentioned in the specification document resulted in the initial idea of the Fuzzy logic controller (FLC). The operator and human intervention with the system was defined in form of linguistic rules which finally entrenched into fuzzy logic system. Systematic ways have been devised to observe and analyses human interaction with the system, and then automating and translating the carried task in control system for better outcome. Through the use of use cases the operator controlled approaches and the connections between inputs and outputs were the main focus of audit group. This procedure mentioned is in compliance with fuzzy logic design methodology.

The audit observation highlights the following points for the fuzzy logic control system: tweaking around and correcting the oxygen input once the deviation of the gas throughput fluctuates from the set point. In order to keep the ration between coal and oxygen constant, coal quantity is fed accordingly. Changes in the pressure parameter of the reactor predict the gas throughput.
Based on the variation of quality present in coal, FLC make use of the below depicted parameters

- Adjusting &maintaining Coal to oxygen ratio through coal intake
- Dissemination of the oxygen residues tangled in the fluid bed & gasification region
- Ash expulsion
- Fluidification mechanism with steam and non-reactive & passive gas

3.2.4. Putting FLC into Operation

Postprocessing and preprocessing both were checked and validated with the help of VisSim which is used for simulating the results being compiled for better analysis. This validation could further assist in developing a design in compliance with standard structure.

The first ever design of the FLC that came to lime light, were tested using the mentioned tool. After testing, an early model was offer to the end users. Figure 3.6 depicts how simulated data is ingested into the FLC for testing

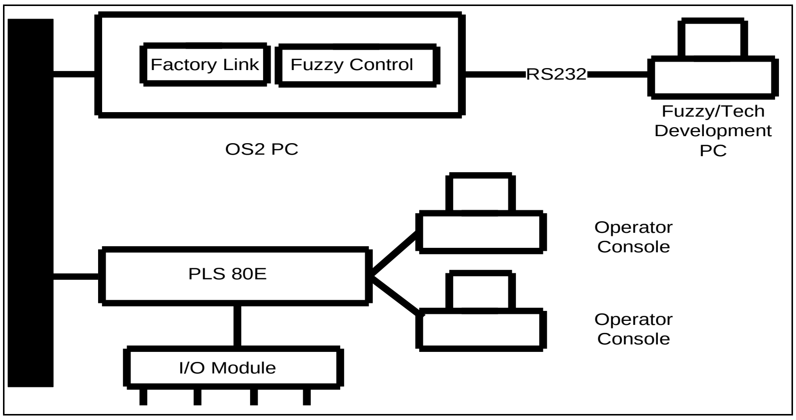


FIGURE 3.6 Integration of fuzzy logic into DCS © S.N. SIVANANDAM

With positive completion of testing in terms of simulation, fuzzy logic was then tested offline with informations loaded from DCS, which resulted in the generation of set points values for the DCS. The DCS were not using the generated set points but only using set points which had been manually set according to human understanding of producing better results. Some deviations were observed between manual and Fuzzy automated points, and a method was devised to remove the deviations detected during the course of process. Gas throughput is increased considerably by adjusting the set points through fuzzy logic set points.

After the offline testing, progressive testing on live environment was initiated. The performance of the fuzzy logic was put on stake by testing through external set points. Both FLC and optimize code defined were tested and by running it on fuzzyTECH on WIN95 OS. This tool presents the visualization of fuzzification, inference processing engine and defuzzification. Any changes and modification to the rule base could be easily updated, which are then sending to the FLC on OS/2 PC.

During the course of few testing fuzzy logic controller was working efficiently. This set the tone for further testing before deployment it on permanent basis. The performance was even scale up to different coal and different loads.

3.2.5. Change of Load

Bracketed by the range 70-100% load, FLC is controlling the gas quantity with a maximum load slope of 4% $\min^{-1}$. Figure 3.7 shows a load decreasing from 94% to 75% and back straight to 94%. The pressure load is bouncing around within this range. Presently the load variation behavior is changed by using adapted pressure estimation technique.

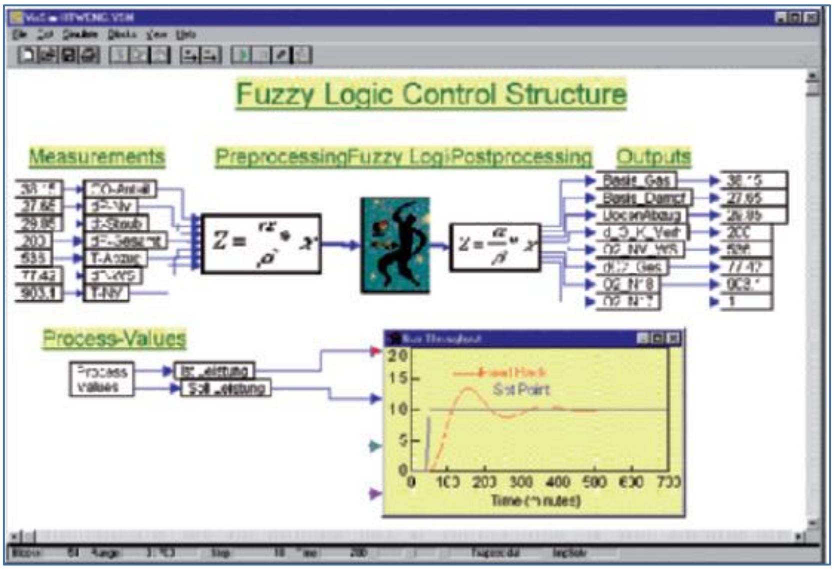


Figure. 3.7 Simulation with VisSim ©S.N.SIVANANDAM

3.2.6. Adaptation to Coal Add-Ons

To further elaborate the usefulness the fuzzy logic controller, the Winkler gasification (HTW) process is ingested with a combination of coal and plastic traces. A great deviation in the process parameters from the standard operating condition in terms of working is observed. But it did not keep away the process parameters to operate in the optimum range. Internal set point for methane is set automatically, when the residue of methane is increased. So set points are working accordingly with any change in the process condition is observed, shifting the processing parameters in the optimum range.

3.2.7. Adaptation to Different Coal Qualities

Coal intake is adjusting according to the quality of coal. For example if the water content is decreased from 18% to 12% then coal input is also decrease to compensate the coal change. So greater the water content the lesser will be coal input to keep the gas throughput constant.

3.3. Fuzzy logic control and Reasoning

To control the navigation of a system i.e. continuum robot in congested, unstructured, uncertain and unconventional environment is the defining characteristic of intelligent control system. Only the fuzzy inference provides this facility of dealing with uncertainty. Fuzzy sets theory provides an organized structure for dealing with diverse types of uncertainty within a particular conceptual framework [48].

In terms of input processing fuzzy controller behave similar to conventional controllers [50]. It model the preprocessing and post-processing of inputs in terms of doing some calculation over it. Figure 3.8 shows a typical fuzzy system. Later on some steps is introduced which is necessary in the designing of fuzzy controller.

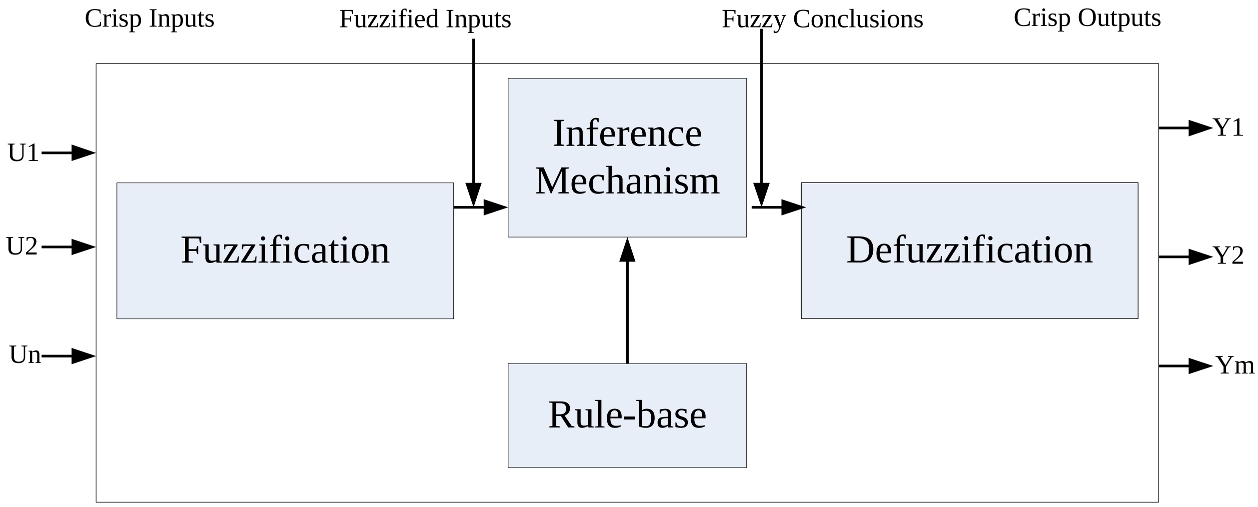


Figure 3.8 Fuzzy System ©Xiao Qing Ma

Step 1: Fuzzification

Fuzzification is the process of converting crisp input into crisp outputs which represents grades of membership function and role part, which are represented in fuzzy rule base as set of rules. Membership is used to allocate a grade to each linguistic variable [49]. Therefore, fuzzification is a mapping from $U \in R^n$ to the unit hypercube $[0,1]^M$. Fuzzy sets were introduced in 1965 by

Lofti A.Zadeh, this concept was mainly introduced to integrate vagueness in the computer systems for intelligent decision making [51]. All the conventional systems is based on binary approach i.e. an element either belongs to the set or not, but in human decision is continuous pattern of decision making within this range.
Let suppose a fuzzy set "A" is represented by a membership function, whose elements x of X is in the interval [0, 1] inclusive. Element x of X is a real number $\mu_A(x)$ which is the grade of membership of element x in the fuzzy set. Membership functions could be define in terms of mathematical functions, user-define functions and simple reflection relation.

Example of Fuzzy sets
It is worth to mention that in control swing algorithm the fuzzy sets are given by

$$XP(x)+XN(x)=1 \qquad \forall x \in X \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{3.1}$$

$$XP(x)=(1+\tanh(\mathrm{a}_x\, x))/2 \qquad \mathrm{a}_x > 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{3.2}$$

Where
$$\tanh(\mathrm{t}) = \frac{e^t - e^{-t}}{e^t - e^{-t}}$$

The graph trace out look like

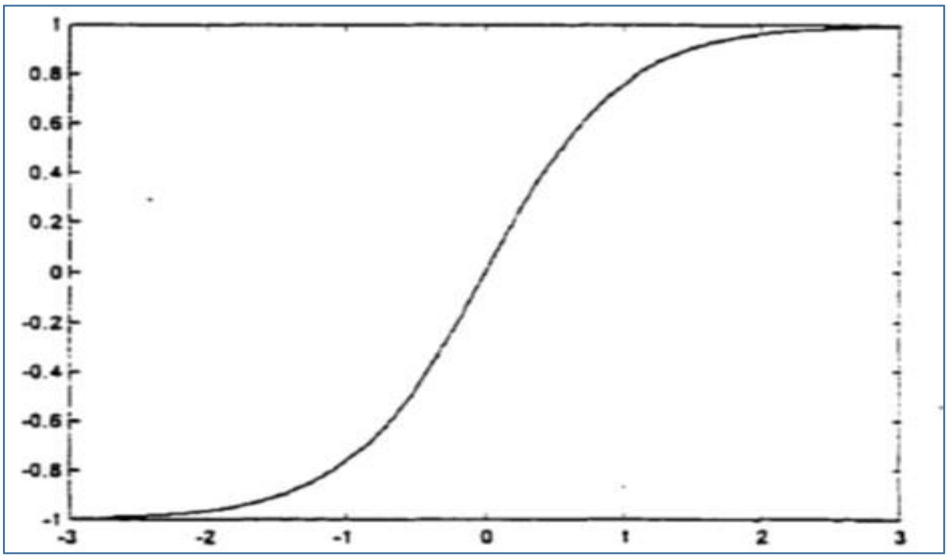


Figure 3.9 Function tanh(t) ©Xiao Qing Ma

Step 2: Rule-Base

A fuzzy rule is linguistic logic relation which provides the bridging between the input and output variables through membership functions. It is expressed as by
IF….THEN…..
Rule base covers a wide range of rules which are formed according the specification, design and functional aspects of controlling system. The conversion and translation of this fuzzy rule base system into fuzzy relations is embarked through the construction and manipulation of R_k a fuzzy relation for each rule r_k. These relations further could be assembled into a single fuzzy relation R. This combining and merging of fuzzy rules into fuzzy relation is called aggregation. Rule base could also be expressed by mathematical method. In this method all the rule bases are aggregated by using mathematization. The degree of importance of different rules is

categorized by allotting different weights, which are represented as $\lambda_i(z(t))$ where i =1, 2,….q. Rules are fired according to this weightage technique.

Step 3: Inference

Inference is also called fuzzy reasoning or fuzzy interpretation. Reasoning is the process by which new facts are emerged from the already existing fact base. Through this process Fuzzy conclusions are drawn from the fuzzy rule base or fuzzy relations. Inference process is the processing part in which the crisp inputs are processed into respective to output. The inputs are in the form of fuzzy rules, with each variable containing one or more membership functions. In addition to logical operator some other operators like implication, aggregation; reasoning and conjunction operator are used.

Step 4: Dufuzzification

Certain set of conclusions are extracted from a certain observation, which within each other assemble to form one conclusion. This one conclusion is called fuzzy set that can be defuzzified to obtain a crisp output. The output resultant obtained as a result of defuzzification, is formed due to some usual method [49] or a particular method [47].

The results of defuzzification are the final of the whole fuzzy system that is composed of 4 main modules.

In the field of control engineering Fuzzy algorithm is the most powerful concept which can be used to provide fuzzy models and fuzzy controllers. Fuzzy rules the integral part of such systems uses the fuzzy sets, and relations defined, to arrive at a control signal necessary for the desired response.

3.4. Conclusion

This chapter gives a brief overview Fuzzy logic, which refers to the unbounded possibilities between binary values. It deals with approximate values, rather than exact and fixed. Unlike binary values i.e. 0 and 1 fuzzy logic variables also includes infinite range of values between them. It also explains Fuzzy logic application for Robot position control. Fuzzy rules are fired according to the tip position, which is being disturbed by the external force. Talking specifically about medical domain, such fuzzy rules play an important role in avoiding the contact of tip position with the interior of walls. Force control which is exerted at the end effector also needs to be controlled along with the tip positional control.

Sample fuzzy rules have also been shown as how it effects and compensate for the bending of tip position of the end effector. Overview of fuzzy logic application for power plants have been shown, which is showing the optimized throughput of gas extraction from the different of coal. The extraction was made set to the nature and kind of coal. Some coals produced were enriched with gas while other did not produce much. Fuzzy logic makes sure that the gas production should be in accordance with the quality of coal, ruling out the bad part of the gas.

Other than this Fuzzy Logic is used in controlling mechanism, such as controlling the bending of end effector of continuum robots while navigating through congested, unconventional and unstructured environment. A comparison of simulations resulted from PID and FLC controller clearly mention the advantages and shortcomings of such controllers. Based on the concept of inverted pendulum it could be scale up to other conventional control systems. Proper selection of IF-THEN rules could effectively model the human expertise in specific applications.

CHAPTER 4
FUZZY CONTROLLER FOR CONTINUUM ROBOT

4.1. Introduction

The main concept of inverted pendulum is self-erecting mechanism, which has wide range of application from missile Control system to other critical control applications. Two problems are associated with inverted pendulum i.e. swing-up control and crane control. Inverted pendulum consists of one or two pendulum arm which is attached with a moving cart. Moving cart is responsible for keeping the pendulum in straight position. Due to the gravitational force the pendulum arm can fall on either side of the moving cart. The control strategy involves the moving of cart in order to keep the pendulum in straight position. Greater the angular velocity of pendulum, greater will be the linear velocity of cart [52].

Like many other complex control problem [53], application of fuzzy logic is very popular which provides the foundation for overcoming control problems associated with other systems. The importance of inverted pendulum can be judge from the fact that they do not require any underlying knowledge of the system parameters. Based on the concept of inverted pendulum it could be scale up to other conventional control systems. Proper selection of IF-THEN rules could effectively model the human expertise in specific applications. Due to the complex nature of the controls system in nonlinear system, hybrid approach has been devised for controlling mechanism. Hybrid system contains both characteristic of fuzzy and PD controller.

As already mentioned, the control problem could be divided into crane problem and swing-up control problem. In the swing up control the fuzzy rule are defined in such a way so that it could bring energy into the system, to help maintain control of pendulum arm to reach its vertical position 90 degree with respect to the x-axis with least possible angular velocity. In crane control, the pendulum is maintained in the vertical upright position ensuring the minimum error for the inverted pendulum stabilization. When the pendulum reaches [-20°, +20°] then system is administered by control logic which consist of two controllers-pendulum angle controller and cart position controller. Both the action should be combining into one single control action, which could work both for pendulum angle subsystem and cart subsystem [54].

Tuning fuzzy logic controller (FLC) is mighty difficult that tuning a conventional controller. In FLC a lot of parameters such as membership functions, control rules and scaling factors (SFs) needs to be adjusted, compared to PID controller where only three parameters are adjusted. Researchers have suggested different methods for the tuning of FLC, but no method are standardized which could be applied on every control system. All the parameters for FLC are time consuming or pose complexity in terms of designing. Apart from this there are some other challenging difficulties such as selection of Scaling factor, the shape of membership functions and their degree of overlapping, the number of membership functions for a particular fuzzy controller, rule exposition & inference mechanism and also the defuzzification scheme.

4.2. Modelling of inverted pendulum

4.2.1. Physical setup and system equations for Inverted Pendulum

In this example we show pendulum ball attached to pendulum which is attached to the moving cart. Pendulum possesses two dimensional movements. Here the pendulum is constrained to move in a vertical plane as depicted in the below figure 4.1. Inverted pendulum is exerted by an external force F which is the control input force that moves the cart horizontally and their outputs are the angular displacement of the pendulum θ and the horizontal displacement of the moving cart x.

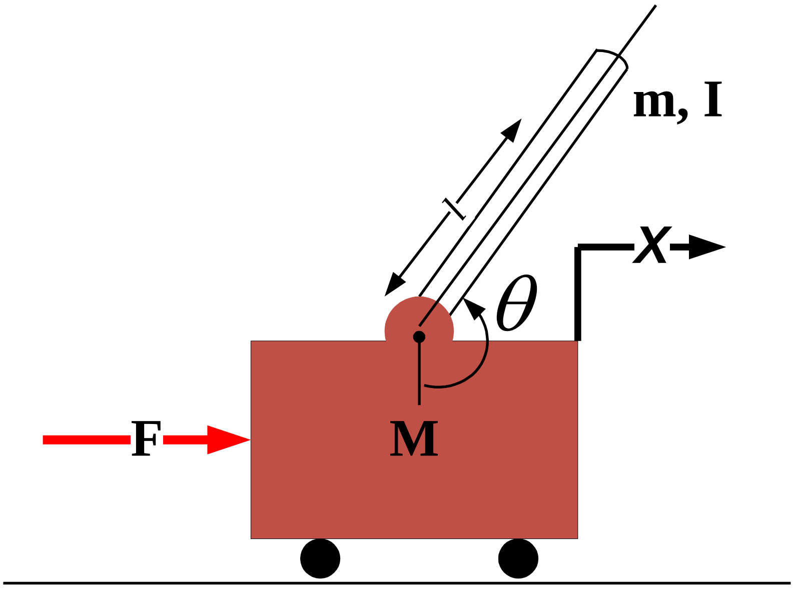


Figure 4.1 Inverted pendulum on a moving cart

For this example, let's consider the following mentioned values:

(m)	*mass of the pendulum*	*0.2 kg*
(M)	*mass of the cart*	*0.5 kg*
(l)	*length to pendulum*	*0.3 m*
(b)	*coefficient of friction for cart*	*0.1 N/m/sec*
(θ)	*pendulum angle from vertical*	
(I)	*mass moment of inertia of the pendulum*	*0.006 kg.* m^2
(F)	*force exerted on the cart*	
(x)	*cart positional location on plane*	

Below are inverted pendulum diagrams of the system.

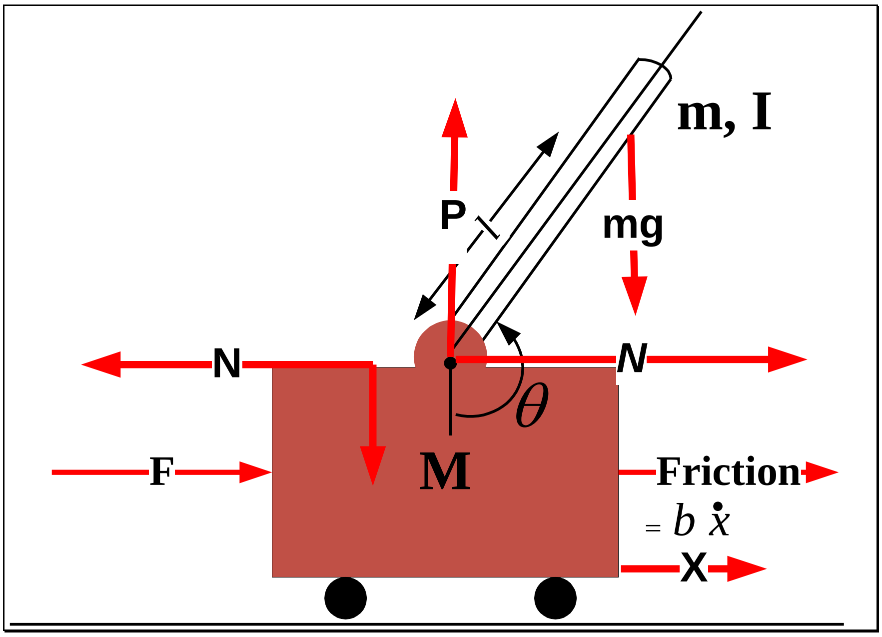


Figure 4.2 Inverted Pendulum with moving Cart with detailed forces resolution

There exhibit a join called pint joint between the cart and pendulum arm, which makes it very challenging to model it in the Simulink, which reduces the degree of freedom in the system. Both the cart and pendulum underwent with one DOF. The differential equations for these degrees of freedom is generated from first principles using Newton's second law ($F = ma$) as depicted below.

$$\ddot{x} = \frac{1}{M}\sum_{cart} F_x = \frac{1}{M}(F - N - b\dot{x}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

$$\ddot{\theta} = \frac{1}{I}\sum_{pend} \tau = \frac{1}{I}(-Nl\cos\theta - Pl\sin\theta) \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

It is very important to mention here, that interactive forces N and P which are actually angular forces needs to be included to completely model the system. The inclusion of these forces further needs the decomposition of forces in x-component and y-component because of the center of mass. Additional x and y component could be modelled as depicted below

$$m\ddot{x}_p = \sum_{pend} F_x = N \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

$$\Rightarrow N = m\ddot{x}_p \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.4)$$

$$m\ddot{y}_p = \sum_{pend} F_y = P - mg \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.5)$$

$$\Rightarrow P = m(\ddot{y}_p + g) \tag{4.6}$$

x_p and y_p are the coordinates relating to x-axis and y-axis, which is exact functions of θ. Any change in the angular displacement will likely to change the positional coordinates. Therefore, their derivatives could be linked with derivatives of θ. First computing the x-component equations we arrive at the following.

$$x_p = x + l\sin\theta \tag{4.7}$$

$$\dot{x}_p = \dot{x} + l\dot{\theta}\cos\theta \tag{4.8}$$

$$\ddot{x}_p = \ddot{x} - l\dot{\theta}^2 \sin\theta + l\ddot{\theta}\cos\theta \tag{4.9}$$

Then computing the y-component equations provides us the following.

$$y_p = -l\cos\theta \tag{4.10}$$

$$\dot{y}_p = l\dot{\theta}\sin\theta \tag{4.11}$$

$$\ddot{y}_p = l\dot{\theta}^2\cos\theta + l\ddot{\theta}\sin\theta \tag{4.12}$$

These expressions can then be replaced into the interactive forces which are N and P from above as follows.

$$N = m(\ddot{x} - l\dot{\theta}^2\sin\theta + l\ddot{\theta}\cos\theta) \tag{4.13}$$

$$P = m(l\dot{\theta}^2\cos\theta + l\ddot{\theta}\sin\theta) + \mathrm{g} \tag{4.14}$$

4.3. Review About Curvature

The curvature of curve is defined as the rate at which the curve is bending along it structure. The direction of curve can be determined through tangent line or velocity vector; this is clear indication, that curvature is the degree at which tangent line is bending. The tangent line is giving the direction of the curve but does not give any idea about how fast the curve is bending. Curvature has nothing to deal with the pace of turning but it is concerned with the geometry of the curve.

At first, recalling the purpose in Calculus I which clearly mention the curve bending in terms bending upward or downwards, which is a clear indication that curvature should carry positive or negative quantity. Some problems are associated with the curvature, from the Calculus point of view a curve is either curving upwards or downwards, which clearly shows that the curvature should be a sign quantity. However, if one look at a circle, the top of the circle is concave down and the bottom is concave up. From the observation it evident that curvature is a positive quantity.

The second problem with defining curvature is the rate at which the velocity vector is turning.

4.3.1. The Curvature of a Graph in the Plane

Lets assume φ angle subtends between the tangent line and the x-axis, then curvature could be expressed as

$$\kappa = \left|\frac{d\varphi}{ds}\right| \qquad (4.15)$$

In the above "s" is arc length

By chain rule we know that

$$\frac{d\varphi}{ds}\frac{ds}{dx} = \frac{d\varphi}{dx} \qquad (4.16)$$

Now we can write

$$v = \frac{ds}{dx} \qquad (4.17)$$

Then

$$\left|\frac{d\varphi}{ds}\right| = \left|\frac{d\varphi}{dx}\right| \Big/ v \qquad (4.18)$$

Determining the curvature, it is required to discover $\frac{d\varphi}{dx}$ and v

Clearly $s = \int v dx$ ………………………………………. . ……………………… (4.19)

Above mentioned formula is for arc-length, then

$$v = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \qquad (4.20)$$

The importance of v could be judge from the fact that it shows speed a point could attain while going along the curve**.** Thus the formula $s = \int v dx$ clearly indicates that in order to compute distance one has to integrate the speed of attainment over the time.

φ is the angle traced between the direction in which the point is going along the curve and the direction formed by the horizontal axis, so we know

$$v = \sec\varphi \quad (4.21)$$

As $\tan\varphi$ is the slope of the curve, i.e.so we simply write as $\tan\varphi = \frac{dy}{dx}$, we get

$$v^2 = \sec^2\varphi = 1 + \tan^2\varphi = 1 + \left(\frac{dy}{dx}\right)^2 \quad (4.22)$$

which is basically the formula for v estimated above.

(An unconventional description is to develop the formula $v = \sec\varphi$ by beginning with the Typical formula for arc length,

$$s = \int \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx \quad (4.23)$$

To see that

$$v = \frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} = \sqrt{1 + \tan^2\varphi} = \sec\varphi \quad (4.24)$$

Here φ represents an acute angle, so $\sec\varphi \geq 0$

Based on the φ kappa κ which is the curvature could easily be derived . Since φ is the angle of tangent line, $\tan\varphi$ which is the slope of the curve can be written as,

$$\tan\varphi(x) = \frac{dy}{dx} \quad (4.25)$$

Differentiating with respect to x produces (through the chain rule)

$$\sec^2\varphi \frac{d\varphi}{dx} = \frac{d^2y}{dx^2} \quad (4.26)$$

And so

$$\frac{d\varphi}{dx} = \frac{\ddot{y}}{\sec^2\varphi} = \frac{\ddot{y}}{v^2} = \frac{\ddot{y}}{1 + \left(\frac{dy}{dx}\right)^2} \quad (4.27)$$

And so the curvature is

$$k = \left|\frac{d\varphi}{ds}\right| = \frac{|\ddot{y}|}{v^2}\frac{1}{v} = \frac{|\ddot{y}|}{v^3} = \frac{|\ddot{y}|}{[1+(\dot{y})^2]^{3/2}} \dots\dots\dots\dots \quad (4.28)$$

4.4. Modelling of Continuum robot: Inspiration Inverted Pendulum

End effector while navigating through unstructured region bent in certain direction due to the external force i.e. fluid running down in opposite direction. In order to model the motion of continuum robot end effector we can translate the equation of inverted pendulum with certain modifications.

4.4.1. Translation of equation for Continuum end effector

Equation (4.11) and (4.12) can be translated as

$$y' = l'\dot{\theta}\sin\theta \dots\dots\dots\dots \quad (4.29)$$

$$y'' = (l')\dot{\theta}^2\cos\theta + (l')\ddot{\theta}\sin\theta \dots\dots\dots\dots \quad (4.30)$$

Equation (4.2) for the angular acceleration of the inverted pendulum could be translated as

$$\ddot{\theta} = \frac{1}{l}(-N(l')\cos\theta - P(l')\sin\theta) \dots\dots\dots\dots \quad (4.31)$$

Where $l' = l + s$
Or
Total length=length of the elastic continuum rod+arc length of the elastic continuum rod
So equation (4.29) (4.30) and (4.31) can be re-written as

$$y' = (l+s)\dot{\theta}\sin\theta \dots\dots\dots\dots \quad (4.32)$$

$$y'' = (l+s)\dot{\theta}^2\cos\theta + (l+s)\ddot{\theta}\sin\theta \dots\dots\dots\dots \quad (4.33)$$

$$\ddot{\theta} = \frac{1}{l}(-N(l+s)\cos\theta - P(l+s)\sin\theta) \dots\dots\dots\dots \quad (4.34)$$

Where s is the arc length, so in case of continuum robot and N and P are the sideways and downwards interactive forces respectively. Slight sideways movement of the continuum controller should be considered which is negligible.
N and P can be represented as

$$N = (l+s)\ddot{\theta}\cos\theta - (l+s)\dot{\theta}^2\sin\theta \dots\dots\dots\dots \quad (4.35)$$

$$P = ((l+s)\dot{\theta}^{2}\cos\theta - (l+s)\ddot{\theta}\sin\theta) + g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.36)$$

In order to gets the curvature equation for the continuum robot end effector putting equation (4.32) and (4.33) in equation (4.28) we get

Here

$y' = \dot{y}$

And

$y'' = \ddot{y}$

$$\kappa = \frac{(l+s)\dot{\theta}^{2}\cos\theta + (l+s)\ddot{\theta}\sin\theta}{[1+[(l+s)\dot{\theta}\sin\theta]^{2}]^{3/2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.37)$$

4.5. Modelling Continuum End effector

4.5.1. Modelling Continuum End effector in presence of external force

In case of external force which could be both constant and variable force, the continuum robot end effector vibrate with different of vibrations about mean position is observed. Assuming the stress and strain across the structure is fixed i.e. coefficient of material is remain fixed before inserting inside the human body.

The block diagram of the subsystem for modelling continuum robot end effector is shown in figure 4.3.

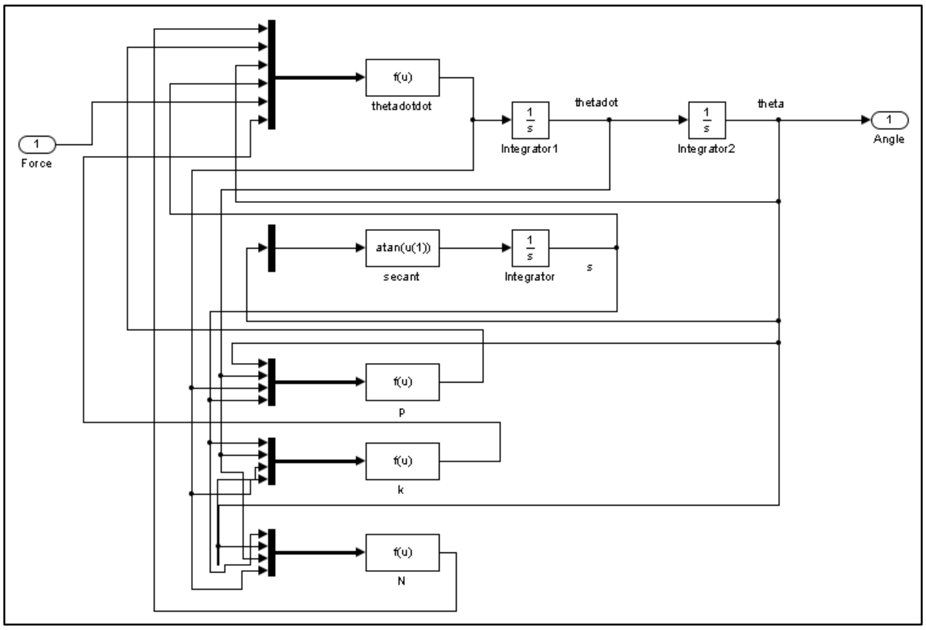


Figure 4.3: Subsystem for continuum end effector modelling.

In the above figure 4.3 the N block functional block has been removed, as the controller is assumed to static at their fixed position. Equations of curvature κ, arc length s and interactive angular force which is acting in downward direction are shown in the functional blocks.

4.5.2. Feedback controller system and the data flow description

Our life is fully occupied by the control systems, and have greater impact in terms of carrying out painstaking job of manual interaction with the system. Two control structures are used in control process mechanisms, which are feedback control and feed forward control. Feedback control is used to measure the difference between the system output and desired output, termed as error, which is further feed to the controlling mechanism in order to minimize the error. This mechanism of data flow is repeated to achieve the best possible result. Contrary to the feedback, feed-forward control is an anticipative control, which predicts the behavior of measured disturbance and takes corrective steps to achieve the desired output.

Feedback control is engaged and employed in variety of applications, ranging from simple thermostats which are maintaining a specific temperature in room, to sophisticated devices that sustain the positional coordinates of satellites for achieving optimized positional coordinates. It is also used for keeping the sugar level at normal range, through regulation of blood sugar levels in the body.

In feedback control, any variable whose value varies with time is first measured and then compared with manually inputted values. In figure 4.4 the difference between desired output and system output is called error. Error can be minimized through manipulation of an input to the system. Feedback control response in a timely manner to frequently change output in continuously operative system, and corrective action is taken in terms of minimizing the erupted error each time produced. Desired output is punched according to the right understanding and interpretation of humans for achieving the desired result. Such input values are entered through a user interface.

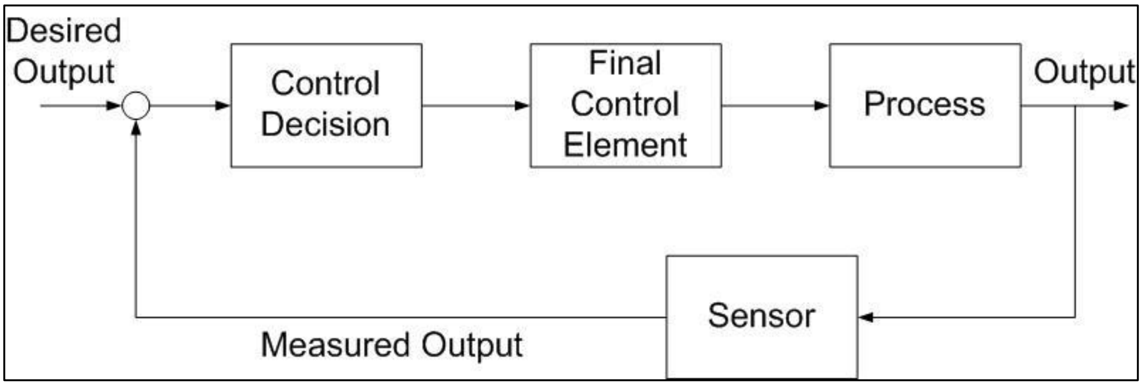


Figure 4.4: Feedback control loop

In below figure 4.5 angular displacements are measured as deviation from the mean position, which is labelled as output in the below figure 4.5. Desired output is the minimum angular displacement i.e. approaching to the mean position. The difference between output and desired output is termed as error

Error=OUTPUT-DESIRED OUTPUT or SP-PV
Where SP is the set point
And PV is the process variable

The error is fed to the Conventional PID controller, which through its controlling parameters computes the controlling control variable (CV) is also called the manipulated variable (MV). MV which is the controlling variable decides how to set the angular displacement, so that to minimize deflection in every iteration. Controlling variable is disturbed by the external force in the form of Bandwidth limited white noise. This white noise could be any fluid but in this case it represents the blood perturbation. Proportional term in the PID controller is set according to the present error produced in terms of deviation from the mean position. In this case optimum value for proportional term is used to cater for small, medium and large deflections. The optimum value could be set according to the maximum deflection incurred on either side of the reference point.

Derivative is another controlling parameter which is actually the slope of the error over time. This considers the rate of change of error, how much angular displacement should be added or subtracted so that it could merge to the mean position. This term smoothens out and reducing the high spikes observed during the course of vibration, which is somehow helping in damping the vibration. Integral is the last controlling parameter which shows the past trend of angular displacements from the mean position, which in a way depends on the magnitude and duration of error. Main theme of integral term is dealing with the query of how to change the end effector in different several steps in proportion to the current produced error.

In FLC system this error turns to be NB, NM, NS, Z, PS, PM or PB which is shown as membership function in figure 3.2. This error is then represented as input variable in fuzzy rules having seven membership functions. After each iteration change in error is also computed over the time which also turns to be NB, NM, NS, Z, PS, PM or PB. Based on these membership functions of both “e” and “de”, controlling parameters which are represented as output variables in the form of Kp, Kd, Ki are tuned according to optimized results. Each one of the output variable constitutes three membership functions which are represented as N,Z and P as shown in figure 3.3.

The errors after passing from PID and FLC controller computes the process variable, which are further input into the subsystem as force which are shown in the below figure. This force is responsible for relocating the angular displaced position and inclining them towards the reference line. All the rules are fired according the positional coordinated points of the tip position inside the unstructured region. Arc parameter gives any idea about the location of tip position.

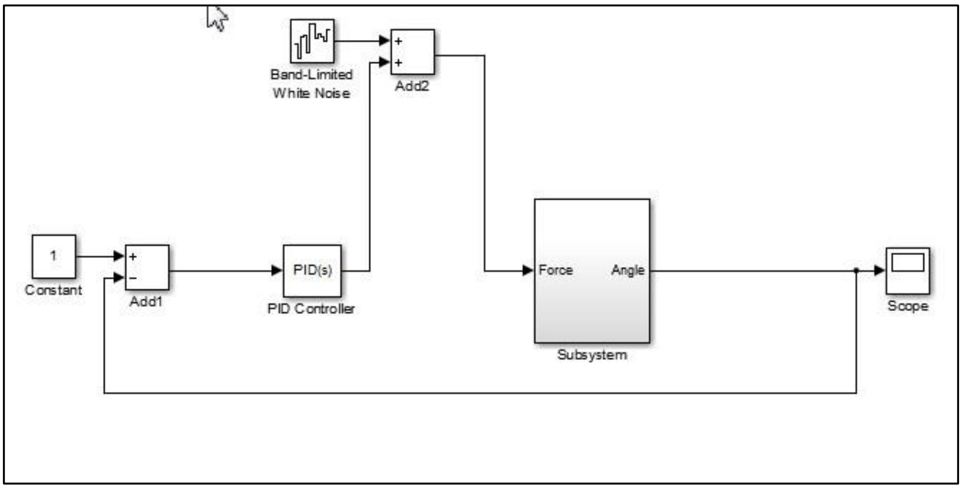


Figure 4.5 Feedback system with PID Controller

4.5.3. Simulation Results of modelling with External force

The external force could be the force exerted by blood flow or any other fluid. Continuum robot end effector simulation in presence of constant and variable force is shown.

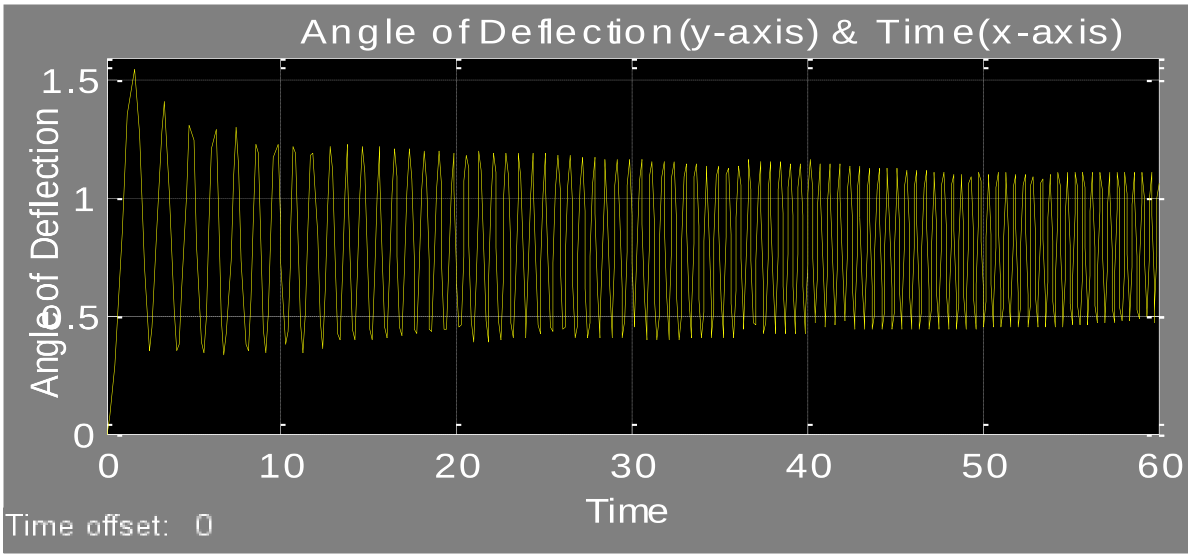


Figure 4.6 Continuum end effector modelling with external force

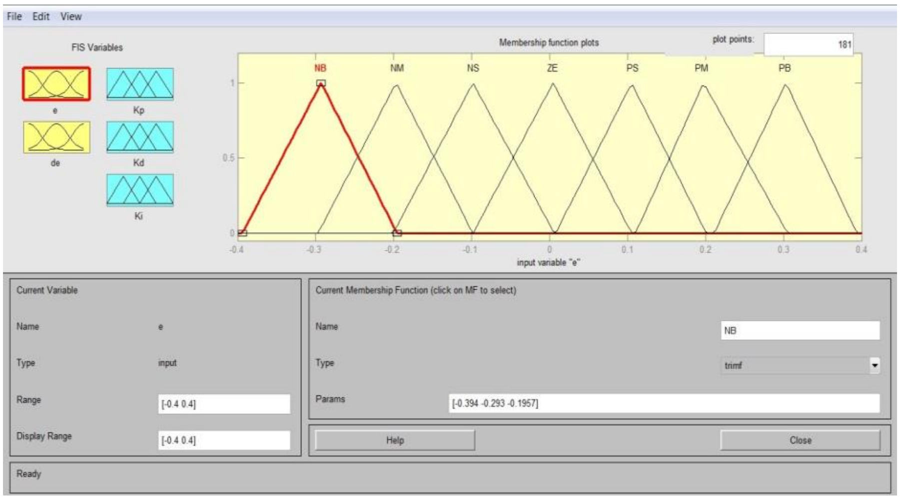
Slight decrease in the amplitude is observed, as the kinetic energy possesses is decreasing with time. The vibrations results are planar in nature with 2-DOF. Further it could be scale up with more degree of freedom. This approach is only applicable on single tendon continuum robot.

4.6. Fuzzy controller for continuum robot

When continuum robot end effector is injected inside human via vein or artery for inspection purposes, then it encounters unstructured region while navigating. Structural design issues and bending may pose threat to the delicate parts and tissues while coming into contact with it.

By incorporating fuzzy controller in the existing model would damp the vibration and having tendency to merge to the mean position. Fuzzy controller here is actually used as adaptive PID controller with fuzzy rules. With fuzzy rules editor we can see that two input variables and three output variables. The input variables further branch out to 7 membership functions. These membership functions could be tweak around for fine tuning.

The whole mechanism is based on feedback controlling, in which the error is computed by the difference of Set point (SP) and Process variable (PV). To finding the strength and magnitude of error, and keep them to minimum further fuzzy rules are defined, which keep the error to minimum. Here the set point is represented in terms of constant block and the Process variable is the angular displacement cover by the end effector from the mean position. It is based on loopback mechanism, so each time it computes new angular displacement.



plot points: 181

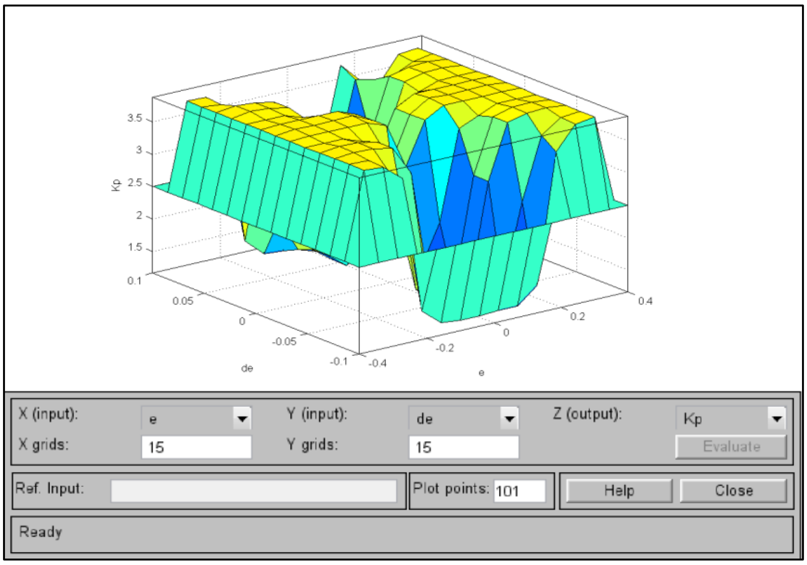
Current Variable
Name e
Type input
Range [-0.4 0.4]
Display Range [-0.4 0.4]

Current Membership Function (click on MF to select)
Name NB
Type trimf
Params [-0.394 -0.293 -0.1957]

Ready

Figure 4.7. Membership function editor for Continuum robot

Surface viewer of the fuzzy rules shows the representation as



X (input): e
X grids: 15
Y (input): de
Y grids: 15
Z (output): Kp
Ref. Input:
Plot points: 101
Ready

Figure 4.8. Surface viewer for Continuum robot end effector navigation

4.6.1. Incorporating Fuzzy Logic Controller

Mechanism of FLC is based on fuzzy logic, this system is different from conventional digital logic one, as it represents analog inputs in terms of logical variables that take on continuous values between 0 and 1 inclusive. As the name indicates the whole system of FLC is based on fuzzy logic which is widely used in machine control. It not only covers true and false values but also encompasses partially true values.

There could be infinite possibilities between 0 and 1. The more you extend your membership functions the more you are fine tuning your system. In many cases genetic algorithm and

Neural networks perform just like fuzzy logic, but due to the user friendly rules it can be easy to understand and manipulate the behavior of system.

One of the pioneer researcher and scientist Lofti A Zadeh extends the concept of Infinite valued concept and shape it into Fuzzy logic in 1965. He gives the concept of linguistic variables which could be closely related to the variables defines in fuzzy sets. The first industrial application was done in Denmark in 1975 in Cement Kiln factory. With its success right from its inception Japanese start implementing in many control systems.

In our case Fuzzy logic controller is used to control the bending of end effector of continuum robot while navigating through unstructured region. Considering single tendon continuum robot with planer bending in either direction could be compensated by the use of fuzzy controller. In design of the end effector the material should have high restoring force, so that it could ease the job for the fuzzy controller in damping the vibration. The fuzzy logic controller in this case is dealing with only kind of curvature, which could be further scale up to number of curvature by extending the actuators and degree of freedom.

4.6.2. Representing fluid perturbation as white noise:

Band-width limited white noise generates random numbers which are normally distributed and used in both continuous and hybrid systems. White noise constitutes flat power spectral density, infinity total energy and correlation time of zero. Talking on practical grounds white noise has no effect whatsoever on the physical systems, it is just useful approximation whenever the noise disturbance is tagged with relationship time, which is very minute in comparison with system natural bandwidth.

In below figure 4.9 white noise block is appended to show fluid perturbation, while resisting the navigational movement of end effector. Here the error is added through parametric perturbation i.e. noise power. Noise power is set to certain value to indicate the pressure exerted by fluid. Main reason of including this block of white noise is that previous research models a perturbation of the fluid with the help of random white noise, which was used to simulate the turbulence on the flutter.

Equation of fluid flow is equally important as bending of end effector. Motion of viscous fluid substance was explained through Navier-stokes equations named after Claude Louis Navier and George Gabriel Stokes. The Navier–Stokes equations are also useful explaining the design of cars and aircraft, the study of how blood flows etc. Having large of applications it is mostly popular for modelling water currents in oceans, water flowing in hollow regions and air flow specifically for weather forecast.

Stochastic Navier-Stokes system has caught considerable attention recently, and has been the active area of research till now. Randomness and variation in the Navier-stokes equation emerges from the understanding (i) velocity variations in wind tunnels and (ii) the initiation of turbulence effect. Forces with different magnitudes arise from random disturbance such as molecular vibrations that act inside the fluid. Main idea was presented by Kolmogorov (see Vishik and Fursikov [75]) to include such noise in Navier-Stokes system in order to obtain the invariant behavior of the system.

Lately, stochasticians have accepted white-noise disturbance for Navier-Stokes system, which is used for modelling fluid flow [76].

Equation of Navier-Stoke which is the conservation form of the equations of continuum motion is

$$\frac{\partial}{\partial t}(\rho\mu) + \nabla.(\rho\mu \otimes \mu + pI) = \nabla.\tau + \rho g$$

Where
ρ -density of fluid
μ -velocity of fluid
p -pressure exerted by fluid
I -identity matrix
τ -cauche stress tensor
g -different accelerations acting on the body i.e. inertial acceleration, gravitational and electric field related acceleration

Kuppianinen has also shown that uncertainties in the velocity of fluid (shown as μ in the above equation) can be rightly modeled through white noise [77]. The velocity of fluid can vary depending the enclosing region, the narrower the region gets, the quicker it will pass and hence greater will be the pressure exerted.

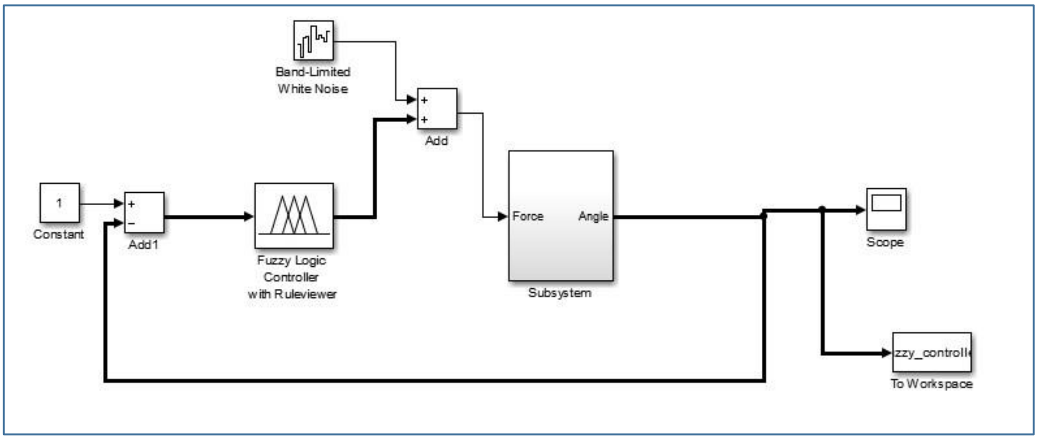


Figure 4.9. Block diagram for Continuum robot end effector navigation with white noise

Blood perturbation which is modelled as white noise is deflecting the end effector from the mean position as shown in figure 4.10. The magnitudes of error also increased with the introduction of white noise, such deflection sometimes pose threat to human lives by producing blockage in blood flow. As soon as the blood exerted force on the end effector, then it is disturbed from the mean position, and start vibration with bigger amplitudes.

The angular displacement from the mean position depends on the velocity of blood flow. With greater velocity, greater deviation is observed which sometimes forces the end effector to make contact with the interior of walls. White noise is helpful for manipulating the behavior of system, with fluctuating input of perturbations. Deviation of end effector with the blood perturbation is shown as

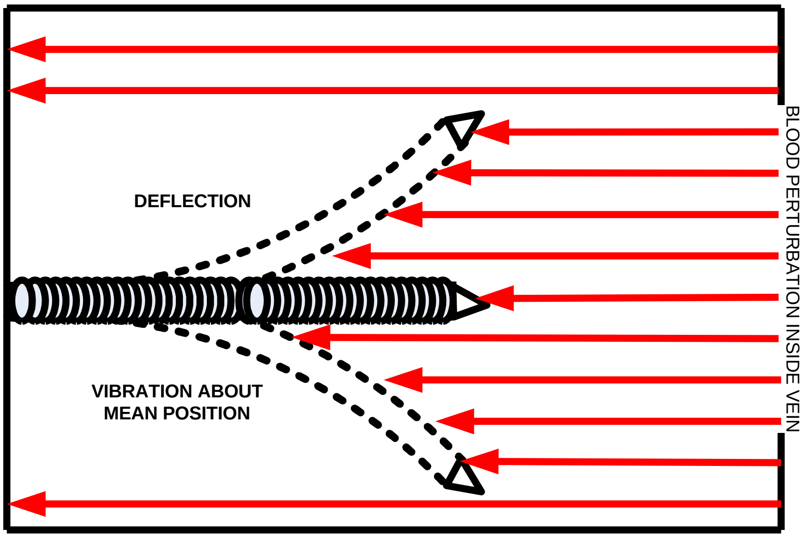


Figure 4.10. End effector deviation with blood perturbation

4.6.3. Simulation Results without white noise in presence of FLC

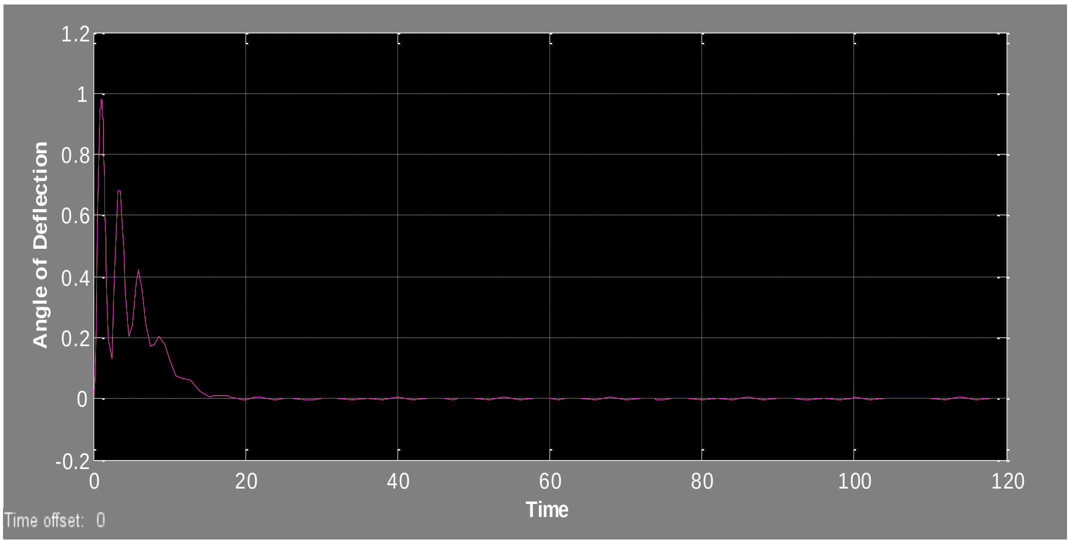


Figure 4.11. FLC: Simulation results without white noise

With no outside force being exerted on the end effector, the end effector merges to the mean position in no time. During translational motion, the end effector also underwent oscillation which last for only 20 seconds as shown above in figure 4.11. Beyond 20 seconds it remains on the mean position. As the angular displacement changes initially, so this change value of position variable are assign to the Process variable (PV). The magnitude of error is then checked against the set point. So the process variables first take non-zero value and hence it manipulates the difference from set point which can be shown as

Error=SP-PV

Where SP is the setpoint and

PV is the process variable which takes angular displacement values

Some values is assigned to the error, which is actually the deviation from the mean position, this deviation in terms of numerical value is fed to the FLC, which on the basis of it IF-THEN rules tuned the output variables membership functions and hence minimize the deviations. Against PV is assigned with comparatively less than the previous value, and then again it is feedback to the controller, through such repetitive mechanism values are minimized, which is approaching to zero ultimately and hence it is fully converged at last.

4.6.4. Simulation Results with white noise in presence of FLC

Parameter of FIS matrix is exported into "Fuzzy logic controller with rule viewer". The above system is closed loop system in which two inputs are ingested "error" & "change of error".

For example

1. *If (e is NB) and (de is NB) then (* K_P *is P)(* K_D *is N)(* K_I *is P)*
2. *If (e is NM) and (de is NB) then (* K_P *is Z)(* K_D *is P)(* K_I *is Z)*
3. *If (e is NS) and (de is NB) then (* K_P *is N)(* K_D *is P)(* K_I *is N)*
4. *If (e is ZE) and (de is NB) then (* K_P *is N)(* K_D *is N)(* K_I *is N)*
5. *If (e is PS) and (de is NB) then (* K_P *is N)(* K_D *is P)(* K_I *is N)*
6. *If (e is PM) and (de is NB) then (* K_P *is Z)(* K_D *is P)(* K_I *is Z)*
7. *If (e is PB) and (de is NB) then (* K_P *is P)(* K_D *is N)(* K_I *is P)*

In fuzzy logic there are three modules, input, processing and output module. Such inputs are also called crisp inputs. Simulation results are shown in below figure.

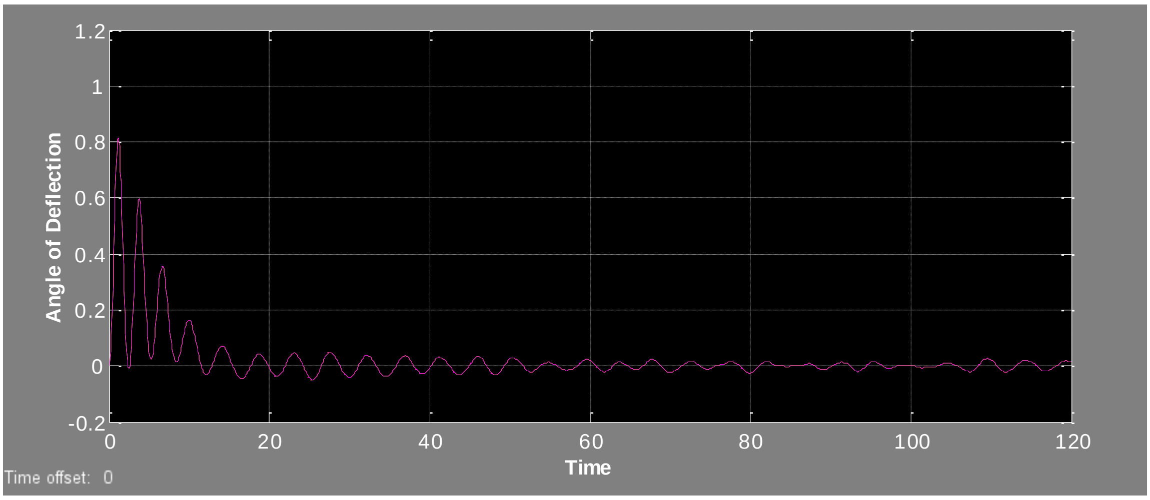


Figure 4.12. FLC: Simulation results with white noise

4.7. Multiple Corrected Trajectories traced by End effector

With the external disturbance, the end effector starts oscillating about its mean position, and thus effecting their navigation during the course of movement inside the unstructured region. This bending of end effector could come in contact with the delicate parts of the body and pose threat to human body.

The medical is thus focusing on robotizing the miniature devices while inserting it inside as colonscopes , arthroscopes etc. With theoretical research background, implementation of the controllers for end effector initiated. One of the efficient controllers is fuzzy controller which based its decision on the fuzzy logic. Fuzzy controller in our case controls the navigation of the end effector by restoring it to mean position in erectile, whenever disturbed by the external force. Different snaps have been shown in figure 9 which shows the corrected trajectories in each snap.

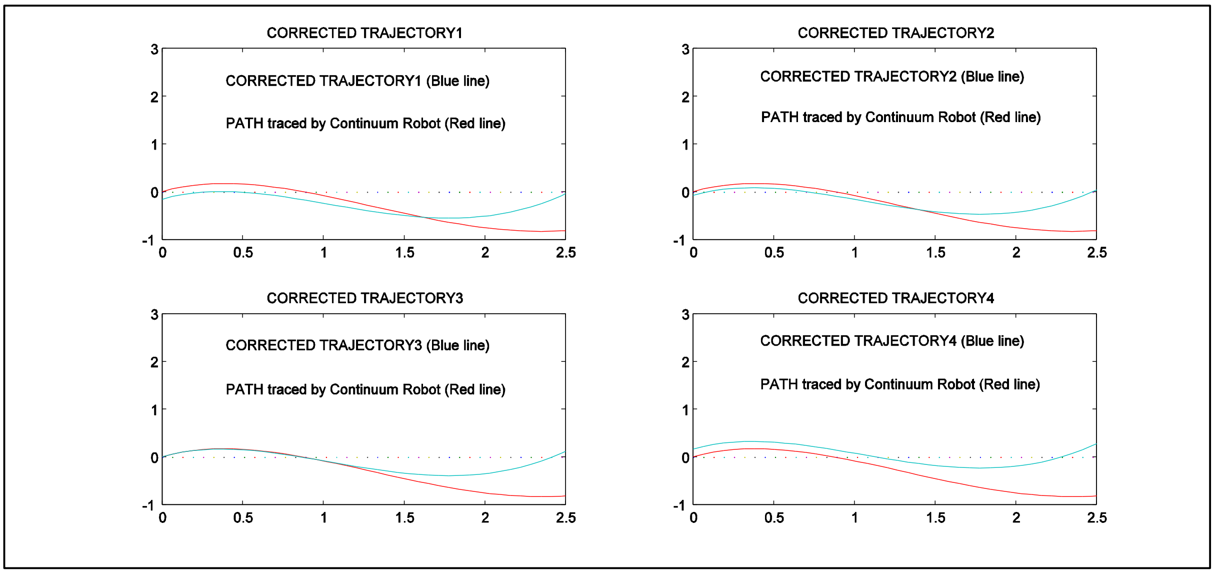


Figure 4.13 Different corrected trajectories of end effector

4.8. PID Controller

PID controller widely used in the industrial applications for controlling purposes, is a control loop feedback mechanism. In PID controller error is computed as the difference of Process variable (PV) and Set point (SP) which is given as

$error = SP - PV$

PID controller minimizes the error through the use of manipulated variable (MV) which is given as

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \qquad (4.38)$$

Where

K_p: Proportional term depends on the present errors

K_i: Integral term depends on gathering of past errors

K_d: Derivative term which depends on the likelihood of future errors

t: Instant time

τ: Variable of integration which take values from 0 to t inclusive

MV: Manipulated variable

PID do not have any internal level details of the system, it only relies on the process variable (PV) [2]. Three constant parameters could be tuned to provide control action according to the process requirement. The timely response could be termed only when the system responded immediately when the error occurred. The controller overshoots the SP and the degree of system fluctuation. It is not necessary that PID controller always ensure optimal control of control system.

4.8.1. PID controller for continuum robots end effector

As the name indicate three tuning parameters Proportional, integrator and derivative tuning parameters are tuned manually to keep the navigation at the desire point.

The tuning parameters are given below:

Proportional term

As discussed proportional gain term produces an output value which is related to error erupted presently. The proportional term could be adjusted by multiplying K_p *with* the error. Here K_p is the proportional constant

The proportional term is given by:

$$P_{out} = K_p e(t) \qquad (4.39)$$

A big change in the output is observed for a given change in error, with high proportional gain. High Proportional gain is needed to touch the reference signal by overshooting the original signal. The larger the magnitude of error gets the smaller the proportional gain should get to compensate the likelihood of huge change in error. If the system is disturbed by external force then low proportional gain would result in small control action. Tuning theory and the industrial practices indicate that the proportional term should contribute the bulk of output change without relying on the rest of tuning parameters.

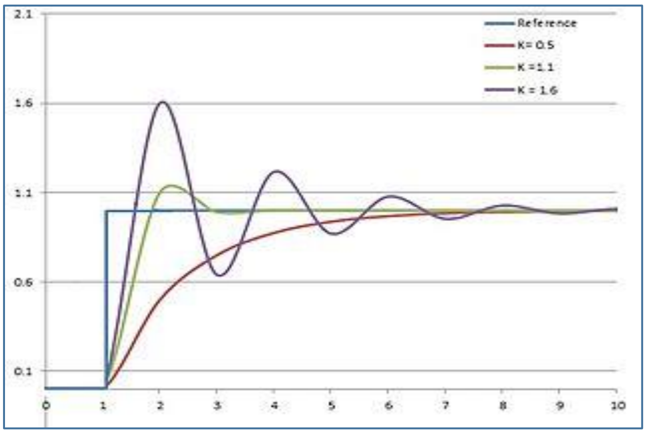


Figure 4.14 Proportional term simulation result

Integral term

The Integral depends on the accumulation of past errors. It depends on two error factors

- Magnitude of error
- Time span of error

Here the integral term is the summation of errors over certain period of time and returns offset of the previous past errors that have been modified. The accumulative error is then increased by multiplying with a constant Integral term K_i and then added to the controller ouput.

The output of integral term equation is shown below

$$I_{out} = K_i \int_0^t e(\tau)d\tau \qquad (4.40)$$

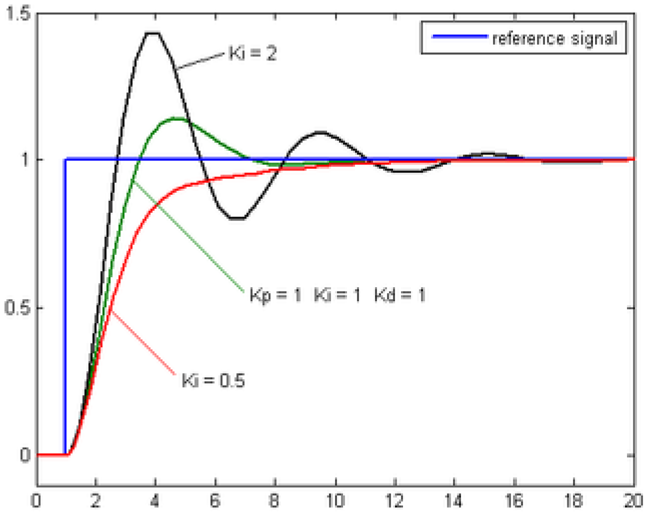


Figure 4.15 Integral term simulation result

Derivative term

The derivative of the error produced is determined by calculating the rate of change of error or slope over period of time and then multiplying with constant derivative parameter K_d . Derivative is depicted below

$$D_{out} = K_d \frac{d}{dt} e(t) \qquad (4.41)$$

Derivative action is having a proactive approach, showing the prediction of future errors, which is important for improving setting time and stability of system. Implementation and design of PID controller should take into consideration the inclusion of low pass filter for the derivative term, to keep and reduce high peaks of frequency and noise [9][10]. Derivative is rarely used in the controllers only 20 percent of it [11].

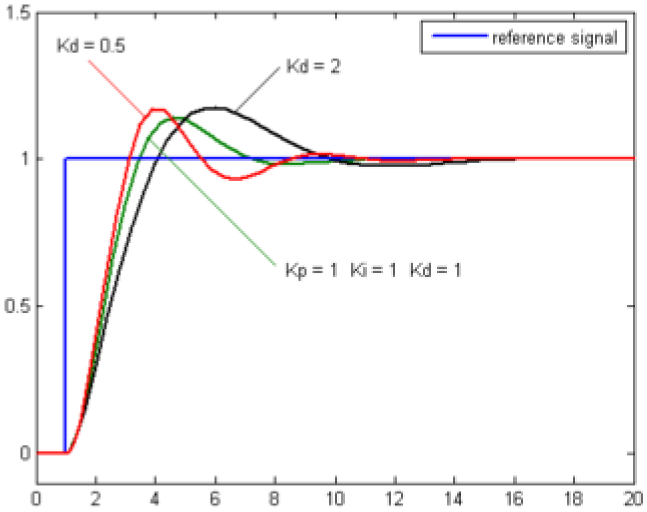


Figure 4.16 Derivative term simulation result

4.8.2. Simulation Results with PID Controller

In the absence of external disturbance the simulation results with PID controller look like

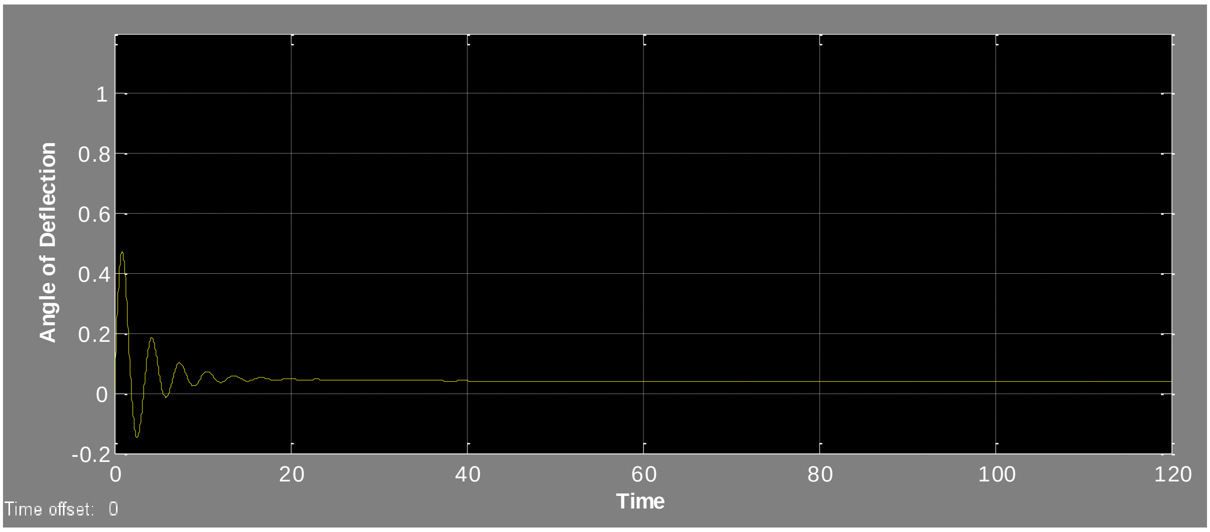


Figure 4.17 PID simulation result without white noise

Similar to FLC, PID controller also converge the end effector after sometime. The time of convergence the end effector of both the controllers remains almost the same. PID controlling parameters are manually tuned to achieve the desire result, and hence depend on the modelling of the system. When PID or FLC is started from a stabilized state with no error (PV = SP), then further modification done by the controller is in reply to the variation incurred in input values, which could be tuned in to the process that disturb the process, and hence the PV. A disturbance originates as a result of variables that affect the process other than manipulated variable.

4.8.3. Adding white noise with PID controller

After adding white noise the simulation results look like:

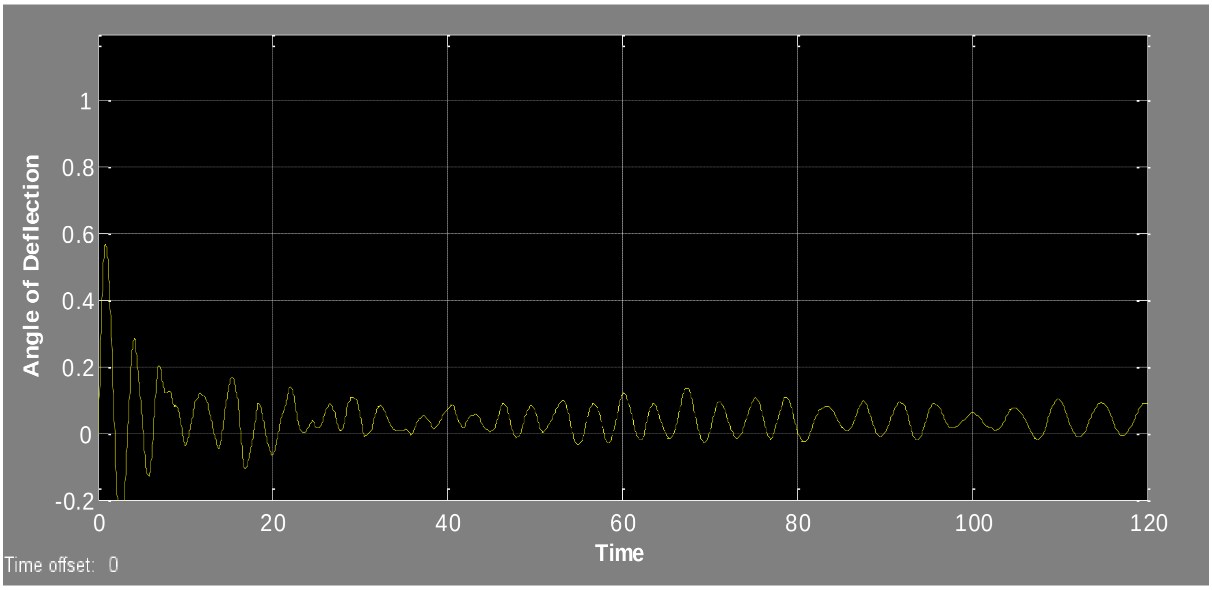


Figure 4.18 PID simulation result with white noise

In the above white noise is deforming the oscillations in irregular manner. PID controller with three Controlling parameters is trying to keep the convergence in range i.e. compensating for the deviation that is produced. PID controller has to rely on these controlling parameters, and should minimize the difference between the setpoint values and Process variable.

In the above figure 4.18 after measuring the angular displacement or position (PV), and then calculating the error, the PID controller then decides how to converge the tip position (MV). Making them converge to the mean position is the Manipulated variable, while deviation from the mean position is represented as PV.

In the convergence of manipulator all the controlling parameter has role to play. Talking about proportional control, the angular displacement covered by the tip position of the end effector is in relation with the current error produced. After this derivative action is also required, which clearly consider the rate of change of error, and thus gradient could decide the degree of compensation each time the Process Variable is assigned with the different values. It decides how much compensation is required for certain degree of bending.

Integral using Angular displacement error produced in terms of deviation in the past to detect whether the angular displacement is converging to mean position too slow or too quick, and thus depends on the magnitude of errors produced each time in terms of angular deviations and set the manipulator proportional to the generated errors produced in the past over time. Integral term plays part by encapsulating all the details of positional coordinate variation produced during the course of bending and set it proportion to the past errors . Over time the steps add up the past errors. Analyses are discussed in detail in chapter 5.

4.9. FLC vs PID Simulation Results

After getting the optimized controller values for both PID and FLC, their simulations are compared. Controlling parameters of PID are manually tuned through manually tuning, and FLC crisp outputs are optimized one. With the same blood perturbation fuzzy controller is showing better simulation results than PID controller. The dampness in oscillation is highly in refined and in translated form than with PID controller.

In FLC 49 fuzzy rules are defined which fired one after another is depending on the angular position of the tip position. Continuously traced position may trigger any of 49 rules defined, and thus helping in decreasing amplitude with the passage of time, and thus dampness is achieved considerably quickly. FLC computation time may be greater and thus timely response is sometimes compromised for the sake comprehensive results. For critical procedures real time response is sometimes of paramount importance, to avoid any blockage of blood inside the arteries or veins. In the below figure oscillation controlling mechanism with the help of fuzzy controller is shown with the help light blue line.

FLC initially starts from either side of the mean position, then at 10 seconds and beyond its continuous with oscillation about their mean position. The dampness is observed and amplitude is decreasing progressively and the tip position converges to the reference point.
With the same external disturbance, optimized controlling parameters are damping vibration with comparatively less degree as compared with FLC. For PID different tuning parameters are devised for tuning controlling parameters. In this case controlling parameters are tuned through error and trial method.

FLC is best for nonlinear system where PID shows poor performance. FLC is used even when the user don’t have underlying knowledge of the control process mechanism used in the system. FLC results in comprehensive outputs which show the overall behavior of system in different working environments. PID response is somewhat good than FLC due to less computational time._From all the above figure it is clearly deduced that Fuzzy Logic controller has improved stability, lesser overshoot, and quick response._In below figure PID simulation result is shown in golden color signal. The amplitude observed is comparatively higher than FLC simulated signal.

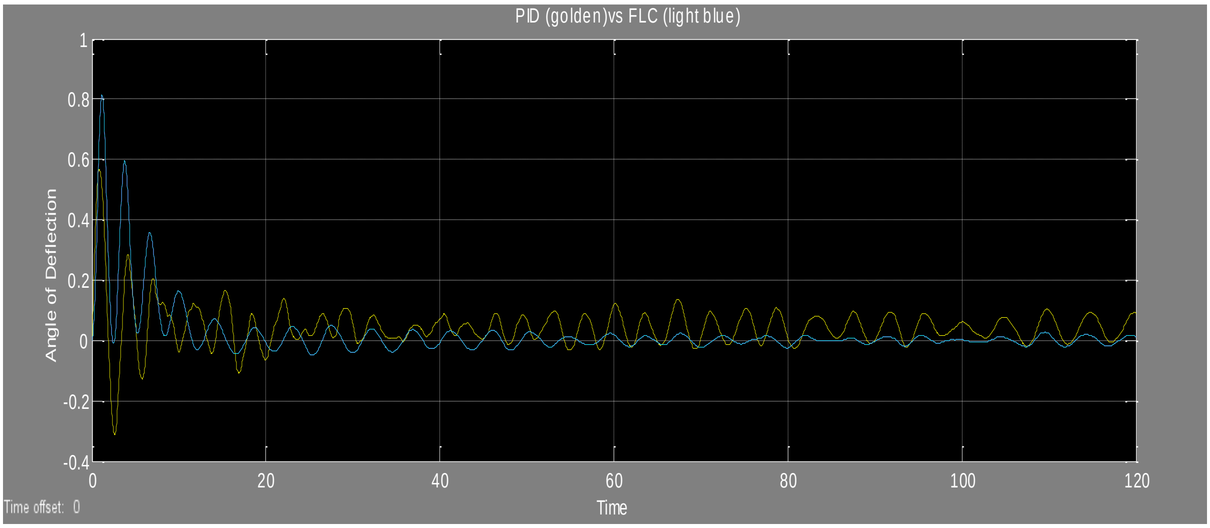


Figure 4.19 Simulation results of PID & FLC

4.10. Conclusions

Fuzzy controllers deal with the non-linear system and use the human operator knowledge to show it in the form of linguistic variables. PID has only three parameters which can be tuned according to the process requirement. Contrary to PID, Fuzzy controller has a lot of parameters to adjust i.e. good selection of rule base and the parameters of membership functions. The control system having FLC is more or less shaping into deterministic system. When the parameters in FLC system are well chosen then it has very good time domain characteristic. Fuzzy controllers behave smartly though don't have any prior knowledge of the system to be controlled. It depends on how the membership functions are distributed and don't depends the various geometrical shapes.

Through analysis of the simulations, one of the problems associated with the fuzzy controller is that the computation is much greater as compare to PID controller, because of different modules fuzzification, inference base and defuzzification. Some optimization can be done when the defuzzification is simplified.

CHAPTER 5

5.1. ANALYSIS OF RESULTS WITH AND WITHOUT CONTROLLER

When continuum robot is navigating through unstructured, congested and unconventional environment, then it has to be intelligent enough to go through, without coming into contact with delicate tissues of human body. The bending of end effector is caused by the external force which could be blood flow moving in the opposite direction that of end effector. Continuum design is a dead structure and bending could be caused by any external force.

Continuum robot end effector modelling results without controller is given below

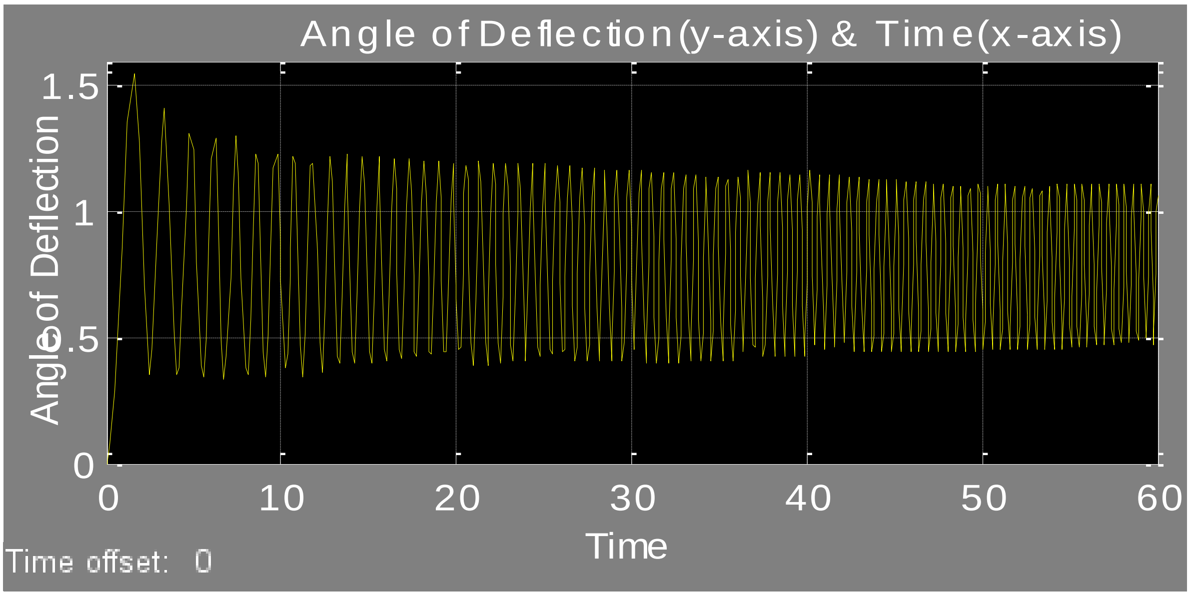


Figure 5.1. Modelling of continuum robot end effector bending

5.1.1 Analysis of Result without Controller

With external force notably the blood flow the end effector starts vibration about their mean position. Amplitude of vibration dips down due to the loss of kinetic energy with time. This vibration of end effector about their mean position is a classic example of mechanical energy conservation. There are two forces acting on the end effector, one is the force of gravitation and other is force exerted by blood flow.

The bending of end effector of continuum robot is also termed as an example of mechanical energy conservation. End effector sweeps out a circular arc, by vibrating about their mean position. Neglecting the internal resistance there are two forces acting on the end effector. One is the gravitational force acting in downward direction. However gravity is the internal force and does not used to change the total mechanical energy of the end effector. Other force acting is the tension force. Tension force could arise in case of cable driven continuum robots.

The whole mechanics of the end effector vibration behaves like vibratory system, storing potential energy due to the material used in the construction, storing Kinetic energy which actually is due to the mass of inertia. During the course of vibration continuous transformation between Kinetic and Potential energy is taking place. Dampness in the vibration is observed mainly because energy is dissipated at each cycle of vibration. In the above figure the frequency of vibration is higher so more energy is dissipated and hence the convergence rate is higher. In order to maintain the vibration at steady position some energy has to be added from the external source. The structure from the base point till end effector behaves like deformable linear objects (DLOs), which is sometimes quite challenging to handle than rigid objects, as it give rise to uncertainty resulting from oscillation and may cause failures in the intended operations.

5.1.2.Fuzzy Controller: Simulation Results without white noise

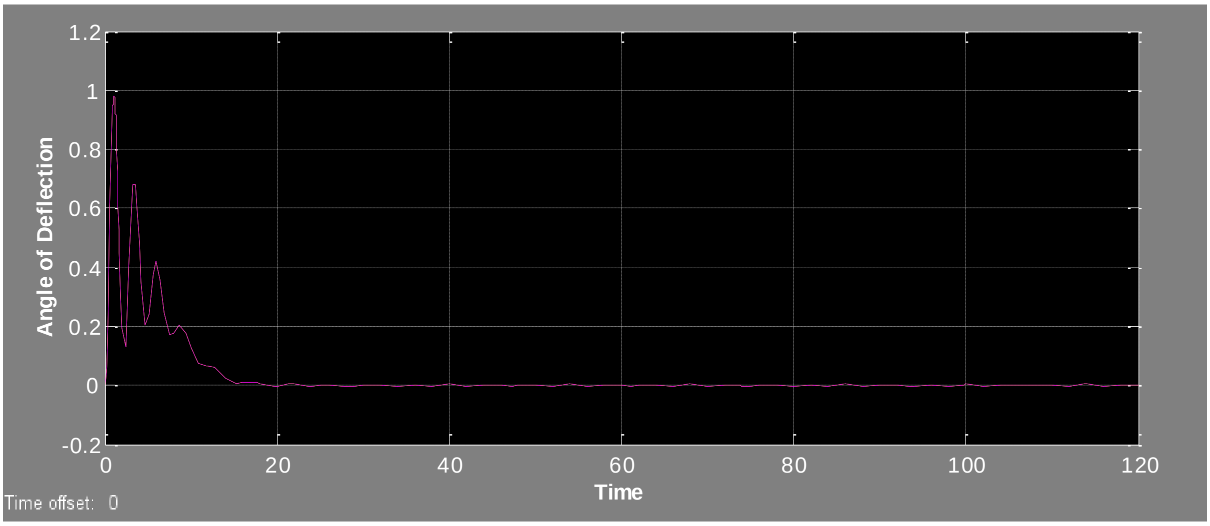


Figure 5.2 Results with Fuzzy controller in the absence of white noise

5.1.3.Analysis of Result with Fuzzy Controller without white noise

During the course of insertion without taking into account the external force, the end effector initially starts vibration on either side of the mean position, and then after 20 seconds it is merged to the mean position and travelling along the mean position. The vibration initially representing the insertion of the robotize device inside the unstructured region and thus set to vibration, as the linear insertion also produces vibration initially.

Such dampness can also be achieved through stiffness controller for continuum robots. End effector or tip stiffness is implemented in a way that it could touch around desire coordinate points on the plane. Such tracing involves the positioning of overall architecture of continuum segments to facilitate the outreach at different unstructured places. This way of implementation has several advantages. Firstly, it enables the working ability of robot end effector bending as a mean to control forces at the tip position. Secondly, it also control the stiffness and flexibility outreach capability to be carefully employed through the changes of the robot end effector controllers.

In the above the position control of the end effector is phenomenal, as it merges quickly to the mean position after being disturbed with high spikes observed. Other than positional control impedance control is also of paramount importance. In impedance control, a vigorous dynamic relation is established between the outside force and manipulator tip bending. In the above case impedance control is not needed as it is without outside force.

Critical damping observed: In critical damping the system returns to mean position as quickly as possible without oscillation. The above figure is an example of critical damping.

The behavior of system depends on two parameters, the natural frequency which is represented as ω_0 and damping ratio as ζ. When ζ =1 the system is said to be critically damped. A critical damped converge to the mean position as quickly as possible although overshoot can occur initially. Door closer on many hinged doors is the typical example of critical damping. Recoil mechanism is also example of critical damping where it comes to original position soon after the firing.

5.1.4.Fuzzy Controller: Simulation Results with white noise

White noise produces deformation initially, but with the introduction of Fuzzy controller the signal is stabilized by merging to the mean position as shown below in figure 5.2.

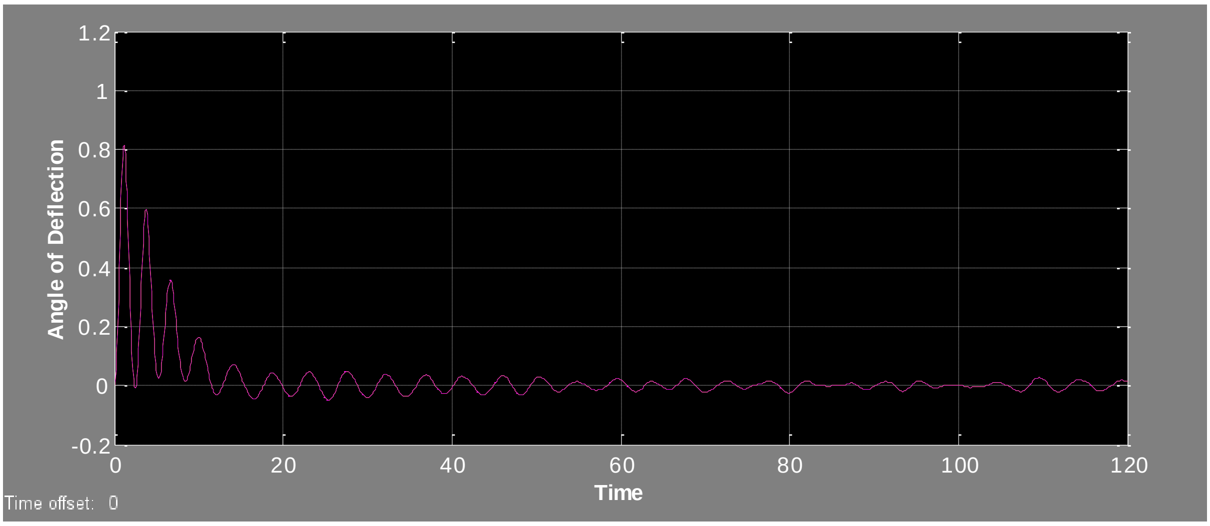


Figure 5.3 Results with Fuzzy controller in the presence of white noise

5.1.5.Analysis of Result with Fuzzy Controller having white noise

By adding white noise initially it overshoots or throws away the end effector but due to restoring force or energy possess by the end effector, its tendency toward the mean position.

CHAPTER 5: ANALYSIS OF SIMULATION RESULTS

Fuzzy logic controller computes the error and change of error through fuzzy inference in which the fuzzy rules are formed manually.

Fuzzy controller reduces the deviation and pulls the end effector toward the means position with decreasing trend. After 100 second the end effector completely stabilizes with very negligible vibration being observed. The convergence without white noise was at the mean position, but introducing white noise has produced some ripples in the vibration but still the vibration remains intact and decreasing amplitude is being along the time line.

In signal processing, white noise is a random signal with varying amplitude having uniform spectral density [1]. White noise is not confined and limited to any particular signal but it is actually referring to statistical model for signals and their source of origination. In the above figure it is overcome by the fuzzy controller through fuzzy rules defined in fuzzy rule base. Noise power in the Band-limited white noise block is set to according to the force by blood fluid. Main purpose of this type of modelling is to scale it up to the medical domain procedures carrying out through robotize device, which is end effector of continuum robot in our case.

Different samples of white noise signal taken are observed to have sequential along the time line. There is nothing like infinite bandwidth white noise signal theoretically. The mechanism of noise generation confined and limited them. Such mechanism of generation includes the transmission medium and also could arise by the observation capabilities. Varying the noise power could also vary the spectral density and different flat spectrum is observed over the range of frequencies that is relevant to the context. In figure 5.3 the density of vibration is consistent along the line with decreasing amplitude and hence increasing frequency.

The blood flow that is coming in contact with the end effector set it to vibration, the deviation from the mean position is termed as error which is fed to the fuzzy controller through feedback mechanism. The rules define in the rule base then decide the magnitude of deviation, and certain rules are fired catering for certain magnitude of deviation. Membership function editor containing two inputs and three outputs and could be termed as MIMO mechanism. Seven membership function are define in each of the input i.e. error and derivative error. The outputs are computed through human understanding and interpretation of the rules, giving rise to 49 rules. With varying deflection each time, different set of fuzzy rules are fired through whole scanning of 49 rules, to compensate for the deflection produced.

The input variables containing several membership functions are generally known as fuzzy sets. The process which is dealing with conversion of crisp input values to fuzzy values is called fuzzification. Given mappings of two input variables into 7 membership functions each and truth values, the system then makes decisions for the kind of action to take through rigorous scanning of the rules set.

For example

1. *If (e is NB) and (de is NB) then (* K_P *is P)(* K_D *is N)(* K_I *is P)*

Here e and de are the input variables with multiple output variables i.e. Kp, Kd and Ki.

As per fuzzy system decision is based on fuzzy rules

- For certain deflections, certain rule are invoked by traversing whole set of rules, using the truth values and the membership functions from the inputs.
- The result in turn is mapped to three membership functions define for output variable.
- The results retrieved are compiled as crisp answers, the procedure is termed as defuzzification.

This combination of fuzzy rule based inference and its operations are termed as fuzzy expert system.

The Input variables with their membership function are shown as

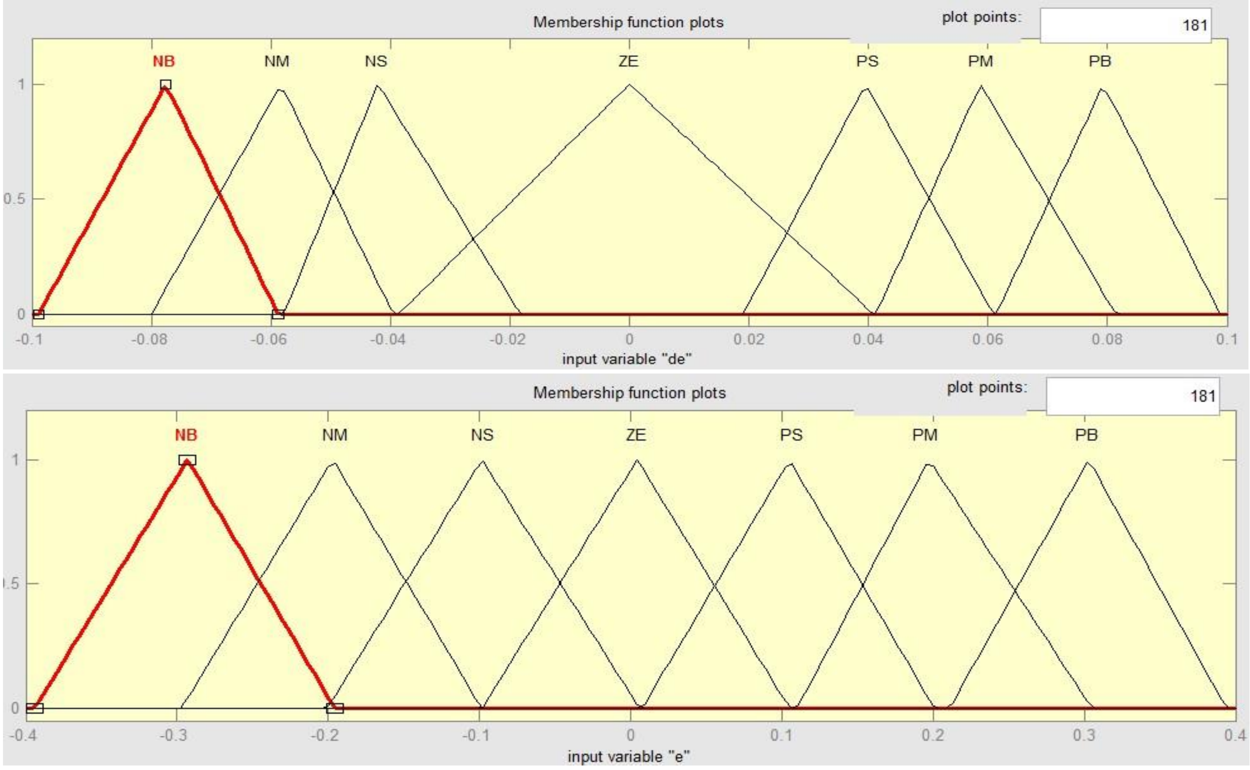
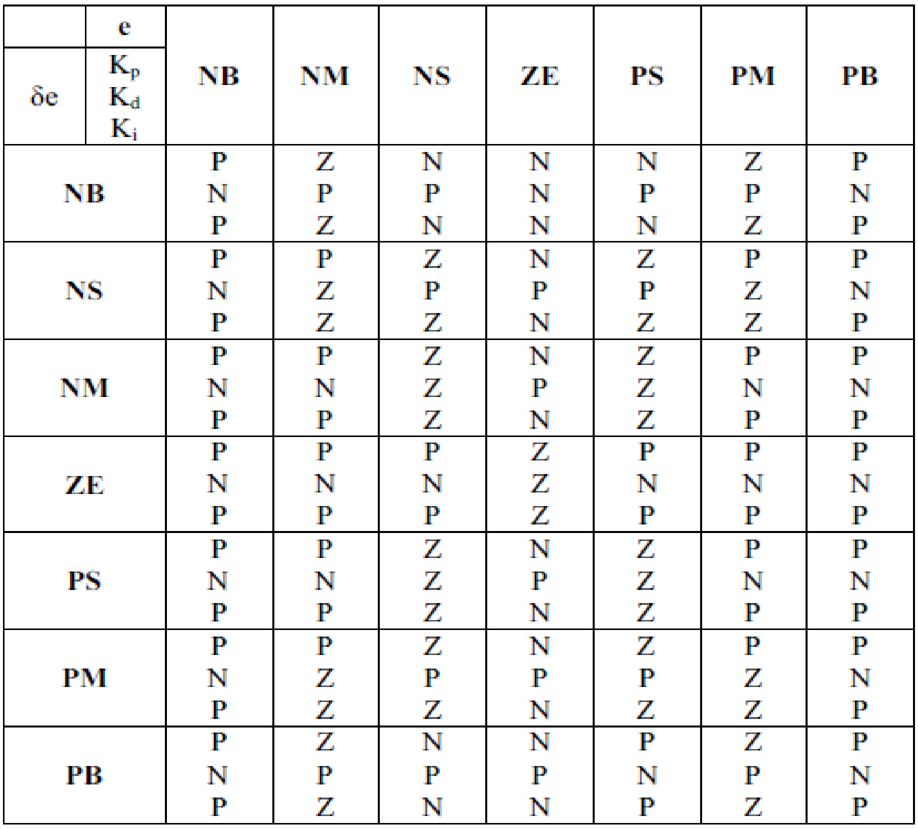


Figure 5.4 Input Variable of e and de

The error and derivative of error shown in figure 5.4 is fed to the feedback controller mechanism by ingesting through Fuzzy logic controller (FLC) system. Band limited white noise is deviating the deflection from the mean position, the resultant 49 rules as described in the below figure 5.5 is overcoming the deviation, and merging it to the mean position.

Bandwidth limited white noise means that bandwidth of white noise is limited in practical usage through the mechanism of noise generation, depends on the origination from the source transmission medium and through careful inspection capabilities. For audible audios the range of frequencies varies from 20 to 20,000 Hz. The white noise generated sounds like hissing and observed in routine through transmission failure observed in TV sets.



e δe K_p K_d K_i	NB	NM	NS	ZE	PS	PM	PB
NB	P N P	Z P Z	N P N	N N N	N P N	Z P Z	P N P
NS	P N P	P Z Z	Z P Z	N P N	Z P Z	P Z Z	P N P
NM	P N P	P N P	Z Z Z	N P N	Z Z Z	P N P	P N P
ZE	P N P	P N P	P N P	Z Z Z	P N P	P N P	P N P
PS	P N P	P N P	Z Z Z	N P N	Z Z Z	P N P	P N P
PM	P N P	P Z Z	Z P Z	N P N	Z P Z	P Z Z	P N P
PB	P N P	Z P Z	N P N	N P N	P N P	Z P Z	P N P

Figure 5.5 49 Fuzzy Rules

Depending on the velocity of blood flow, the end effector is deflected at certain degree, which is sensed by the system and inputting such values to the feedback mechanism system. Locating the position of end effector at different from the mean position is giving to the system, and certain set of rules are fired which help in narrow down the deflection produced. Once the deflection is decreased, then this change is again given to the system which further narrows down the amplitude from the previous position. This pattern is repeated and hence helping the end effector to converge the end effector even in the presence of white noise.

The values used in the above truth table are derived based on human interpretation and understanding and thus are the tuned values. Number of rules could be tweaked based on how finely the system has to be tuned. Greater the number of rules greater it might get finely tuned. Fuzzy rules are defined in terms of controlling parameters of PID controllers just for the sake of comparison.

Output variables and their membership functions are given below

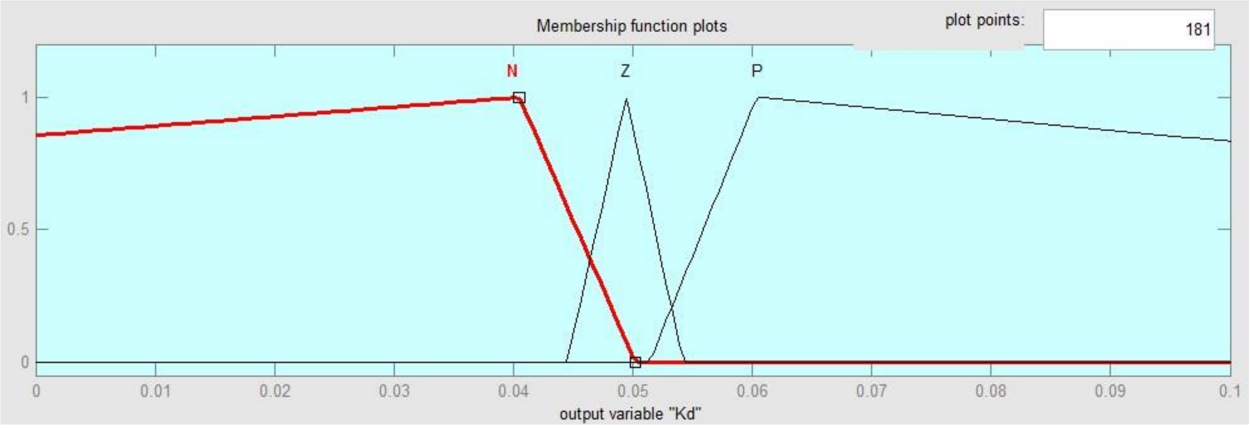


Figure 5.6 output Variable of Kd (same as Kp and Ki)

5.1.6.PID Controller: Result without External force

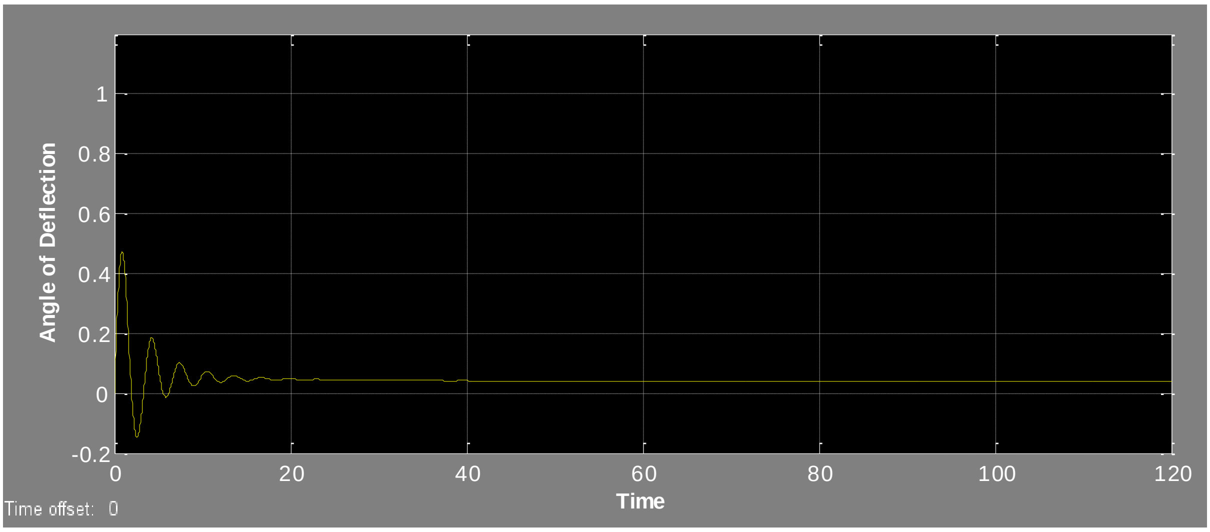


Figure 5.7 Result with PID controller without white noise

5.1.7.Analysis of Results with PID Controller

A PID controller is widely used in the industrial control systems. PID controller consists of three constant parameters i.e. proportional, integral and derivative. PID controller is very useful controller because it does not have any internal underlying system knowledge and only depend on the measured process variable.

In the above figure constant parameters have been tuned to get the desire result, to minimize the amplitude of vibration on either side of the mean position. In the above figure 5.3 absence of white noise does not mean the absence of external force. In this example the error is manipulated as the difference between SP-PV. The external initially overshoots the end effector but after 10 seconds it stabilizes and move along the mean position. In contrast to the fuzzy logic controller, PID controller completely brings the system to mean position removing even the slightest of vibration.

5.1.8.PID Controller: Simulation Results with white noise

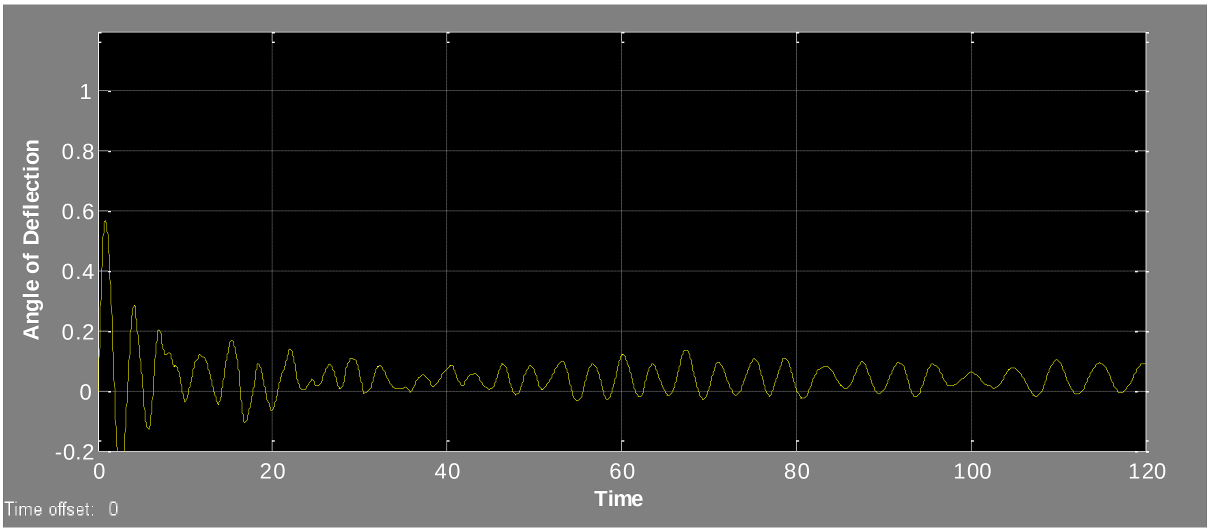


Figure 5.8 Result with PID controller with white noise

5.1.9.Analysis of Results with PID controller having White Noise

With introduction of white noise Deformation in the vibration occurred, but the dampness still intact both crest and trough Get closer to each other i.e. merged to the mean position. Without white noise, the magnitude was comparatively less in the presence. Through the controlling parameters of Proportional, Integral and Derivative term the value of error which is actually the subtraction of the PV and SP is minimized to great degree.

Deformation in the signal mentioned in figure 5.8 is due to the introduction of white noise. White noise with specific power noise value deforms the signal to a much degree but the amplitude still remains intact through the control parameters introduce in the PID Controller. PID Controller try to minimize the magnitude of error produced the use of manipulated variables. Once the signal is deformed through the white noise, then the weighted sum of these three controlling parameters is used to adjust the process by minimizing the deviation.

Through the proper tuning of control parameters in the PID, it is controlling the position of the end effector in presence of blood flow in the form of white noise. The response of the controller to external disturbance is very critical, because through real time response there are less chances of blood blockage in the veins and arteries. The use of PID controller in such case does not ensure the optimal control and robustness of the system stability. Deflection sensed in presence of white noise is the PV and the desired deflection SP. Input to continuum robot end effector system and output of the PID controller is termed as the control variable or the MV (manipulated variable).

After manipulating the deflection, and then calculating “e”, the PID controller selects how to set the end effector position to keep the deflection to minimum. In PID controller the proportional term works on the present error produced in terms of deflection in the presence of white noise, Integrative terms works on the accumulation of errors each time produced, and the Derivative error works on the likely hood of future errors that might occur. In the proportional control, tip position of the end effector is set in proportion to the current error. Derivative term consider the rate of change of error, by adding more or less bending towards the mean position depending on how rapidly the error is approaching zero. Finally the integral term this depends on the magnitude of error and duration of error, consider the accumulated error in terms of deflection over the past, and showing their trend in terms of their behavior of deflection. The trend observed was the decreasing trend of deflection over the time. The blurriness in the signal is observed with the introduction of white noise but the signal attitude towards mean position is also observed.

In the figure 5.8 it is clearly shown that at 40 seconds it is almost converge to the mean position, but as the white noise has continuous spectral density it is again showing that amplitude is raising. The integral terms again come into play for the accumulated errors. Some low rising spikes has been observed which starts at 40 seconds and last till 80 seconds. Beyond 80 seconds it is again tilt down and approaching towards the mean position. White noise gets spiral out of control at some time and then again PID converge it. So this thug of war is being observed between the PID controller and white noise which is contrary to the Fuzzy logic controller. Fuzzy logic controller is continuously converging the deflection towards the mean position.

Chapter 6

Conclusion & Future Work

6.3. **Conclusion**

Control of a continuum Robot through better techniques is of vital importance. Research is focusing on the planar deflection of end effector on encountering the external disturbance. The planar deflection is achieved by modifying the tip position of the end effector, making it slope from the tip position. Through this it set to oscillate the end effector to the left and right direction. This movement underwent 2-degree of freedom during the course of its navigation in unstructured and congested environment. This extends the existing model to multidimensional covering many degrees of freedom, which rule out the possibility of relying on one structural design of the tip position.

When continuum robotize manipulator are navigating through unstructured, congested environments, it may encounter external force or objects, which may deflect them and set them oscillate. Our aim mainly focuses on keeping the end effector in erectile position. This is achieved with the help of Fuzzy and PID controllers. Simulations results from both the controllers are compared and evaluated, in order to achieve the best possible result. Controlling parameters in both the controllers are made optimized, which utilizes these parameters based on the angular position of the end effector. Both controllers damped the vibration and converges them to the mean position, with FLC simulation results found to be more comprehensive than PID results.

6.4. **Future Work**

Future work includes designing a 3D verification test bench, which will focus on the deflection of continuum manipulator from various angles. Through such experiments main focus will be on the end effector, and the path traced by it during the course of bending. The essential step for modeling continuum robots is dynamics. The work presented in this thesis lays a foundation and set the tone for multi-section dynamics and real time shape computation.

Talking specifically medical domain, robotizing the medical devices is necessary for inspection purposes inside the human body. This research will include optimizing the automated sensor feedback control, generating a quick response to the outside disturbance. Controlling mechanism is designed for smaller upcoming forces, which could be scale up in presence of high impedance. This research covers only the medical domain, which will be extending to the nuclear vicinities, welding ships underneath the water. In such cases external forces and disturbances will be comparatively of high magnitude, which can be problematic in terms of carrying out activities in hollow unstructured regions.

Continuum robot with a diversity of applications in many domains, it is mainly used for navigation purposes due to its compliant structure. Most of the research is carried out on continuum robots in the medical domain, where precision and control of the end effector is of paramount importance. In the deployment main focus will be on increasing human safety, by taking into consideration the uncertainties in the surgical systems. Uncertainties originate due to three factors. First is the physical error that could erupt in the error tolerance of the robot machining processes? Second arises due to rounding errors which trickled due to mathematical error. Third error is due to oversimplification and modification of inverted pendulum model and translating them into continuum model by assuming homogenous bending of continuum manipulator. Very little research has been carried out on the crucial issue of manipulating system uncertainties in the continuum robots.

Research done on system uncertainties will be further carried out by observing the behavior of already designed active catheters. Errors could be further decomposed by observing low level details, such as holes in the base disk and the spacer disk as well as the local deformation of continuum robot lying between the spacer disks. System uncertainties could be bring to the lime light by using the inverse kinematics, which compute it due to rounding error as well physical uncertainties. The efficacy of the results could be further guaranteed to achieve the highest degree of precision by using the interval analysis to solve the inverse problem and to find out the optimal solution while taking care of system uncertainties in a rigorous way.

Main focus will be on optimizing the results of interval analysis further, which could add a better solution to the problem of uncertainty, detecting and exploiting anomalies in an efficient manner. Interval analysis takes into consideration the undesired behavior of system considering system error, which could result from imprecision in modeling and parameters identification. In medical domain robotize medical devices requires certain characteristics, such as high security and error-tolerance.

To further refine the work, integrate the solution of collision avoidance algorithm to existing model which will perform two tasks. One to avoid obstacle during navigation and other to restore the position of end effector while encountering external disturbance. Approximating the shape of the hollow unstructured prior to the insertion of robotize device, and triggering the collision avoidance algorithm at same time will make sure for the safe traversing without coming into the walls of the contained environment.

Bibliography

1. Y. Hyun-Soo and Y. Byung-Ju, “A 4-DOF flexible continuum robot using a spring backbone,” in *Proc. Int. Conf. Mechatronics and Automation*, Changchun, China, Aug. 2009, pp. 1249–1254.
2. D.B. Camarillo, C.F. Milne, C.R. Carlson, M.R. Zinn, and J.K. Salisbury. Mechanics modeling of tendon-driven continuum manipulators. Robotics, IEEE Transactions on, 24(6):1262 –1273, dec. 2008.
3. P. Kallio, M. Lind, Q. Zhou, H.N. Koivo, "A 3DOF Piezohydraulic Parallel Manipulator", IEEE International Conference Robotics and Automation, Belgium, pp **1823 - 1828, 1998.**
4. W. Kier, K. Smith, "Tongues, Tentacles and Trunks; the Biomechanics of Movement in Muscular Hydrostats", Zoological Journal of the Linnean Society, vol. 83, pp. 307 - 324, 1985.
5. D.M. Lane, J. Sneddon, D.J. O'Brien, J.B.C. Davies, G.C. Robinson, "Aspects of the Design and Development of a Subsea Dextrous Grasping System", IEEE OCEANS **'94,** Brest, France, Sept **13-16,** VOI **11,** pp **174-181, 1994**
6. G. Robinson, J.B.C. Davies, J.P.P. Jones Development of the Amadeus Dextrous Robot End- Effectors, IEEE Oceans **'98,** Nice, France, Sept. **29 - Oct 1. vol. 2, pp. 703 - 707, 1998**.
7. A. Hemami, "Design of Light Weight Flexible Robot Arm", Robots **8** Conference Proceedings, Detroit, June **4-7,** pp **16-23 16-40, 1984.**
8. G. Robinson and J. Davies, “Continuum Robots - A State of the Art,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Detroit, MI, 1999, pp. 2849–2854.
9. K. Ikuta, H. Ichikawa, K. Suzuki, and D. Yajima, “Multi-degree of freedom hydraulic pressure driven safety active catheter,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Orlando, FL, 2006, pp. 4161–4166.
10. Goldman, Roger E.; Bajo, A.; Simaan, N., "Compliant motion control for continuum robots with intrinsic actuation sensing," *Robotics and Automation (ICRA), 2011 IEEE International Conference on* , vol., no., pp.1126,1132, 9-13 May 2011
doi: 10.1109/ICRA.2011.5980000
11. B.A. Jones and I.D. Walker. Kinematics for multisection continuum robots. Robotics, IEEE Transactions on, 22(1):43 – 55, feb. 2006.
12. I. Tunay. Spatial continuum models of rods undergoing large deformation and inflation. Robotics, IEEE Transactions on, 29(2):297–307, 2013.
13. Robinson, G.; Davies, J.B.C., "Continuum robots - a state of the art," *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on* , vol.4, no., pp.2849,2854 vol.4, 1999
doi: 10.1109/ROBOT.1999.774029
14. R.L. Orndorff, "Gripping Device", US Patent No. 3601442,1971.
15. G. Lim, K. Minami, K. Yamamoto, M. Sugihara, M. Uchiyama, M. Esashi, "Multi-link active catheter snake-like motion", Robotica, vol **14,** pp **499 - 506, 1996.**
16. S. Aramaki, S. Kaneko, K. Arai, Y. Takahashi, H. Adachi, and K. Yanagisawa, “Tube type micro manipulator using shape memory alloy (SMA),” in *MHS’95. Proc. 6th Int. Symp. Micro Machine and Human Science*, 1995, pp. 115–120.
17. G. Chen, M. Pham, and T. Redarce, “Sensor-based guidance control of a continuum robot for a semi-autonomous colonoscopy,” *Robotics and Autonomous Systems*, vol. 57, no. 6-7, pp. 712–722, Jun. 2009.
18. K. Suzumori, K. Akihiro, F. Kondo, R. Haneda, "Integrated Flexible Micro-Actuator Systems", Robotica, vol 14, pp 493 - 498, 1996.
19. P.E. Dupont, J. Lock, B. Itkowitz, and E. Butler. Design and control of concentric-tube robots. Robotics, IEEE Transactions on, 26(2):209–225, 2010.
20. I. A. Gravagne and I. D. Walker, “Manipulability, force, and compliance analysis for planar continuum manipulators.” *IEEE Trans. Robot. Autom.*, vol. 18, no. 3, pp. 263–73, Jun. 2002.
21. Robert J Webster and Bryan A Jones. Design and kinematic modeling of constant curvature continuum robots: A review.
22. J.B.C. Davies "An Alternative Robotic Proboscis", Proc NATO Advanced Research Workshop on Traditional and Non-Traditional Robots, Maratea, Italy, Aug 28 - Sep 2, pp 49-55, 1989.
23. J.B.C. Davies, "Elephants Trunks an Unforgettable Alternative to Rigid Mechanics", Industrial Robot, VOI 28, ~ ~ 2 9 - 3109,9 1 .
24. G. Robinson, J.B.C. Davies, "The Amadeus Project: An Overview", Industrial Robot, vol **24,** no **4,** pp **290-296,** 1997.
25. J. Jayender, R. Patel, and S. Nikumb, “Robot-assisted Active Catheter Insertion: Algorithms and Experiments,” *Int. Journal of Robotics Research*, vol. 28, no. 9, pp. 1101–1117, May 2009.
26. M. W. Hannan and I. D. Walker, “Kinematics and the implementation of an elephant’s trunk manipulator and other continuum style robots,” *Journal of Robotic Systems*, vol. 20, no. 2, Feb. 2003, pp. 45–63.

27. H. Tsukagoshi, A. Kitagawa, and M. Segawa, “Active hose: an artificial elephant's nose with maneuverability for rescue operation,” *Proc. IEEE Intl. Conf. on Robotics and Automation*, Seoul, Korea, May 2001, vol. 3, pp. 2454–2459.

28. A. Wolf, H. B. Brown, R. Casciola, A. Costa, M. Schwerin, E. Shamas, and H. Choset, “A mobile hyper redundant mechanism for search and rescue tasks,” *Proc. IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems*, Taipei, Taiwan, May 2003, vol. 3, pp. 2889–2895.

29. N. Simaan, “Snake-like units using flexible backbones and actuation redundancy for enhanced miniaturization,” *Proc. IEEE Intl. Conf. on Robotics and Automation*, Barcelona, Spain, April 2005, pp. 3023–3028.

30. N. Simaan, R. Taylor, and P. Flint, “A dexterous system for laryngeal surgery”, *Proc. IEEE Intl. Conf. on Robotics and Automation*, New Orleans, April 2004, pp. 351–357.

31. G. Chen, M. T. Pham, T. Redarce, C. Prelle, and F. Lamarquem, “Design and modeling of a micro-robotic manipulator for colonoscopy,” *Proc. 5th Intl. Workshop on Research and Education in Mechatronics*, Annecy, France, June 2005, to appear.

32. I. A. Gravagne and I. D. Walker, “Large deflection dynamics and control for planar continuum robots,” *IEEE/ASME Trans. on Mechatronics*, vol. 8, no. 2, June 2003, pp 299–307.

33. S. Hirose, *Biologically inspired robots*, Oxford University Press, 1993, pp. 147– 155.

34. S. Hirose, *Biologically inspired robots*, Oxford University Press, 1993, pp. 20–30.

35. G. S. Chirikjian and J. W. Burdick, “A modal approach to hyper-redundant manipulator kinematics,” *IEEE Trans. on Robotics and Automation*, vol. 10, no. 3, June 1994, pp. 343–354.

36. G. S. Chirikjian, “Hyper-redundant manipulator dynamics: a continuum approximation,” *Advanced Robotics*, vol. 9, no. 3, pp. 217–243, 1995.

37. G. S. Chirikjian, “Design and analysis of some nonanthropomorphic, biologically inspired robots: an overview,” *Journal of Robotic Systems*, vol. 18, no. 12 , pp 701– 713, 2001.

38. F. Fahimi, H. Ashrafiuon, and C. Nataraj, “An improved inverse kinematic and velocity solution for spatial hyper-redundant robots,” *IEEE Trans. on Robotics and Automation*, vol. 18, no. 1, Feb. 2002, pp. 103–107.

39. I. A. Gravagne and I. D. Walker. “On the kinematics of remotely-actuated continuum robots,” Proc. *IEEE Intl. Conf. on Robotics and Automation*, San Francisco, 2000, pp. 2544–2550.

40. Novák, V., Perfilieva, I. and Močkoř, J. (1999) *Mathematical principles of fuzzy logic* Dodrecht: Kluwer Academic.ISBN 0-7923-8595-0

41. Ahlawat, Nishant, Ashu Gautam, and Nidhi Sharma (International Research Publications House 2014) "Use of Logic Gates to Make Edge Avoider Robot."*International Journal of Information & Computation Technology* (Volume 4, Issue 6; page 630) ISSN 0974-2239 (Retrieved 27 April 2014)

42. "Fuzzy Logic". *Stanford Encyclopedia of Philosophy*. Stanford University. 2006-07-23. Retrieved 2008-09 30.

43. Zadeh, L.A. (1965). "Fuzzy sets". *Information and Control* **8** (3): 338–353. doi:10.1016/s0019-9958(65)90241-x

44. Pelletier, Francis Jeffry (2000). "Review of *Metamathematics of fuzzy logics*" (PDF). *The Bulletin of Symbolic Logic* **6** (3): 342–346. JSTOR 421060.

45. Kosko, B (June 1, 1994). "Fuzzy Thinking: The New Science of Fuzzy Logic". *Hyperion*.

46. Bansod, Nitin A., Marshall Kulkarni, and S.H. Patil (Bharati Vidyapeeth College of Engineering) "Soft Computing- A Fuzzy Logic Approach". *Soft Computing* (Allied Publishers 2005)

47. Y.Tsukamoto, “An approach to fuzzy reasoning method”, *Advances in Fuzzy Set Theory and Applications,* M/M Gupta, RiC.Ragade, and R.R.Yager Eds.,Amsterdam, North-Hollamd, 1979.

48. Lotfi A. Zadeh, Abraham Kandel, and Gideon Langholz, “Fuzzy Control Systems”, *ISBN 0-8493-4496-4, ©1994 by CRC Press, Inc,* 1994.

49. Witold Pedrycz, “Fuzzy Control and Fuzzy Systems”, *Second Edition, ISBN 0-471- 93475-5, ©1993 by Research Studies Press Ltd,* 1993.

50. Kudret Demirli, ‘'Notes of Fuzzy Sets & Fuzzy Logic”, *Department o f Mechanical Engineering, Concordia University,* 1999.

51. G.S.Virk, “Digital Computer Control Systems”, *ISBN 0-07-067512-0, First published 1991 by Macmillan Education Ltd, ©1991 by G.S. Virk,* 1991.

52. Radhamohan, S. V., A. Subramaniam and M., Nigam, M. J., “Fuzzy swing-up and stabilization of real inverted pendulum using single rulebase”, Journal of Theoretical and Applied Information Technology, pp. 43-49, 2010.

53. R. Precup and H.Hellendoorn, “A survey on industrial applications of fuzzy control”, Computers in industry, vol. 62(3), pp. 213-226, 2011.

54. C.W. Tao, “Fuzzy hierarchical swing- up and sliding position Controller for the inverted pendulum–cart system”, Fuzzy Sets and Systems, Science Direct, 2008.

55. M.P. Sameet and P.G. Devendra, “Fuzzy logic-based reinforcement learning of admittance control for automated robotic manufacturing”, *Engineering Applications of Artificial Intelligence*, vol. 11, pp. 7-23, 1998.

56. F.L. Lewis, C.T. Abdallah and D.M. Dawson, “Control of robot manipulators”, MacMillan Publishing Company, New York, 1993.

57. M.T. Mason, “Compliance and force control theory for computer controller manipulators”, *IEEE Trans. on SMC*, vol. 6 pp. 418-432, 1981.

58. M.H. Raibert and J.J. Craig, “Hybrid position/force control of manipulators”, *Trans. of ASME, J. Dynamics Systems Measurement and Control*, vol. 102, pp. 126-133, 1982.

59. S. Jung, T.C. Hsia and R.G. Bonitz, “Force tracking impedance control for robot manipulators with unknown environment: Theory, Simulation and Experiment”, Int. J. of Robotics Research, vol. 20, No. 9, pp. 765-774, 2001.

60. H. Seraji and R. Colbaugh, “Adaptive force-based impedance control”, IEEE Int. Conference on Robotics and Automation, Yokohama, Japan, pp. 1537-1544, 1993.

61. G. Ferreti, G. Magnani, P. Rocco, F. Ceccolleo and G. Rossetti, “Impedance control for industrial robot”, IEEE Int. Conference on Robotics and Automation, San Francisco, CA, pp. 4027-4032, 2000.

62. S. Chiaverini and B. Siciliano, “A survey of robot interaction control schemes with experimental comparison”, IEEE Trans. on Mechatronics, vol. 3, No .4, pp. 701-710, 1999.

63. J. Park. “Control Strategies for Robots in Contact“. PhD thesis, Stanford University, 2006.

64. Z. Doulgeri, Y. Karayiannidis, “Force/Position Tracking of a Robot in Compliant Contact with Unknown Stiffness and Surface Kinematics“, *Proc. of Int. Conference on Robotics and Automation*, ICRA 2007, pp. 4190 4195, Roma 2007.

65. Tsoukkas. Fuzzy-logic based vibration suppression control experiments on active structures. In: Proceedings of the 8th VPI-SU symposium on dynamics and control of large structures; 1991.

66. Yan G, Zhou LL. Integrated fuzzy logic and genetic algorithms for multi-objective control of structures using MR dampers. J Sound Vib 2006;296(1–2):368–82.

67. Sharma M, Singh S, Sachdeva B. Fuzzy logic based modal space control of a cantilevered beam instrumented with piezoelectric patches. Smart Mater Struct 2005;14(5):1017.

68. Teng TL, Peng CP, Chuang C. A study on the application of fuzzy theory to structural active control. Comput Meth Appl Mech Eng 2000;189(2):439–48.

69. 9(2):439–48.

70. Zeinoun I, Khorrami F. An adaptive control scheme based on fuzzy logic and its application to smart structures. Smart Mater Struct 1994;3:266–76.

71. Kwak M, Sciulli D. Fuzzy-logic based vibration suppression control experiments on active structures. J Sound Vib 1996;191(1):15–28.

72. Lin J. A vibration absorber of smart structures using adaptive networks in hierarchical fuzzy control. J Sound Vib 2005;287(4–5):683–705.

73. Lin J. An active vibration absorber of smart panel by using a decomposed parallel fuzzy control structure. Eng Appl Artif Intell 2005;18(8):985–98.

74. Malhis M, Gaudiller L, Der Hagopian J. Fuzzy modal active control of flexible structures. J Vib Control 2005;11(1):67.

75. Vishik, M. J., and Fursikov, A. V. (1988) Mathematical Problems in Statistical Hydromechanics, Kluwer Academic Publ., Boston

76. Da Prato, G., and Debussche, A. (2008). On the martingale problem associated to the 2D and 3D Stochastic Navier-Stokes equations. Preprint, at http://arxiv.org/abs/0805.1906 .

77. Kuppiainen, A. (2000) Statistical theories of turbulence; Lecture Notes Random Media 2000, Madralin.