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DESIGN, SIMULATION AND CONTROL OF A TENDON DRIVEN ROBOTIC ARM

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Master's Thesis

Supervisor

Asst. Prof. Dr. Serdar AY

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The thesis titled DESIGN, SIMULATION AND CONTROL OF A TENDON DRIVEN ROBOTIC ARM prepared by HUSSAM HAKIM and submitted on 24/11/2023 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Hussam Saleh Hakim HAKIM

Signature

DEDICATION

I dedicate this research to my beloved parents, wife, and children. They were always supporting me in every way they can. They were always trying their best to create a suitable environment and motivational atmosphere that played a great role in helping me achieve my research goals and do my research work to the highest quality and proficiency possible. I would like to dedicate it to the field of robotic arms and to all individuals around the world who are struggling to live with an amputated limb.

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ABSTRACT

DESIGN, SIMULATION AND CONTROL OF A TENDON DRIVEN ROBOTIC ARM

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Over the latest years, additional research and development efforts have been adopted to model and mimic human body motion, such as human arms and legs. These parts are featured with their higher accuracy and complication. Traditional approaches and conventional methods are employed to address and describe human motion, which may fail because of the complexity of human movement. In this context, numerical approaches are implemented to describe the motion and beneficial function of robots using tendons to perform some torsion, compression, and tension tasks. A tendon-driven robotic arm is a novel example of exploiting complex functions in human organs to perform beneficial and active tasks that can reduce the significant level of effort, time, and cost in various applications such as the automotive industry, manufacturing and production lines, and challenging construction activities. In this study, 3DOF modelling and simulations are conducted using SOLIDWORK software to investigate and locate remarkable parameters that substantially impact the tendon-driven robotic arm's performance and functionality of motion to perform tasks efficiently. The results of the numerical analysis revealed that the design and control of a tendon-driven robotic arm can significantly impact its performance and efficiency in performing tasks. The simulation results indicate that the selection of appropriate materials for the tendon, the geometric design of the arm, and the control strategy are the primary factors affecting the arm's performance.

Keywords: Robotics, Tendon-Driven Robotic Arm, Simulation, Numerical Analysis, ANN.

TABLE OF CONTENTS

Pages

LIST OF TABLES

Pages

LIST OF FIGURES

Pages

ABBREVIATIONS

DOF	:	Degree of Freedom
FBD	:	Free Body Diagram
PID	:	Proportional Integral Derivative Controller
TDR	:	Tendon Driven Robot
CRs	:	Continuum Robots
FDM	:	Fused Deposition Modelling
ANN	:	Artificial Neural Networks

LIST OF SYMBOLS

Ө	:	Angular Velocity
θ_m	:	The Angular Position of Motor
θ_L	:	Angular Position of the Link
n	:	Gear Ratio
ӨD	:	Different Input Angle

1. INTRODUCTION

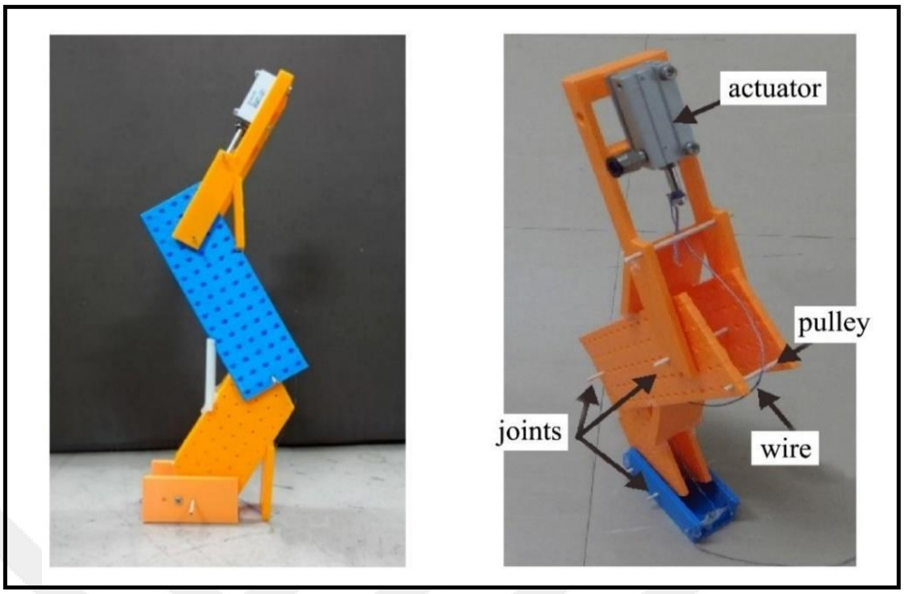
1.1 RESEARCH BACKGROUND

Robotics research has been broadly expanded worldwide, leading to significant improvements and development in the working principles of robotics and remarkable enhancements in their accuracy and performance [1] , [2]. Besides, the research and development efforts dedicated by several scholars and students globally led to considerable elaborations and amendments in the reliability, functionality, and operation of different robotic systems. Robotics is an innovative engineering field characterized by its great benefits and advantages for various engineering applications. Robotics can be employed to perform other complex tasks that a human cannot efficiently execute. These tasks include lifting heavy materials, working on dangerous sites, operating under severe and challenging weather conditions, such as snow and rain, and working with toxic chemical substances and harmful conditions for workers. Furthermore, robots are significantly functional and beneficial for doing repetitive tasks and long-duration jobs in automotive and aircraft factories, manufacturing different large-scale products, and other medical purposes[3], [4].

Robots can provide higher levels of accuracy and effectiveness for longer-term operations. Robots can also be employed in construction where various complex activities and workflow are implemented. They can perform advantageous jobs for construction engineers and builders and various construction activities that may be hard for laborers to do. Therefore, employing robotic systems can offer some critical benefits and substantial interests to engineers and other people, including their functional role in cutting down much time, cost, and effort to do tasks, eliminating dangerous jobs for workers, and achieving a higher rate of productivity and outputs in different industries[5], [6].

A tendon-driven mechanical arm can be portrayed as a mechanical plan on an arm that depends on the business of ligaments, mimicking those used in human organs to perform cyclic activities or repetitive jobs, which can be challenging to achieve by labors and humans. Significant applications of tendon-driven robotic arms include their utilization in production lines, manufacturing processes, industrial activities, construction activities associated with cyclic and repetitive tasks, and the automotive industry[7], [8].

Figure 1.1 illustrates a configuration of the side view and a prototype of the tendon-driven robotic arm.



(A) The Side views of the prototype (B) The front view prototype

Figure 1.1: A Tendon Driven Robotic Arm [9].

Further, Figure 1.2 represents the design, analysis, and free-body diagram inspection of the tendon-driven robotic arm shown in Figure 1.1.

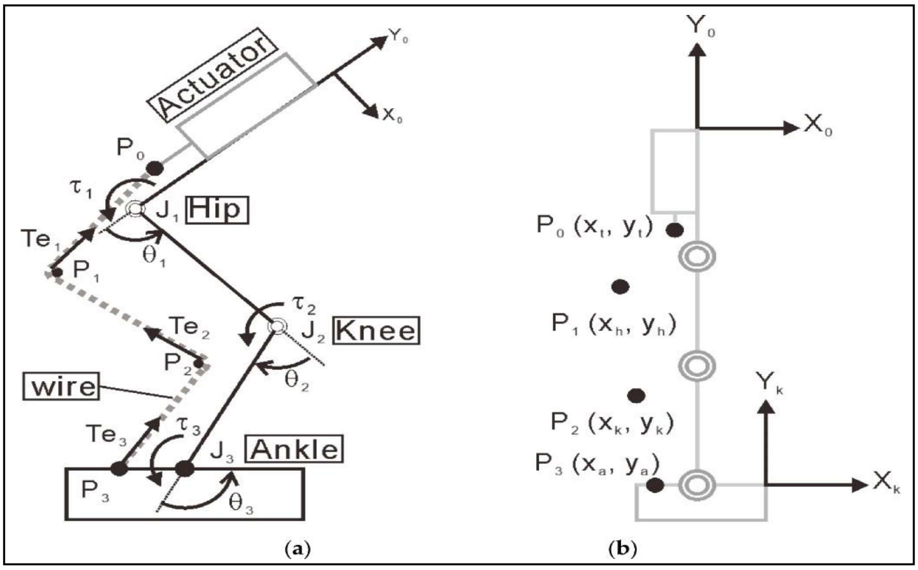


Figure 1.2: Design, Analysis, and FBD Inspection of the Tendon-Driven Robotic Arm [9].

1.2 PROBLEM STATEMENT

Through recent years, various research and development (R&D) efforts are adopted and dedicated to modelling and mimicking the human body motion, such as human arms and legs, characterized by significant levels of accuracy and complication[9], [10]. Traditional approaches and conventional methods employed to address and describe human motion may fail because of the considerable degree of complexity related to human movement. Furthermore, tendons used in the human body and robots are necessary to performing tasks relying on torsion, compression, and tension [11], [2] . Various scientists explored the employment of the tendon-driven robotic arm to execute several activities and tasks according to tension, compression, and torsion measurements and assessments [12] , [13].

Various modelling methods and numerical analysis techniques are implemented and adopted to model and analyze the tendon-driven robotic arm. Only recently, adequate and practical tendon-driven robotic arm modelling strategies have been used to address and describe human motion with higher accuracy and performance. This study investigates the critical part of a tendon-driven robotic arm in performing specific construction tasks reflected in their cyclic motion and repetitive kind to cut off multiple levels of effort, time, and cost required by labors and humans to do the same tasks. This robotic arm is examined with the help of the SOLIDWORK software package depending on 3DOF modelling and the Simulink environment to classify and determine significant parameters that substantially impact the tendon-driven robotic arm's performance and functionality in specific cyclic construction activities.

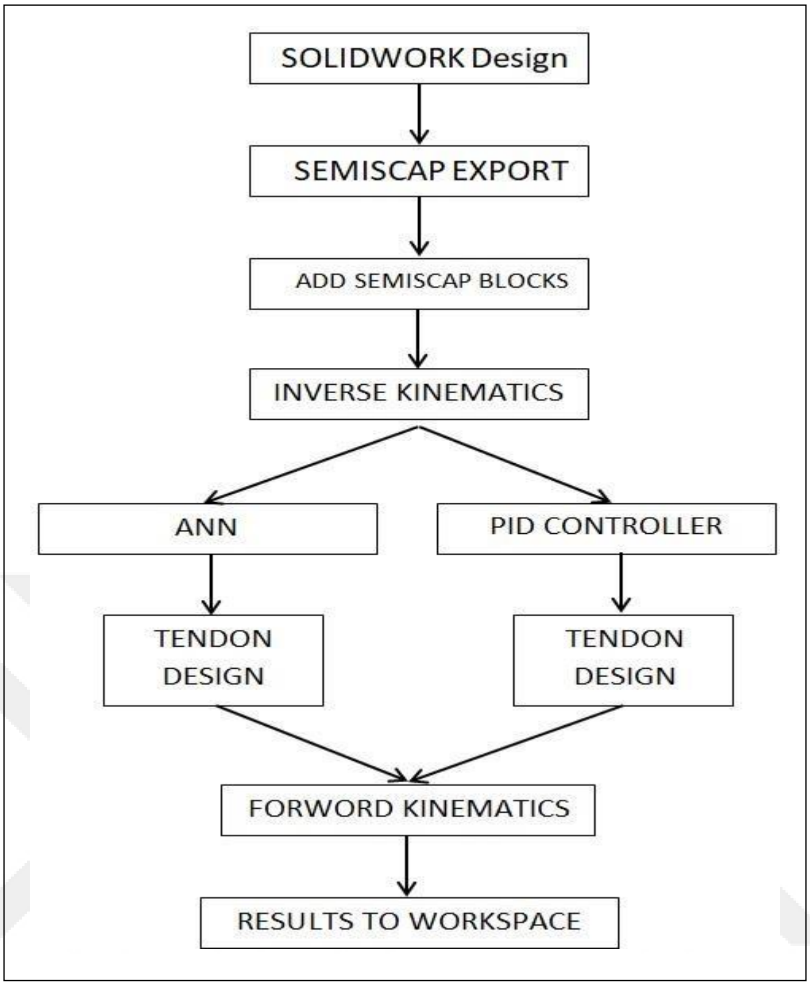


Figure 1.3: Flowchart of the Study.

1.3 RESEARCH SIGNIFICANCE

This research comes with a group of vital relevancies. It consists of methodological, theoretical, and practical relevancies. The methodological relevance of this work is reflected in its contributions and critical benefits in providing 3DOF simulating, numerical analysis, and mathematical simulations with the help of the SOLIDWORK software tool to examine and investigate the performance of the tendon-driven robotic arm depending on some defined boundary conditions and constraints.

In addition, the methodological importance of this research is mirrored by offering extra knowledge and remarkable information for researchers and students that explains the significance of numerical simulation principles and 3DOF simulating importance using SOLIDWORK software. Also, a few academic research publications and peer-reviewed articles address the analysis and examination of the performance of the tendon-driven robotic arm.

At the same time, the theoretical relevance of this research is evident by the importance of the literature review in chapter two in enriching the content and literature of the global web journals with critical knowledge and useful ideas related to the use of tendon-driven robotic arms and their use in various engineering applications. Moreover, there are few studies in the literature that address the critical role of tendon-driven robotic arms and their use in various engineering disciplines. Moreover, the practical significance of this study is to provide important results and research findings necessary for engineers and scientists to improve the performance and efficiency of tendon driven robotic arm [14], [15].

1.4 RESEARCH STATEMENT

The title of this research is "*Design, Simulation, and Control of a Tendon-Driven Robotic Arm*". This research is executed to investigate and identify the critical factors and significant variables that affect the tendon-driven robotic arm's functionality, efficiency, and performance using MATLAB software and the Simulink environment for specific cyclic construction activities.

1.5 RESEARCH ORGANIZATION

a. Introduction provided vital details on the research background, problem statement, work significance, research objectives, research questions, and. Following the architecture of this thesis and its organization can be explained in the following paragraphs:
b. Literature review it is representing the literature review and previous research, collecting secondary data from various academic publications and peer-reviewed research articles to address and examine the critical characteristics and features of the tendon-driven robotic arm and illustrate its role in performing several vital activities in various engineering applications.
c. Methodology it is describing the research method, significant steps, procedures adopted and implemented to perform this research. Additionally, this chapter describes major parameters determined and identified to investigate the tendon-driven robotic arm numerically via the SOLIDWORK software package and Simulink environment.

d. Results and discussions explain and shows the main research findings from the numerical analysis using SOLIDWORK software. Furthermore, this chapter represents the discussions, relating the results of this work to other scholars' outputs.
e. Conclusions and recommendation describe the main study's conclusions based on the findings obtained.

2. LITERATURE REVIEW

2.1 MAJOR APPLICATIONS AND CHARACTERISTICS

Analyzing the motor-joint routing matrix to ascertain the tendon routing between the joints and the motors, it was possible to classify and evaluate fully actuated joint modules with two and three degrees of freedom.

The (2M2D) modules, having the same motor-joint routing matrix configuration, have been sorted into four different types in accordance with the motor placement: hybrid-actuated, externally actuated, internally separately actuated, and internally coaxially actuated.

On the basis of the four different types of the motor-joint routing matrix, (3M3DOF) modules are broken down into four distinct categories:

a completely routed motor-joint, a 3-unrouted motor-joint, a 2-unrouted motor-joint, and a a. unrouted motor-joint.

Studies of the 2M2D and 3M3D coupled tendon-driven joint modules are conducted to identify the connection between joint torque and motor torque. To demonstrate the value of the proposed joint modules, a seven-degrees-of-freedom (7DOF) anthropomorphic robot arm was created using two 2M2D modules for the elbow joint and one 3M3D module for the shoulder joint and wrist joint, respectively.

The arm of a mass of 2.2 kilograms and had the capacity to lift a load of 1.5 kilograms when extended to its full length.

The researcher's analysis showed that employing tendon-driven robotic arms on anthropomorphic robots has the potential to assist in boosting both their performance and their efficacy. Additionally, making use of a tendon-driven robotic arm can make it easier to carry out a variety of beneficial jobs and active tasks, having increased precision and efficiency. In addition, the performance of the robot arm was tested in a manipulation master-slave experiment featuring dexterous motions. Both the current consumption experiment and the position accuracy experiment were conducted to assess the properties of the joint modules. Conducted research exploring critical tendon-driven robotic arms' beneficial uses and vital features to provide higher durability and safety for various engineering applications [17]. In order to investigate the performance, simulations and static force analysis were carried out. According to the findings of the researchers, anthropomorphic robotic arms have been garnering a growing amount of interest due to the fact that they are human-friendly and possess the same dimensions and movement characteristics as human arms.

A study led assessing the advantageous benefits of Tendon-driven Robotic Arms for some engineering applications [18]. They reported that new forms of wearable robots known as supernumerary robotic limbs (SRL) are being developed to function alongside humans as additional limbs. The functionality of the wearer's supplementary abilities will be improved as a result of the gadget. Hence, through their study, the design and implementation of lightweight, compact, and multi-assistive for wearers are presented.

The scholars conducted in which an investigation into the usage of proprioceptive sensors in soft continuum robots inspired by elephant trunks was carried out. Following the introduction of the fundamentals of this project, the author executed a comprehensive review through which a discussion and illustration of soft continuum robots and tendon-robotic arms were taken into account. Stretch sensors that are readily available on the market were utilized in this study. These sensors are rubber strands that have been treated with carbon black. The planning and execution of the robot's construction are broken down here. A method of calibration that makes use of the features of the material was devised in order to make the sensor more consistent. After that, both an open-loop experiment and a closed-loop experiment are performed on the robot. The findings from those experiments revealed that using a tendon-driven robotic arm to do some vital tasks and perform activities with higher performance and efficiency. However, the degrees of accuracy, performance, and durability for carrying out the identical activities have significantly increased when the sensors were integrated into this robotic arm. Thus, it can be concluded from this research that adding sensors to tendon-driven robotic arms can significantly improve the way these robots function and are accurate when doing useful tasks. The study used pneumatic principles to investigate the inherent correlations and usefulness of a string-driven robotic arm for carrying out tasks that need actuating or actuating actuators. [19].

The analysts detailed that it is by and large accepted that the steadfastness of delicate mechanical frameworks is the obstruction that anticipates their full selection. Most strikingly, weakness disappointment issues are a major concern. Subsequently, unwavering quality and constancy ought to be taken into consideration from the exceptionally begin of the improvement prepare. Be that as it may, so distant, no endeavors have been made to test the constancy and constancy of delicate mechanical machines based on a systematic approach. Since delicate robot structures are built with delicate fabric constituents, unwavering quality is regularly the beat need when utilizing delicate robots for force exchange applications. This can be due to the surprising nonlinear properties of delicate materials, which result from expansive disseminations in fabric properties. The unwavering quality ought to too be assessed from the robot framework to the components utilizing space information related to the robot gadget. Hence, this information requires a precise approach.

The researchers decided to conduct this study in order to develop a framework for soft robotic device reliability analysis. The framework takes into account the probability distribution which has not been extensively studied in previous research. The case study analyzes a tendon driven soft robot. The study focused mainly on process a (idea design), process b (lifetime analysis), and process c (optimization and design). The researchers developed a life model taking into account distribution using accelerated life testing. The life model was derived from an investigation of failure criteria related to the tendon driven design. During the experiment the tensile stress of the wire was changed by changing the bend angle as well as the output tension.

The results of the investigate recommended that utilizing cautious plan and recreation displaying made a difference to optimize the unwavering quality and execution of delicate mechanical technology, which utilize tendon-driven mechanical arms. This was finished by utilizing cautious plan and reenactment demonstrating. In expansion, the comes about were approved by applying changing sums of stretch to a test bed that was outlined to imitate the conditions of an genuine application. The unwavering quality examination methodology that was proposed can be connected to other delicate automated frameworks, such as pneumatic actuators, in arrange to make strides the reliability-related properties amid the robot plan arrange. Also, the life demonstrate might be utilized to gauge the device's lifetime beneath a assortment of diverse push conditions. The analysts conducted an examination exploring the advantageous part of the tendon-driven mechanical arm, taking into thought an ideal assessment of the joint point [20].

The findings of the researchers indicated that their proposed approach could be actively employed in wearable robot applications. This verification was accomplished by applying the proposed method to a particular robot. In addition to this, it was discovered that the work that they did result in a revolutionary wearable robot that was given the name Exo-Index. This robot supported a human's index finger by making use of three actuators. As a consequence of this, the identification methods that they suggested enable control of the wearable robot to result in acceptable postures for grabbing things of various shapes and sizes. Guided a study investigating the beneficial role of effective tendon-driven robotic arm design and modelling in performing different activities accurately [21]. The scholars designed, fabricated, and tested a tendon-driven robotic arm that is related to a continuum soft robot having 3 modular segments. Each of these segments has a tunable stiffness that is enabled using layer jamming technology. Their research was undertaken in order to accomplish these goals. The robotic arm design of their study has a modular structure, which means that the length of the robotic arm may be altered by adding new arm segments or modules to the present robotic prototype. This is in contrast to the designs of robotic arms that were used in earlier studies. In addition to this, the novel arm prototyping model is capable of motion inside a space that is three-dimensional.

The design and manufacturing of a variable-stiffness robotic arm with a compliant primary structure and a layer-jamming mechanism have both been completed so that the researchers can reach the objectives of their investigation. Additionally, the design and manufacture of the connection that will be used to combine numerous link modules into a single multi-segmented robotic arm have both been completed. The actuator that can be found at the end related to the arm has been previously formulated and put through its paces in terms of testing. In the end, a stiffness test was performed on one arm segment in order to verify the load-carrying capacity of the variable stiffness robotic arm. Followed by the stiffness ratio associated with the layer-jammed structure was estimated in order to analyze the improvement in stiffness when compared with an unstiffened soft robot. According to the findings of their research, taking into account these crucial parameters - such as the stiffness ratio, layer jamming mechanism, and load carrying capacity—during the design and fabrication of a tendon-driven robotic arm plays a significant part in improving the tendon-driven robotic arm's overall performance and effectiveness. Led research examining the design and analysis of a tendon-driven robotic arm that mimics the motion and design of human fingers to make practical tasks of grasping[22]. According to what they found, the human hand is capable of performing a variety of grasping and manipulation activities, and it is considered to be one of the most ingenious and varied effectors that are currently known.

These tests initially focused on determining different functionalities related to the sensors, including the sensors of the force that were designated as FSRs. In the following lesson, the gripper's potential to secure things was put to the test by means of the manipulation of a wide variety of items. The findings from a considerable degree of dexterity were observed in the practical testing related to the tendon-driven robotic gripper. The findings based on the conclusions indicated that the adaptability of the system could be ensured by the utilization of various mechanical components. In addition to this, it was discovered that the gripping processes could be controlled by utilizing the sensor system in some fashion. However, the data also demonstrated that the majority of the system's power is lost due to friction that occurs in the system itself. Carried out a study analyzing and assessing the design and major characteristics of tendon-driven robotic arms in performing vital and beneficial tasks[23]. They mentioned that continuum robots could be featured with their small size compared with other types of robots. In addition, these robots could exhibit nonlinear geometries with many curves and are flexible and compliant. Continuum robots are flexible and compliant. Particularly, tendon-driven and concentric-tube continuum robots are able to be developed on a small scale with diameters that are less than 10 millimeters. These robots can be inserted through narrow entrance sites because they have a small diameter in comparison to their length. This allows them to reach areas that are difficult to reach by avoiding impediments. This kind of circumstance frequently arises in technically oriented inspections and minimally invasive surgical procedures. However, in order to get to the desired location, it is frequently necessary to carry out the deployment over a winding and congested route. Conventional tendon-driven continuum robots are inherently unable to perform such deployment, whereas concentric-tube continuum robots need specific path conditions and rigorous parameter adjustment in order to function properly. Other types of robots that have been proposed, including pneumatically actuated and hyper-redundant robots, have diameter-to-length ratios that are less desirable and, as a result, are not suitable for the jobs in question. They presented a revolutionary tendon-driven continuum robot design, since the limiting limitations are identified in the design of continuum robots.

Tendon-driven robotic arms have gained significant attention in recent years due to their ability to achieve high precision and accuracy in various applications. Several studies have focused on the design, simulation, and control of tendon-driven robotic arms to optimize their performance and enable them to perform complex tasks.

Designed and developed a tendon-driven robotic arm was for industrial automation applications, the authors focused on optimizing the mechanical design of the robotic arm, including the tendon routing and actuation mechanism, to achieve high precision and accuracy, they demonstrated the effectiveness of the proposed design by conducting experiments on a prototype of the robotic arm[24].

The proposed design and control algorithms simulation has been developed and validate for a tendon-driven robotic arm, the authors used a virtual reality simulator to simulate the motion of the robotic arm and evaluate its performance in various tasks, they demonstrated the effectiveness of the simulation environment in validating the proposed design and control algorithms [25].

The authors used a combination of motion planning and force control techniques to achieve the desired performance [26]. They demonstrated the effectiveness of the proposed control algorithm by conducting experiments on a prototype of the robotic arm.

The characteristics of tendon-driven robotic arms include the following features.

a. High precision and accuracy: Tendon-driven robotic arms have high precision and accuracy in their movements, which enables them to perform complex tasks with minimal error.
b. High compliance: Tendon-driven robotic arms have high compliance, which allows them to operate safely in environments with humans or delicate objects.
c. Lightweight and compact: Tendon-driven robotic arms are lightweight and compact, which enables them to operate in tight spaces and perform tasks that require high mobility.
d. High dexterity: Tendon-driven robotic arms have high dexterity, which enables them to perform complex tasks with multiple degrees of freedom.
e. Low power consumption: Tendon-driven robotic arms have low power consumption, which enables them to operate for longer periods of time without requiring frequent battery changes or recharging.

Overall, tendon-driven robotic arms are a promising technology for various applications due to their high precision, accuracy, compliance, and dexterity.

This chapter represents a comprehensive review through which recent previous research and peer-reviewed articles from various secondary data resources are discussed and reviewed to address and examine the essential characteristics and features of the tendon-driven robotic arm. Further, chapter two illustrates various beneficial roles and critical aspects of the tendon-driven robotic arm in performing several activities that are vital to the operation of a number of diverse engineering applications.

2.2 SIMULATION, MODELING AND NUMERICAL ANALYSIS

According to what the researchers reported and studied, the tendon-driven robot, also known as TDR, is a continuum robot which is utilized to obtain minimally invasive surgeries (MISs), in particular laparoscopic procedures (LSs). They went on to say that the number of TDR segments can differentiate between the various types of TDR. It was found that there is a clear correlation between the number of segments that make up a system and the degree of difficulty of its closed-form reverse kinematics. The more sections that make up a system, the more difficult it is to understand fully. In order to construct the inverse kinematic of the TDR, an intelligent training strategy that is according to an adaptive neuro-fuzzy inference system (ANFIS) could be offered as a solution. During the process of tracking a path in the workspace, an additional computer simulation program is utilized in order to validate the ANFIS inverse kinematic solution of the TDR and make a comparison with the closed-form solution associated with inverse kinematics. The results of the numerical modelling, simulation analysis, and theoretical inverse kinematics investigations showed good path tracking and the possibility of using the ANFIS inverse kinematics solution in place of the closed-form solution. Additionally, the results showed that the ANFIS inverse kinematics solution could be used. In addition to this, it was discovered that the greatest mean error in all three axes based on the ANFIS inverse kinematics solution is 0.6135 mm. This was determined by using the ANFIS software. The researchers led an analysis investigating the performance and efficiency of tendon-driven continuum robots in performing some advantageous tasks [28]. Additionally, as a methodology of their (researchers) research, a MATLAB code package that simulates the dynamic behavior of these robots was developed. Researchers have access to a valuable and condensed resource in the form of the approach and codes that are described here, which may be used to advance the development of tendon-driven continuum robots. In addition, the results of their study served as a guide to the process of dynamically modelling continuum robots. They mentioned that in recent years, the popularity of continuum robots, often known as CRs, has increased thanks to their flexible backbone structures. The researchers made modelling and control of CRs, providing the impetus for developing dynamic models that are accurate and efficient. Simulation of dynamic behavior, advancements in structural design, and the creation of dynamics-based control systems for CRs are critical aspects that will be made possible by such models. The Cosserat rod-based modelling of tendon-driven CRs is utilized as the basis for the modelling methodologies that are addressed in their work. This modelling methodology is employed as a unified underlying approach. In addition to the traditional continuum robot assemblies, they take into consideration the novel and developing robot assemblies, such as the tendon-bent concentric tube and the cooperative robots. First, a summary of the governing equations of motion for conventional CRs was presented, and then these equations were extended to include tendon-driven CRs. Also, their (the researchers) research outputs indicated that the tendon-driven robotic arm investigated in their work had accomplished different beneficial tasks and critical activities, offering active flexibility and significant motion performance. Executed research examining the effectiveness and reliability of tendon-driven continuum robots [29].

The researchers used modelling, simulation, and numerical analysis to achieve their research goal. The scholars stated that continuous deformations could be achieved by tendon-driven continuum robots thanks to the contraction of tendons that are incorporated within the robotic arms. The fixed curvature related to the assumption-based kinematic model has the potential to be accurate and useful for the analysis of certain continuum robots. The assumption of constant curvature may not be valid in certain circumstances, such as when it comes to soft robotics or interactions between robots and their environments. The exact beam geometric theory, which may also be referred to as the Cosserat rod theory, has been used to construct computational mechanics models, which have been utilized to describe the complicated deformation of continuum robots. Unlike the preceding computational models, which made use of finite difference techniques for spatial discretization, this model takes a different approach. Additionally, a three-dimensional geometrically precise beam theory depending on the finite element analysis and modelling principles was considered and developed associated with tendon-driven continuum robots. It was found through the use of a number of numerical examples, it was found that our recently developed numerical model related to tendon-driven continuum robots is accurate, efficient, and applicable. Also, they determined that employing modelling, simulation, and numerical analysis may provide essential data and significant features associated with the performance and efficacy of tendon-driven robotic arms and continuum robots. This was something that they found out via their research. In addition, it was shown that tendon-driven robotic arms and continuum robots provide a useful, effective, and accurate performance of motions that demand a greater level of accuracy and effectiveness to carry out certain essential functions. Conducted research work analyzing tendon-driven continuum robots' performance and functionality with the help of simulations, modelling, and numerical analysis[30].

The researchers developed the first ever reliable control related to tendon-driven continuum robots, which are modelled using the Cosserat rod theory. Continuous robots are characterized by their high level of nonlinearity and complexity. Those robots were formed from deformable and elastic backbones. The majority of the existing control strategies get around this issue by making presumptions around the structure of the robot in an effort to construct models that are accurate and can be used in real-time control applications. The performance that can be expected from robots is hindered when such approaches are utilized because maintaining the relevant modelling assumptions is required. They overcame the disadvantages by employing a dynamic model based on the Cosserat Rod that did not consist of these constraints and was able to account for the general deformations of the backbone. Due to the high amount of computational effort required to simulate this broad model for usage in real-time control applications, it has never been utilized in the design of robust control systems before. The results indicated that these simulation models, that considered real-time control uses, were successful in resolving the problem of time-consuming computing by making use of a complex numerical approach that is recognized as the Generalized- Method. Sliding mode control was utilized in the development of the robust controller that was used for the control mechanism. Control input saturations were taken into consideration during the design phase so that sudden shifts in the actuating tension could be avoided. Examples taken from simulations were incorporated into the document in order to validate the efficiency related to their suggested design approach. Published a manuscript investigating the performance and effectiveness of tendon-driven manipulative continuum robots[31]. Their research provided a broad framework related to the dynamic and numerical analysis, modelling, and simulations associated with tendon-driven co-manipulative continuum robots working with flexible objects. Because of this, the bending of the arms has been used to give the actuations. In addition, the goal of their research was to create a model of their tendon-driven arm in the form of a flexible rod. This would allow them to take into consideration the flexibility of the object inside the coupled dynamic characteristics related to the robot. In order to take into consideration significant deflections, a summary of the equations of motion was developed according to Cosserat-rod model process related to the item and the arms. For the purpose of solving the equations of motion and determining the dynamic response, a numerical solution approach was created. The experiments provided confirmation that the numerical findings were accurate. Also, based on the findings, it was determined that the algorithm that was presented possesses a significant amount of potential related to the dynamic model associated with the cooperative continuum robot. The coupled flexibility of the arms and object has inescapable impacts on the dynamic response of the robot and should be incorporated for purposes of analysis and identification, even though the incorporation of the object flexibility would elevate the model's complexity. Conducted a numerical analysis investigating the performance of a tendon-driven robot[32]. Utilizing the Green-Lagrange strain and establishing analytical formulas for the fluctuation of the equivalent value of Young modulus associated with the configuration because of the big strains were both necessary steps in order to successfully capture the behaviors associated with large strains. Regarding either the compression or the stretching of the structure, there were no assumptions made that were meant to simplify the situation. Additionally, a range of diverse application scenarios were found and defined as a result of the research, and an iterative strategy was recommended in relation The structure of the equations they discovered was complex and not straightforward. A soft arm segment with tendons was used in an experiment to test the accuracy of the model. This soft arm part has bendy and stretchy rubbery material added to its structure. Performed a thorough analysis to study the concept and design process for a new type of pulley. This pulley can change its size depending on the amount of force applied to it by a robotic system. It does this by using a belt-driven system. This was done as part of a robotic joint that was moved by the tendon. They believe that when a force is applied to the wheel, the part of the wheel that is used expands because of a special piece and a flexible piece. This idea is the foundation for their design of the mechanism. The size of the pulley in a transmission determines how fast it can go and how much power it can transfer. Researchers discovered that a transmission system using a belt and pulley with a fixed size has a set limit to its top speed and power. On the other hand, a pulley that can change size allows for the torque and speed to adjust, which makes the driving more efficient. In addition, the researchers conducted a study on a new pulley system and explained how it works. Using a robotic joint controlled by tendons has the potential to improve how well it works and how efficient it is when used with a new type of pulley that can change its size. This was shown by using computer simulations and doing experiments to study how the joint and pulley would work together. Furthermore, if we add a tendon-driven robotic joint to the pulley system, it can enhance its performance. This means it will be able to do many helpful tasks more reliably and accurately. Furthermore, the results showed that the variable-radius pulley, which the scientists created, can be used to change the transmission percentage based on the amount of torque applied to the robot joint. I helped with a research project that looked at how well a robotic arm that relies on tendons to move performs [34].

The researchers reported that continuum robotic arms have several advantages over conventional manipulators, which motivates them to continue researching in this sector. The modelling and control of these systems' dynamics are tough endeavors because of the complex nonlinearities and uncertainties that are present in the system. As a result, in their research, they constructed a three-dimensional system based on dynamics modelling related to such manipulators by using an appropriate system identification approach. This model is validated by experimental data, and after that, it is utilized in the construction of a PID-fuzzy controller. When it comes to managing the location linked to the end-effector, this strategy is known as a model-free controller because it does not require an exact model of the system. Following that, an analysis was done to determine how well different spots within the workspace could be reached. The research study outcomes of the indicated that using a tendon-driven arm on a continuum robot would make it easier to complete a variety of useful and productive tasks, as well as boost the performance and efficiency of the continuum robots. Incorporating a tendon-driven robotic arm into one of these machines would help make it possible for it to do a wider range of tasks more effectively and with greater flexibility. Carried out an analysis investigating the critical role of modeming, simulations, and numerical analysis to enhance the performance of a parallel tendon-driven continuum robot [35]. Additionally, they (researchers) compared the assumptions made by pseudo-stiff bodies to those made by conventional rigid parallel robots. On the basis of these constraint criteria, the Jacobian matrices and speed equations for this type of parallel continuum robots were derived. These conditions were calculated for the legs of the robot. Also, the matrices were then utilized further for inverse kinematic analysis as well as singularity research, for which they were built, developed, and changed. Under the premise of a pseudo-rigid body, static models of both the robot and every continuum link was generated and analyzed. The research simulation scheme was shown as a final step in the process of validating the kinematic models. It has been demonstrated that singularities can be located by employing Grossmann line geometry or by identifying the numerical quantities related to three performance indices. Doing any of these things results in increased levels of accuracy, performance, and dependability. Executed research examining the performance and effectiveness of a tendon-driven robot gripper considering a passively switchable ineffective surface [36]. The scholars took into account some research steps, including physics-based simulation depending on a tendon-driven robotic arm’s parameter optimization. In addition to its capability as a normal parallel gripper, they suggested developing a gripper with a single actuator that is capable of lifting thin objects that are lying on a smooth surface. The most crucial data includes a crawler located on the fingertip. This crawler, along with the other finger joints, is under actuated, and the mechanism that switches it is a passive one that is spring-loaded. Even though the concept of a finger that can crawl is not new, the study that they conducted helped significantly to the realization that a finger can crawl without the need for an additional motor. Depending on the condition of the gripping, the parallel approach mode, the pull-in mode, and finally the power grab mode can all be automatically switched between by the gripper. They optimized the severely underactuated device by combining black-box optimization with a physics-based simulation technique pertaining to the full grip operation. They were better able to comprehend how to make it better as a result. The researchers went on to show that the simulation-based technique had produced results that were capable of properly accounting for failure mode, power grab stability, in-hand manipulation, and pre-contact motion. This is something that is difficult to do using approaches that are based on static equilibrium analysis. The researchers showed that their prototype gripper with the suggested configuration and design variables has successfully been optimized under their suggested procedure and effectively power-grasped a thin sheet, a cylinder lying on a flat surface, and a softcover book. These steps were the final element of their effort.

2.3 COMPARISON WITH LITERATURE WORKS

Tendon-driven robotic arms have gained significant attention in recent years due to their potential to enhance the functionality and dexterity of robotic systems [37].

Unlike conventional robotic arms that rely on electric motors, tendon-driven robotic arms use cables or tendons to transmit force and motion, making them more lightweight and efficient [38].

The modified design also allows for greater flexibility and maneuverability, making it well suited for a wide range of applications such as surgical assistance, rehabilitation, and industrial automation [39].

The use of simulation using MATLAB has been a common approach in the design and control of tendon-driven robotic arms [40].

Many researchers have explored the use of simulation to design and control these robotic systems in different ways, resulting in a broad range of findings and arguments in the literature ([39]; [37]; [38]).

One common approach in the literature is to use simulation to optimize the design of the robotic arm [38]. This involves using MATLAB to model the mechanics of the robotic arm and to test different design configurations to determine the optimal parameters that result in the best performance [37]. Researchers have used this approach to optimize the dimensions and materials of the arm, the placement of tendons and actuation points, and other design parameters that affect the overall performance of the system [39]. Another common approach in the literature is to use simulation to develop control algorithms for the robotic arm [2]. Researchers have used MATLAB to model the dynamics of the robotic arm and to test different control algorithms, such as impedance control, admittance control, and model predictive control, to determine the best approach for controlling the arm [38]. Researchers have also used simulation to test the robustness and stability of different control algorithms under different conditions, such as changing load conditions or variations in the environment [39]. A third common approach in the literature is to use simulation to validate experimental results [38]. Researchers have used MATLAB to model the robotic arm and to compare simulation results with experimental results obtained from actual physical prototypes [37]. This has allowed researchers to validate the accuracy of their models and to identify areas for improvement in the design and control of the robotic arm.

In general, the literature provides a comprehensive picture of the current state of research on the design and control of tendon-driven robotic arms using simulation with MATLAB. The studies demonstrate that simulation is a useful tool for optimizing the design of the arm, developing control algorithms, and validating experimental results. However, there is still much room for improvement in the accuracy of simulations and the development of more sophisticated control algorithms, particularly in the areas of real-time control and the handling of large amounts of data [39].

The use of simulation with MATLAB continues to be an important approach in the design and control of tendon-driven robotic arms, and researchers are making steady progress in developing more effective and efficient systems. However, further research is needed to fully realize the potential of these systems, particularly in terms of real-time control and handling of large amounts of data. The design and control of tendon-driven robotic arms, however, present a number of challenges. For example, controlling the tension in the tendons to achieve precise movements and maintaining stability and safety in the system are crucial considerations in the design of these systems. Furthermore, the design must also take into account the interaction between the tendons and the environment, including the presence of obstacles and external loads [38].

Despite the growing interest in tendon-driven robotic arms, there is a need for a comprehensive overview of the current state of research in this field. The aim of this literature review is to examine the existing literature on the topic of tendon-driven robotic arms with a focus on the design and control aspects. The objective is to identify the major trends, gaps, and challenges in the current research and to provide a comprehensive understanding of the field.

In terms of applications, tendon-driven robotic arms have been used in a variety of fields, including manufacturing, healthcare, and search and rescue. For example, in manufacturing, tendon-driven robotic arms have been used to assemble small components with high precision, while in healthcare, they have been used for minimally invasive surgery [38].

It can be concluded from reviewing different peer-reviewed articles and critical research publications that employing tendon-driven robotic arms in various engineering applications, such as continuum robots and other robots, would boost motion performance, transmission effectiveness, and robot movement flexibility. Furthermore, it is concluded from all these research articles that tendon-driven robotic arm employment in diverse robotic applications would enhance the robots' capability to do different critical tasks and perform important activities with higher levels of accuracy and efficiency. Moreover, each research used a distinct research methodology to help authors and scholars effectively achieve their study goals, including Jacobian matrices and speed equations. Also, most authors employed simulations, modeming, and numerical analysis to analyze the critical benefits and relevance of tendon-driven robotic arms.

2.4 LITERATURE REVIEW CRITICAL CONTRIBUTION

Table 2.1: Brief of the Literature Review.

No	Author(s)	Year	Title	Journal/ Conference	Critical Contributions
1	Lahiri, A. [7]	2022	Design, Simulation and Control of a Tendon-Driven Robot Arm	Doctoral dissertation, Rutgers The State University of New Jersey, School of Graduate Studies	The outcomes related to the mathematical simulations, software modeling, and numerical analysis revealed that the experimental model of the tendon-driven arm provided higher accuracy and performance in relation to the tendon-driven robotic arm, which were significant, and that a variety of activities and tasks were successfully carried out using the tendon-driven arm. In addition, it was discovered that the experimental results had been validated by the comparison results that were carried out with the numerical output plots that were the result of MATLAB calculations.

Table 2.1: Brief of the Literature Review " Table Continued".

2	Li, W., Chen, P., Bai, D., Zhu, X., Togo, S., Yokoi, H., & Jiang, Y [16]	2020	Modularization of 2-and 3-DOF coupled tendon-driven joints	IEEE Transactions on Robotics	Their research and analysis showed that employing tendon-driven robotic arms on anthropomorphic robots has the potential to assist in boosting both their performance and their efficacy. Additionally, making use of a tendon-driven robotic arm can make it easier to carry out a variety of beneficial jobs and active tasks, having increased precision and efficiency. In addition, the performance of the robot arm was tested in a manipulation master-slave experiment featuring dexterous motions.
3	Li, W., Chen, P., Jiang, Y., Bai, D., Togo, S., & Yokoi, H [17].	2018	Structure design of a tendon-driven robotic arm considering safety and durability	In 2018 IEEE International Conference on Intelligence and Safety for Robotics (ISR) (pp. 71-76). IEEE.	It was found that the designed robotic arm weighed 2.2 kilograms and had a maximum load capacity of 1.5 kilograms. Also, all of the motors are connected to one another via cables in order to generate high torques while simultaneously reducing the overall weight. The shoulder joint is a three-motor, three-degrees-of-freedom coupled driving structure, whereas the elbow joint and the wrist joint are two-motor, two-degrees-of-freedom coupled driving structures. When designing the structures, safety and durability concerns brought on by the qualities of the wires were taken into consideration.

Table 2.1: Brief of the Literature Review " Table Continued".

4	Sperling, R. [18]	2018	Design of a Tendon-Driven Soft Continuum Robotic Arm Using Proprioceptive Sensors	Master Thesis in the Mechanical Engineering. The University of Rhode Island.	The discoveries from those tests uncovered that employing a tendon-driven mechanical arm to do a few crucial assignments and perform exercises with higher execution and effectiveness. In any case, after joining proprioceptive sensors into this automated arm, the precision, execution, and unwavering quality levels to doing the same assignments were altogether improved. Hence, it can be gathered from this work that sensors' business in tendon-driven mechanical arms might give profitable commitments to the execution and exactness of these robots to do useful exercises.
5	Jeong, U., Kim, K., Kim, S. H., Choi, H., Youn, B. D., & Cho, K. J. [19]	2021	Reliability analysis of a tendon-driven actuation for soft robots	The International Journal of Robotics Research	The results of the investigate recommended that utilizing cautious plan and reenactment modeling made a difference to optimize the unwavering quality and execution of delicate mechanical autonomy, which utilize tendon-driven mechanical arms. This was finished by utilizing cautious plan and recreation modeling. In expansion, the comes about were approved by applying shifting sums of push to a testbed that was outlined to imitate the conditions of an genuine application. The unwavering quality investigation methodology that was proposed might be connected to other delicate automated frameworks, such as pneumatic actuators, in arrange to move forward the reliability highlights amid the robot plan organize. Furthermore, the life demonstrate might be utilized to gauge the device's lifetime beneath variation diverse push conditions.

Table 2.1: Brief of the Literature Review " Table Continued".

6	Kim, B., Ryu, J., & Cho, K. J. [20]	2020	Joint angle estimation of a tendon-driven soft wearable robot through a tension and stroke measurement	Sensors	The findings of their research indicated that their proposed approach could be actively employed in wearable robot applications. This verification was accomplished by applying the proposed method to a particular robot. In addition to this, it was discovered that the work that they did resulted in a revolutionary wearable robot that was given the name Exo-Index. This robot supported a human's index finger by making use of three actuators. As a consequence of this, the identification methods that they suggested enable control of the wearable robot to result in acceptable postures for grabbing things of various shapes and sizes.
7	Ouyang, Z. [21]	2019	Development of a Tendon-Driven Variable Stiffness Continuum Robot with Layer Jamming	arXiv preprint arXiv	According to the findings of their research, taking into account these crucial parameters—such as the stiffness ratio, layer jamming mechanism, and load carrying capacity—during the design and fabrication of a tendon-driven robotic arm plays a significant part in improving the tendon-driven robotic arm's overall performance and effectiveness.
8	Odenkirchen, T. [22]	2021	Robotic manipulator inspired by human fingers based on tendon-driven soft grasping	Doctoral dissertation, Pontificia Universidad Catolica del Peru-CENTRUM Catolica (Peru)	The findings based on the conclusions indicated that the adaptability of the system could be ensured by the utilization of various mechanical components. In addition to this, it was discovered that the gripping processes could be controlled by utilizing the sensor system in some fashion. The data showed that the majority of the system's power is lost due to friction occurring in the system.

Table 2.1: Brief of the Literature Review " Table Continued".

9	Amanov, E., Nguyen, T. D., & Burgner-Kahrs, J. [23]	2021	Tendon-driven continuum robots with extensible sections A model-based evaluation of path-following motions	The International Journal of Robotics Research	It was discovered that the repeatability of their 165-millimeter-long robot prototype was less than 2.38 millimeters. In addition, the findings suggested that the accuracy of the model had improved to a median level of 3.16 percent across 25 different configurations with regard to the length of the robot. In addition, the path-following error was calculated over five different curvilinear courses, and the result was a median error of 2.59% with regard to the length of the robot.
10	Abdel-Nasser, M., & Salah, O. [27]	2020	The inverse kinematics analysis for tendon-driven robot based on an adaptive neuro-fuzzy inference system.	International Computer Engineering Conference (ICENCO)	It was found that there is a clear correlation between the number of segments that make up a system and the degree of difficulty of its closed-form reverse kinematics. The more sections that make up a system, the more difficult it is to understand fully. Also, the results of the numerical modeling, simulation analysis, and theoretical inverse kinematics investigations showed good path tracking and the possibility of using the ANFIS inverse kinematics solution in place of the closed-form solution. Additionally, the results showed that the ANFIS inverse kinematics solution could be used. In addition to this, it was discovered that the greatest mean error in 3 axes based on the ANFIS inverse kinematics solution is 0.6135 mm.

Table 2.1: Brief of the Literature Review " Table Continued".

11	Janabi-Sharifi, F., Jalali, A., & Walker, I. D. [28]	2021	Cosserat rod-based dynamic modeling of tendon-driven continuum robots: A tutorial.	IEEE Access	The results of the study on using Cosserat rods to model tendon-driven Robots are helpful and can be used as a starting point for future modeling methods. Moreover, their approach for studying the functioning and effectiveness of the tendon-controlled robotic arm proved to be successful. Their research showed that the robotic arm they studied was able to do helpful tasks and important activities. It could move flexibly and perform motions really well. They said that their findings could help with creating models of continuum robots.
12	Li, X., Yu, W., Baghaee, M., Cao, C., Chen, D., Liu, J., & Yuan, H. [29]	2022	Geometrically Exact Finite Element Formulation for Tendon-Driven Continuum Robots.	Acta Mechanica Solida Sinica	. It was found through the use of a number of numerical examples that our recently developed numerical model related to tendon-driven continuum robots is accurate, efficient, and applicable. Also, they determined that employing numerical analysis may provide essential data and significant features associated with the performance and efficacy of tendon-driven robotic arms and continuum robots. In addition, it was shown that tendon-driven robotic arms and continuum robots provide an accurate performance of motions that demand a greater level of accuracy and effectiveness to carry out certain essential functions.

Table 2.1: Brief of the Literature Review " Table Continued".

13	Mousa, A., Khoo, S., & Norton, M. [30]	2018	Robust control of tendon driven continuum robots.	International Workshop on Variable Structure Systems	The results indicated that these simulation models, that considered real-time control uses were successful in resolving the problem of time-consuming computing by making use of a complex numerical approach that is recognized as the Generalized- Method." Sliding mode control was utilized in the development of the robust controller that was used for the control mechanism. Control input saturations were taken into consideration during the design phase so that sudden shifts in the actuating tension could be avoided. Examples taken from simulations were incorporated into the document in order to validate the efficiency related to their suggested design approach.
14	Jalali, A., & Janabi-Sharifi, F. [31]	2021	Dynamic Modeling of Tendon-Driven Co-Manipulative Continuum Robots.	IEEE Robotics and Automation Letters	The experiments provided confirmation that the numerical findings were accurate. Also, based on the findings, it was determined that the algorithm that was presented possesses a significant amount of potential related to the dynamic model associated with the cooperative continuum robot. The coupled flexibility of the arms and object has inescapable impacts on the dynamic response of the robot and should be incorporated for purposes of analysis and identification, even though the incorporation of the object's flexibility would elevate the model’s complexity.

Table 2.1: Brief of the Literature Review " Table Continued".

15	Chairopoulos, N. C., Vartholomeos, P., & Papadopoulos, E. [32]	2019	Modeling, Simulation and Experimental Validation of a Tendon-driven Soft-arm Robot Configuration-A Continuum Mechanics Method	IEEE/RSJ International Conference on Intelligent Robots and Systems	Their think about comes about recognized and decided a assortment of different application scenarios and recommended an iterative approach related to the nonlinear numerical arrangement of the framework of coupled differential conditions that was the item of their exertion. The show was approved utilizing an test set-up that comprised of one portion of a tendon-driven delicate arm. This delicate arm section joins compressible and stretchable hyperelastic (or rubber-based)materials into the non-homogeneous spine setup.
16	Park, J., Kim, J. C., Nguyen, C. D. T., Kim, K. S., & Kim, S. [33]	2018	A passively adaptive variable-radius pulley for a tendon-driven robotic joint.	Mechanism and Machine Theory	It was discovered that using a regular pulley with a fixed length in a belt-driven transmission has a limit on how fast it can go and how much force it can produce. In contrast, a pulley that can change its size allows for more power and speed adjustments, resulting in more efficient driving. Additionally, they considered conducting a static-based investigation on the proposed framework and explained how the new variable-radius pulley they developed works. Using a type of mechanical joint that is operated by tendons was discovered to have the ability to enhance performance and effectiveness when connected to a new type of pulley that can change its shape. This was proven through computer simulations and experiments.
17	Parvaresh, A., & Moosavian, S. A. A. [34]	2018	Modeling and Model-free Fuzzy Control of a Continuum Robotic Arm.	2018 6th RSI International Conference on Robotics and Mechatronics	The outcomes of the research indicated that using a tendon-driven arm on a continuum robot would make it easier to complete a variety of useful and productive tasks, as well as boost the performance and efficiency of the continuum robots. Incorporating a tendon-driven robotic arm into one of these machines would help make it possible for it to do a wider range of tasks more effectively and with greater flexibility.

Table 2.1: Brief of the Literature Review " Table Continued".

18	Wen, K., & Burgner-Kahrs, J. [35]	2023	Modeling and Analysis of Tendon-Driven Parallel Continuum Robots Under Constant Curvature and Pseudo-Rigid-Body Assumptions.	Journal of Mechanisms and Robotics	It has been demonstrated that singularities can be located by employing Grassmann line geometry or by identifying the numerical quantities related to three performance indices. Doing any of these things results in increased levels of accuracy, performance, and dependability. The research simulation validated the kinematic models.
19	Ko, T. [36]	2020	A tendon-driven robot gripper with passively switchable under actuated surface and its physics simulation-based parameter optimization.	IEEE Robotics and Automation Letters	The results indicate that the gripper can switch between three different modes automatically. These modes are the parallel approach mode, the pull-in mode, and the control get mode. They used a method called black-box optimization along with a physics-based simulation to improve the control system of a machine. This allowed them to understand how to improve it much better. The experts explained that the results they got using the simulation-based method could effectively consider failure mode, control stability, control of an object, and movement before contact.
20	Zhang, Q., Li, C., Jing, H., Li, H., Li, X., Ju, H., ... & Zhu, Y. [46]	2022	Rtsras:a series-parallel-reconfigurable tendon-driven supernumerary robotic arms	IEEE Robotics and Automation Letters	The results indicated that the use of the coupled tendon-driven joint module resulted a significant reduction in the motion inertia of RTSRAs as well as an improvement in their load capacity. In the end, they do the evaluation of RTSRAs by using both forward and inverse kinematics analysis as our foundation. In addition, it was found that their proposed RTSRAs have been implemented effectively in a load operating scenario.

3. METHODOLOGY

3.1 INTRODUCTION

Math Works', the creator of MATLAB and Simulink, has developed a powerful simulation program called Simscape. This program allows researchers and engineers to model and simulate complex physical systems, including mechanical, electrical, and hydraulic systems. Simscape can be used to simulate a tendon drive for a 3-DOF robotics system, revealing crucial details about the system's behavior, functionality, and control. It can also be used for control system development, optimization, and real-time visualization. Simscape also allows for safety and cost evaluation, allowing for the evaluation of potential problems and safety concerns in a controlled setting. This approach can lead to more effective and efficient robotic solutions. Overall, Simscape is a valuable tool for control development, analysis, and design.

3.2 GEOMETRY MODEL

SOLIDWORKS is a popular tool in robotics and mechatronics engineering for modeling the geometry of a robotic system. It allows for precise design, analysis, and control development of the robot's mechanical parts. SolidWorks allows for part modeling, assembly modeling, and defining kinematic and dynamic properties. After creating the model, it can be exported to Simscape for further simulating. Simscape supports multi-domain physical modeling, including mechanical, electrical, and control systems. The process involves exporting the model in various file formats, importing it into Simscape, and using its collision detection and contact modeling to ensure the robot's performance and safety. Simscape also allows for specifying the robot's dynamics, creating control algorithms, and viewing the simulated behavior. This process optimizes the robot's design; tests control schemes, and confirm functionality before real-world use, saving time and money during the development process.

The two models were designed with the dimensions shown in Table 3.1 for the first geometric represented by the presence of the tendon link as in Figure 3.1.

Table 3.1: List of Design Parameters for Tendon Arm.

Parameter	Value
Length of base part (mm)	100
Length of arm 1 part (mm)	141
Length of arm 2 part (mm)	174
Length of arm 3 part (mm)	180
Radius of Pulley (mm)	20
Radius of motor (mm)	20

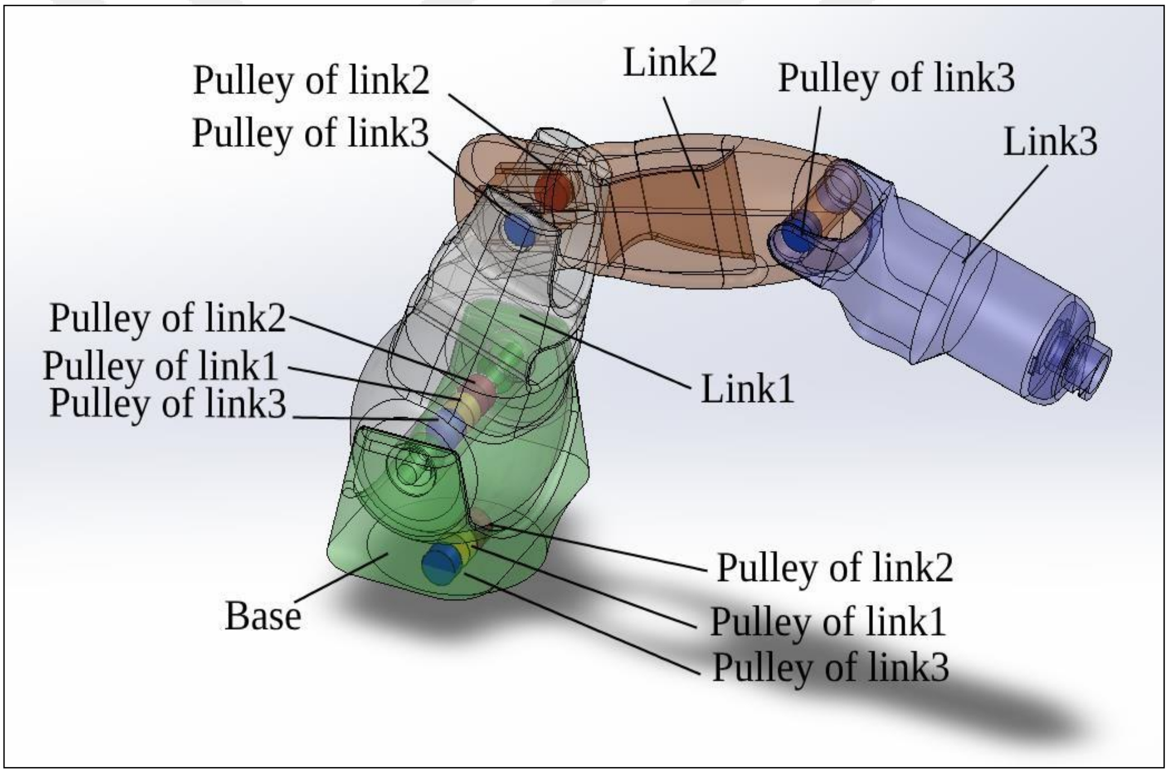


Figure 3.1: 3-DOF Robotics Drive by Tendons.

3.3 SIMULINK PROGRAMING

MATHWORKS' Simulink is a popular model-based design and simulation tool used in robotics to program and simulate various robotic systems, including three-degree-of-freedom (3-DOF) systems. It allows for precise 3-DOF robot models, control development, simulation, real-time testing, and integration with other domains like MATLAB and

Simscape. Simulink allows for precise modeling of the robot's geometry, dynamics, and physical characteristics, as well as the incorporation of actuators and sensors. It also supports real-time hardware-in-the-loop (HIL) testing, allowing for real-world validation of control algorithms. Simulink's principal benefits include fast prototyping, visual representation of the robot's behavior, multi-domain integration, and customization. Its adaptability allows for modification and tailoring of models to meet specific project needs. Overall, Simulink is a flexible tool for designing and controlling three-degree-of-freedom robots, enabling researchers and engineers to create reliable and effective robotic systems.

3.4 3-DOF ROBOTICS DRIVE BY TENDONS

All the main parts that make up the organization will be explained in detail.

Provides access to the world or ground frame, a unique motionless, orthogonal, right-handed coordinate frame predefined in any mechanical model. World frame is the ground of all frame networks in a mechanical model. A model can have multiple World Frame blocks, but all represent the same frame. Port W is a frame port identified with the world frame. Any frame port directly connected to W is also identified with the world frame. As figure 3.2.

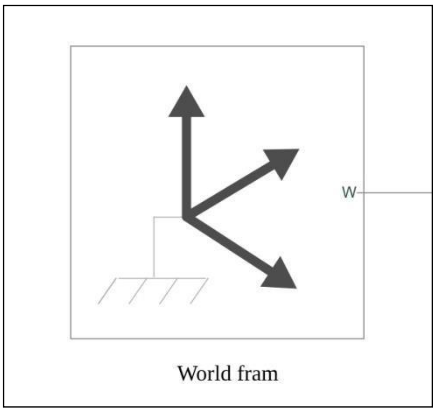


Figure 3.2: World Frame Block of Each Link.

Sets mechanical and simulation parameters that apply to an entire machine, the target machine to which the block is connected. Specify uniform gravity -9.8 m/s^2 for the entire mechanism and also set the linearization delta 0.001. The linearization delta specifies the perturbation value that is used to compute numerical partial derivatives for linearization. Port C is frame node that you connect to the target machine by a connection line at any frame node of the machine. As figure 3.3.

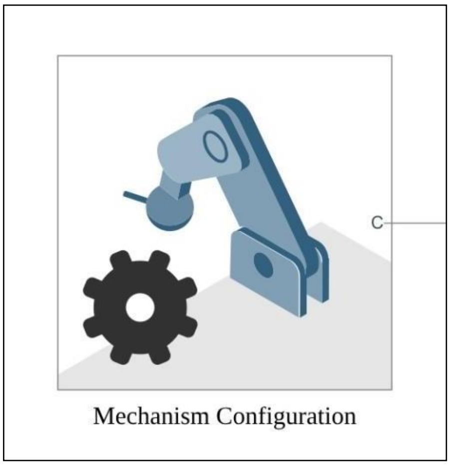


Figure 3.3: Mechanism Configuration Block of the Arm.

Defines solver settings to use for simulation. Consistency tolerance 1e-9, the linear algebra is auto, and delay memory budget was 1024 kb. As figure 3.4.

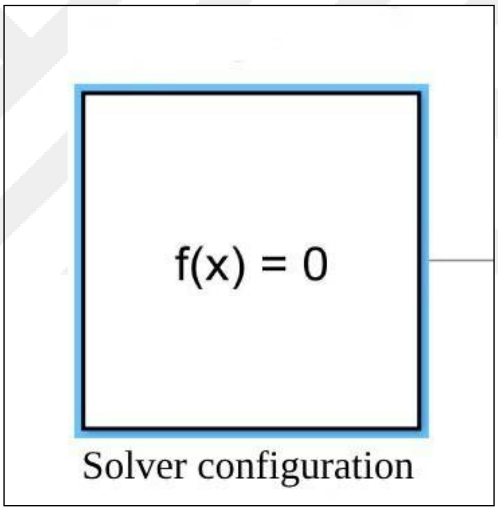


Figure 3.4: Solver Configuration Block of the Arm.

Two components independently specify the translational and rotational parts of the transformation. Different translations and rotations can be freely combined. In the expandable nodes under Properties, choose the type and parameters of the two transformation components. Ports B and F are frame ports that represent the base and follower frames, respectively. The transformation represents the follower frame origin and axis orientation in the base frame. As figure 3.5.

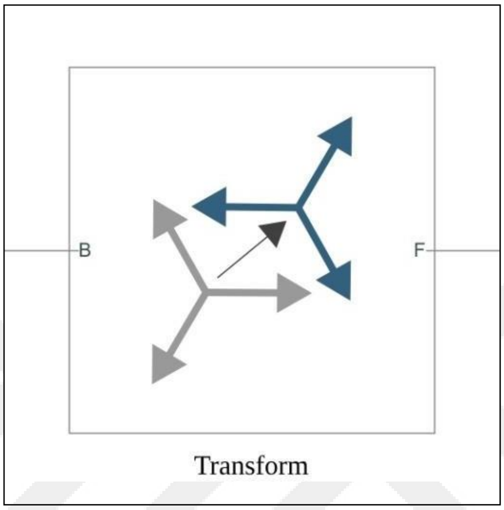


Figure 3.5: Rigid Transform Block of Each Link.

Represents a revolute joint acting between two frames. This joint has one rotational degree of freedom represented by one revolute primitive. The joint constrains the origins of the two frames to be coincident and the z-axes of the base and follower frames to be coincident, while the follower x-axis and y-axis can rotate around the z-axis. In the expandable nodes under Properties, specify the state, actuation method, sensing capabilities, and internal mechanics of the primitives of this joint. After you apply these settings, the block displays the corresponding physical signal ports. Ports B and F are frame ports that represent the base and follower frames, respectively. The joint direction is defined by motion of the follower frame relative to the base frame. As figure 3.6. Where q represents the input of the received signal, and q, which is on the left side of the sensor from which movement emerges, is represented by displacement, while w is speed, and b is acceleration [35].

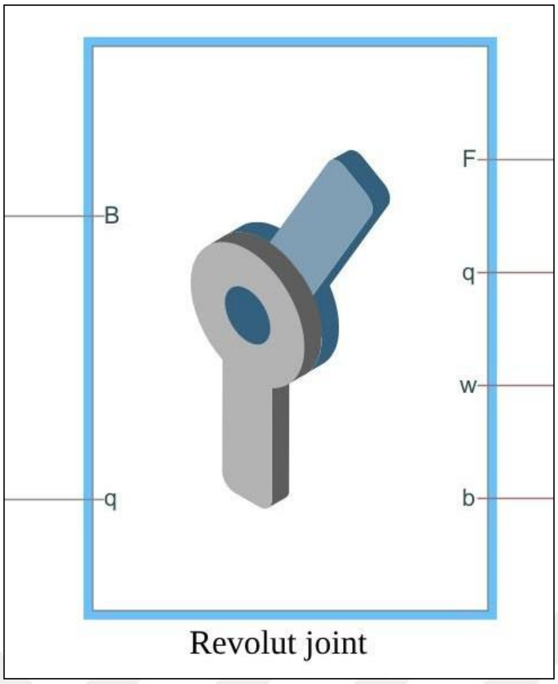


Figure 3.6: Revolute Joint Block of Each Link.

Represents a pulley of a belt-cable circuit. The pulley rotates about the reference frame z-axis. The belt-cable must enter and leave the pulley in the x-y plane of the pulley. During simulation, this alignment must be maintained by the rest of the mechanism. The belt-cable wraps from port A to port B in the standard counter-clockwise direction. Port R is a frame port identified with the reference frame of the pulley. Ports A and B are belt-cable ports to connect the pulley to the belt-cable circuit. As figure 3.7.

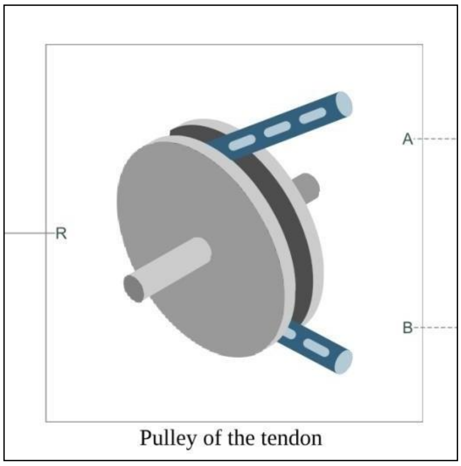


Figure 3.7: Pulley Block of Each Joint.

Set belt-cable properties and parameters that apply to the entire belt-cable circuit to which the block is connected. Each belt-cable circuit must have exactly one Belt-Cable Properties blocks connected. In the expandable nodes under Properties, specify the graphic properties of the belt-cable. Port P is a belt-cable port that you connect to the target belt-cable circuit by a connection line at any belt-cable node of the circuit, as in figure 3.8.

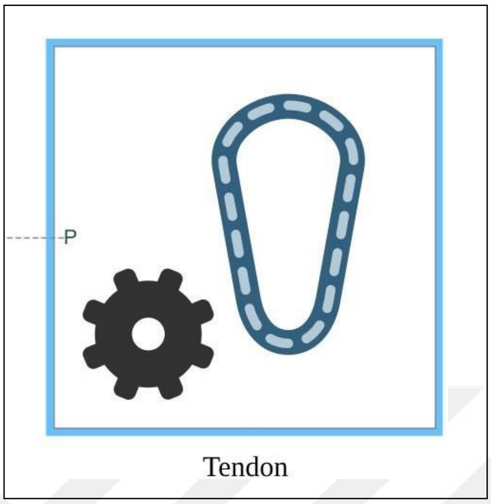


Figure 3.8: Belt-Cable block of the link.

The configuration map of the robot system, which consists of 3 axes of movement by tendons, requires complex connections, as each belt is formed between two segments of one link in Figure 3.9.

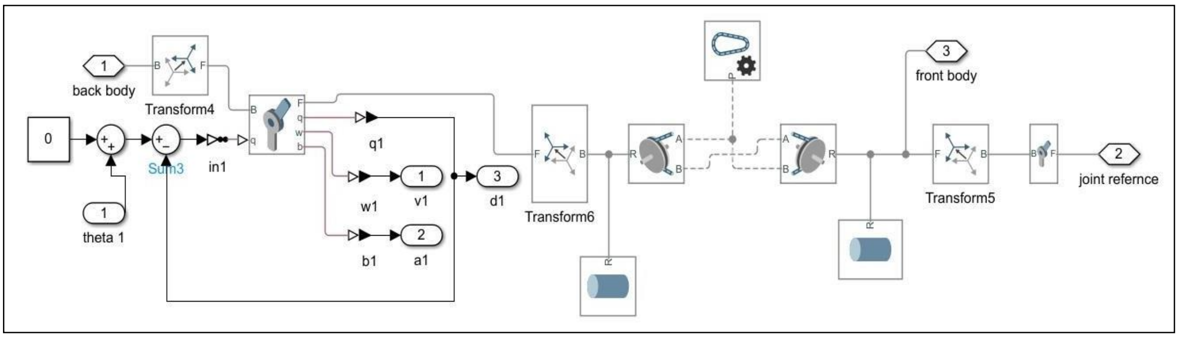


Figure 3.9: First Link System Block.

The connection of the first link requires a pulley unit, one linking between the base and the beginning of the first link. As for the second link, it requires two pulley units like the previous one, and one between the end of the first link and the beginning of the second link. As for the third link, it needs three pulley units, two like the previous ones, and a third between the end of the second link and the beginning of the third link.as figure 3.10.

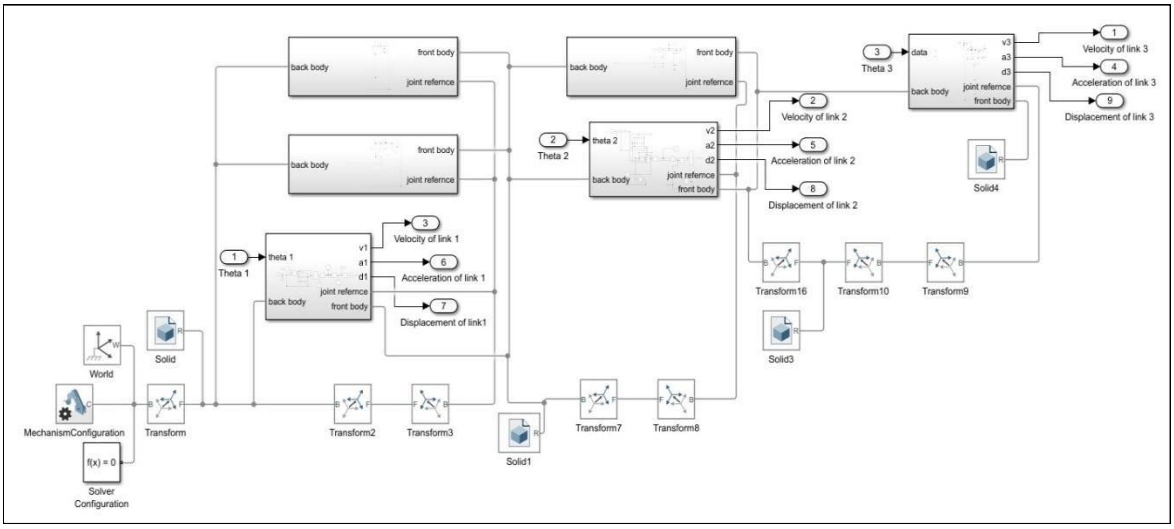


Figure 3.10: Over all Component of 3-DOF TDR.

3.5 METHOD OF INVERS KINEMATIC

Inverse kinematics is a crucial field in robotics, focusing on determining the joint angles required for a desired end-effector position and orientation in a robot's workspace. The goal of a 3-degree-of-freedom robotic arm is to precisely position the end-effector where it is desired. Three joint variables,θ_1,θ_2, andθ_3, regulate the end-effector's orientation and position. The problem involves determining the corresponding joint angles (θ_1, θ_2, θ_3) that allow the end-effector to assume its desired pose, given the required position and orientation (X_d, Y_d, Z_d) and its orientation parameters (roll_d, pitch_d, yaw_d).

The equations for solving the inverse kinematics problem in a 3-DOF robotic system can be quite complex and depend on the robot's specific geometry and kinematic structure. Here, I'll provide a simplified example that assumes a simple 3-DOF planar robotic arm where each joint has a rotational degree of freedom. In this scenario, the inverse kinematics equations are as follows [36]:

Position Equations:

$$X = L_1 *\cos(\theta_1) + L_2 *\cos(\theta_1 + \theta_2) + L_3 *\cos(\theta_1 + \theta_2 + \theta_3) \tag{3.1}$$

$$Y = L_1 *\sin(\theta_1) + L_2 *\sin(\theta_1 + \theta_2) + L_3 *\sin(\theta_1 + \theta_2 + \theta_3) \tag{3.2}$$

Orientation Equations:

$$\text{roll} = \theta_1 + \theta_2 + \theta_3 \tag{3.3}$$

$$\text{pitch} = 0 \text{ (for a planar robot)} \tag{3.4}$$

$$\text{yaw} = 0 \text{ (for a planar robot)} \tag{3.5}$$

These equations describe the relationship between the joint angles (θ_1, θ_2, θ_3) and the end-effector's position and orientation (X, Y, roll). Solving these equations can be complex due to the nonlinear trigonometric terms, and it may involve iterative techniques such as the Newton-Raphson method or numerical optimization to find the joint angles that satisfy the desired end-effector pose.

3.5.1 PID Controller

MATLAB is a widely used programming language and computing environment for various fields, including engineering, science, finance, and data analysis. It offers a vast library of functions that can perform various tasks, from simple arithmetic calculations to complex data analysis and simulation. MATLAB functions are pre-written blocks of code that can be reused in a program, making it easier to read, debug, and maintain. Input arguments are variables passed into the function for computation, while output arguments are variables returned by the function after computation. The code block is the actual code that performs the computation inside the function. MATLAB functions should be named according to conventions, starting with a letter and not containing spaces. They are saved in a separate file with a.m extension and located in the MATLAB search path. A function can be called from another MATLAB program or function using its name and required input arguments.

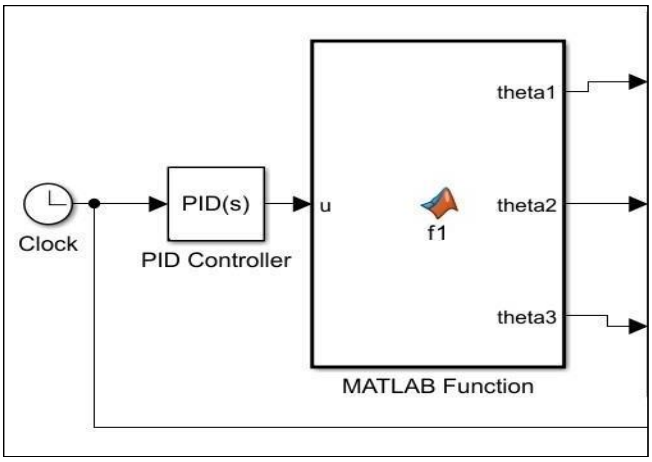


Figure 3.11: MATLAB Function Block.

There are also many types of controller used in the industry, such controller is PID controller. PID controller or proportional–integral–derivative controller is a generic control loop feedback mechanism widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. So by integrating the PID controller to the DC motor were able to correct the error made by the DC motor and control the speed or the position of the motor to the desired point or speed. [37]

PID Control (proportional-integral-derivative) is by far the widest type of automatic control used in industry. Even though it has a relatively simple algorithm/structure, there are many subtle variations in how it is applied in industry [5]. A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism widely used in industrial control systems A PID controller will correct the error between the output and the desired input or set point by calculating and give an output of correction that will adjust the process accordingly. A PID controller has the general form.

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

Where Kp is proportional gain, Ki is the integral gain, and Kd is the derivative gain.

3.5.2 ANN (Artificial Neural Network)

Artificial neural network (ANN) is a class of nonlinear regression and discrimination models. It offers great advantages in learning, adaptation, fault tolerance, parallelism, and generalization. Because of the complexity of the excavator system, the output of the fuzzy controller is fed back to the input of the neural network, which is presented in Fig.3.13. With its ability to learn, this hybrid technique can be used to improve the performance of the control system. The proposed neural block is designed with a single node neural structure and consists of one input layer and output layer where the input layer receives the signal output from fuzzy block. The output layer contains a set of adjustable parameters w_i, only one neural node with input function.

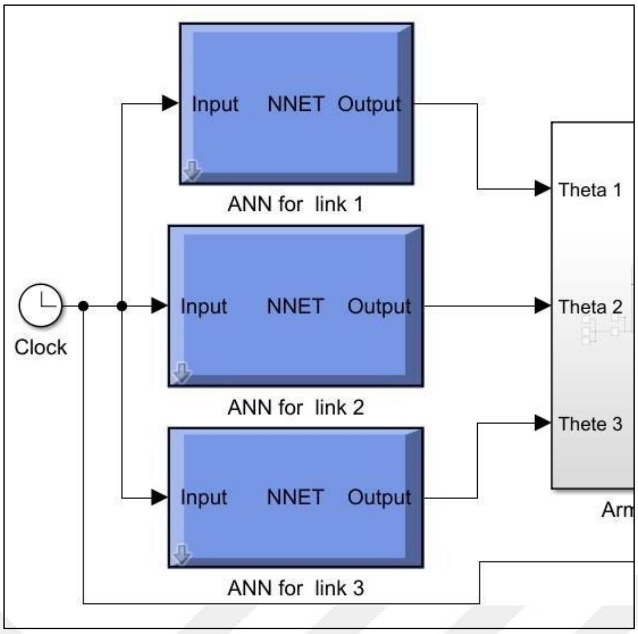


Figure 3.12: ANN Input Blocks.

In the figure 3.12 is a screenshot of the Simulink file for using ANN, as the only difference between it and MATLAB Simulink using PID controller is the input block for drawing the circle. An artificial neural network (ANN) must be trained to provide the necessary motor commands for the links to follow a circular path.

We can create the ANN block by writing in command window in MATLAB (nnstart) , then the new window will appear, then pressing (Pattern Recognition app), to choose the input data which the same function as a text that used in MATLAB cod previously, then choose the correct validation and testing percentage, choose the number of hidden neurons , doing training for ANN finally generate a simulink diagram to be used, Copy this block for each angle of link and then past it to be used .

$$f = \sum_{i=1}^{m} w_i \times u_{F_i} \text{ with } m = 3 \tag{3.6}$$

where $u_{F,}$ is the input signal of this node The activation function of the neural output is given by equation [3]:

$$a = u_m \frac{J}{\sum_{i=1}^{m+1} u_{F_i}} \tag{3.7}$$

The learning algorithm of the neural block is based on the minimization of the cost function which is defined as

$$E = \frac{\varepsilon^2}{2} \tag{3.8}$$

where ε is calculated as the following equation [3]:

$$\varepsilon = u_{\text{cantrol}} - u_{nn} = u_{PD} \tag{3.9}$$

This means that the energy of the control effort is minimized.

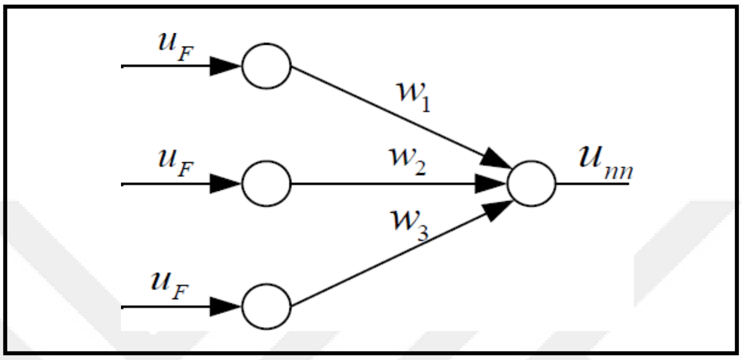


Figure 3.13: Neural Output Node [38].

The update process of the synaptic weights or adjustable parameters w_i is computed as follows.

$$w_i(t+1) = w_i(t) + \eta \times u_{PD} \times \frac{u_{F_i}}{\sum_{i=1}^{m} u_{F_i}} \tag{3.10}$$

Simulink is a graphical programming environment integrated with MATLAB that offers a block diagramming interface for modeling, simulating, and analyzing dynamic systems, including neural networks. It provides a user-friendly interface for defining network architecture, specifying training algorithms, and providing training data. The Neural Network block is a useful tool for implementing various neural network architectures, such as feedforward, recurrent, and convolutional neural networks. The choice of training algorithm depends on the specific problem and network architecture. Simulink offers various import methods for training data, including workspace, file, and Simulink blocks. Performance metrics like mean squared error, cross-entropy loss, and classification accuracy are available for evaluation.

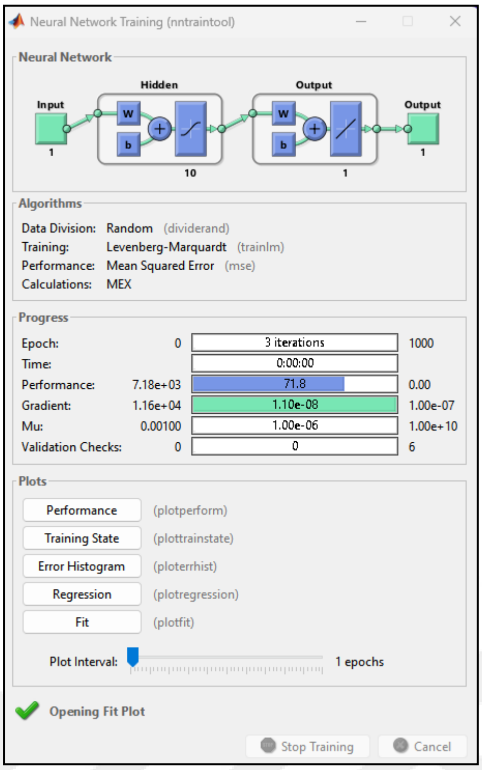


Figure 3.14: Neural Network Training.

The training state is the current state of a neural network during the training process, characterized by its parameters, weights, biases, and performance on training data. It is updated iteratively based on the error between predicted output and true output, with each epoch containing new parameter values and performance data. The training state is typically stored in memory, allowing for pauses and resumes, evaluation on new data, and early stopping when validation set performance degrades. Visualization of the training state, such as plots of training and validation error over time, helps monitor progress and identify potential issues like overfitting. In summary, the training state is a crucial concept in neural network training, allowing for better analysis and understanding of the training process.

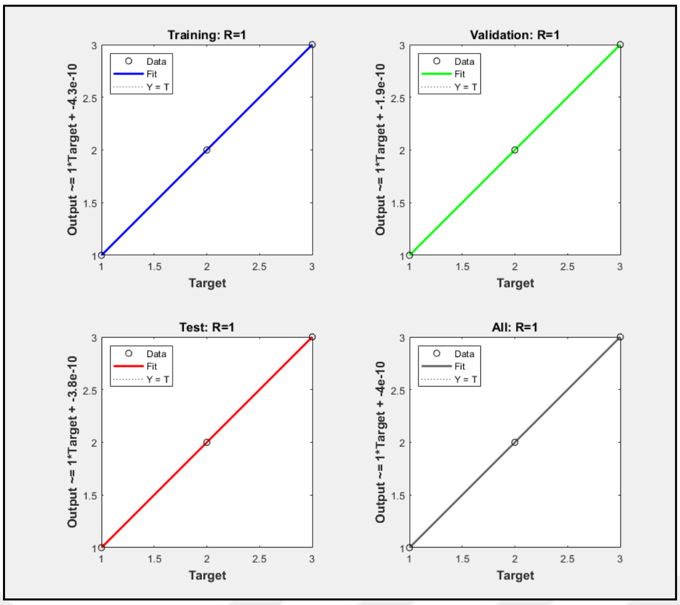


Figure 3.15: Regression.

An error histogram is a visual representation of the distribution of errors between a model's predicted and true output. It provides a summary of the model's performance by showing the frequency of errors and the magnitude of errors. The magnitude of errors can be measured using various metrics, such as mean squared error or mean absolute error, or classification error or cross-entropy loss. The error histogram can reveal the model's strengths and weaknesses, such as skewed towards larger errors indicating insufficient data capture or overfitting, or small errors indicating good performance on training data and generalization. It can also identify specific patterns or trends in errors, such as spikes at a particular error magnitude, indicating difficulties with a specific data point or a problem with the model's architecture or training process. An error histogram is a valuable tool for analyzing machine learning model performance by providing a visual representation of errors and revealing patterns or trends.

4. RESULTS AND DISCUSSION

In this chapter, all the results obtained through the Simulink program will be reviewed regarding the two cases of the robot 3DOF, the case of the tendon driven robotic arm with PID controller and with ANN.

4.1 THE EFFECT OF METHOD ON VELOCITY

Figure 1 illustrates the effect of artificial intelligence in obtaining more accurate equations through trial and error, it is noted that PID controller has the ability to apply equations only without learning from mistakes. The circle formation is better observed in the one using ANN than in the one using PID controller. Where the figure shows the x-y axes, the formation of the circular shape by the robot link 3, and the drawing of the axis points, which were fed using MATLAB equations or ANN with an error percentage 2%.

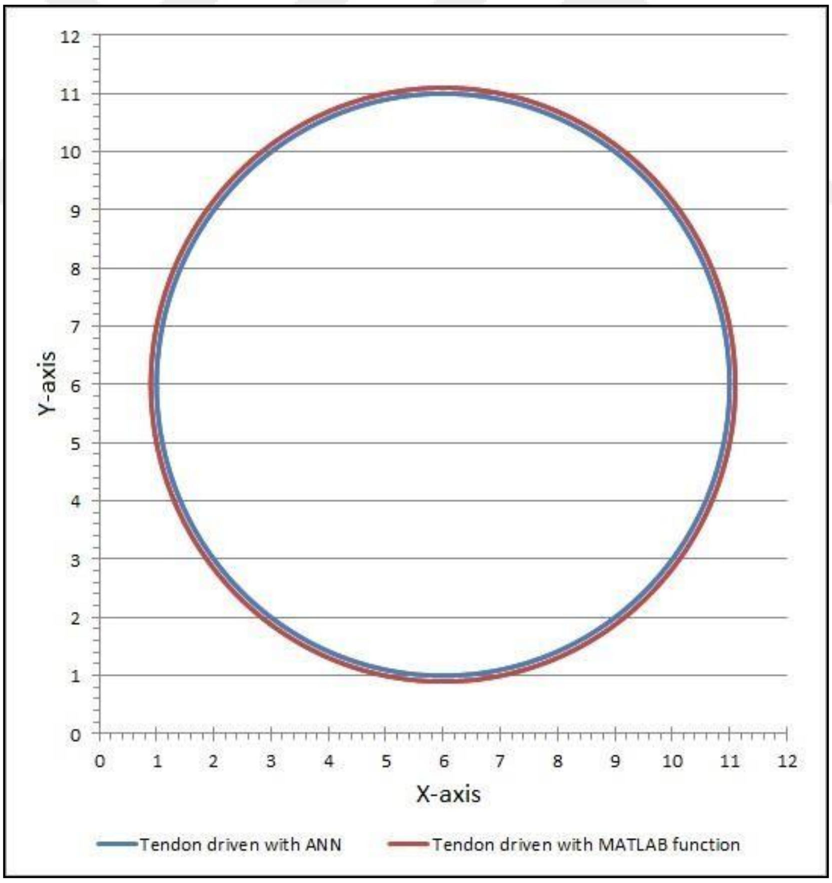


Figure 4.1: The Drawing of Circle on X-Y Plan When Using ANN or PID.

4.2 THE EFFECT OF METHOD ON VELOCITY

The velocity of a tendon system in a 3DOF robotic configuration can be influenced by the two-control method used, either a PID controller or an artificial neural network (ANN). ANN-based control can be flexible and adaptive, but requires significant training data and computer power. PID controller provides exact control over velocity by determining motor commands and using dynamic modeling and kinematic equations. The precision of these control methods and mathematical models determines their performance. Feedback control, inverse kinematics, and mechanical design also play a role in achieving the intended velocity. Both approaches require precise kinematics, feedback control, and a well-thought-out mechanical system to achieve and sustain the desired velocities. The decision between these strategies depends on factors like task complexity, training data availability, computer resources, and desired control precision.

Figure 4.1 shows the effect of artificial intelligence on the movement of the links and their speed. It is noted that the amount of speed decreased clearly in the first link to draw a circular shape, where it reached 0.4 cm/s through artificial intelligence, while with PID controller it reached 0.76 cm/s.

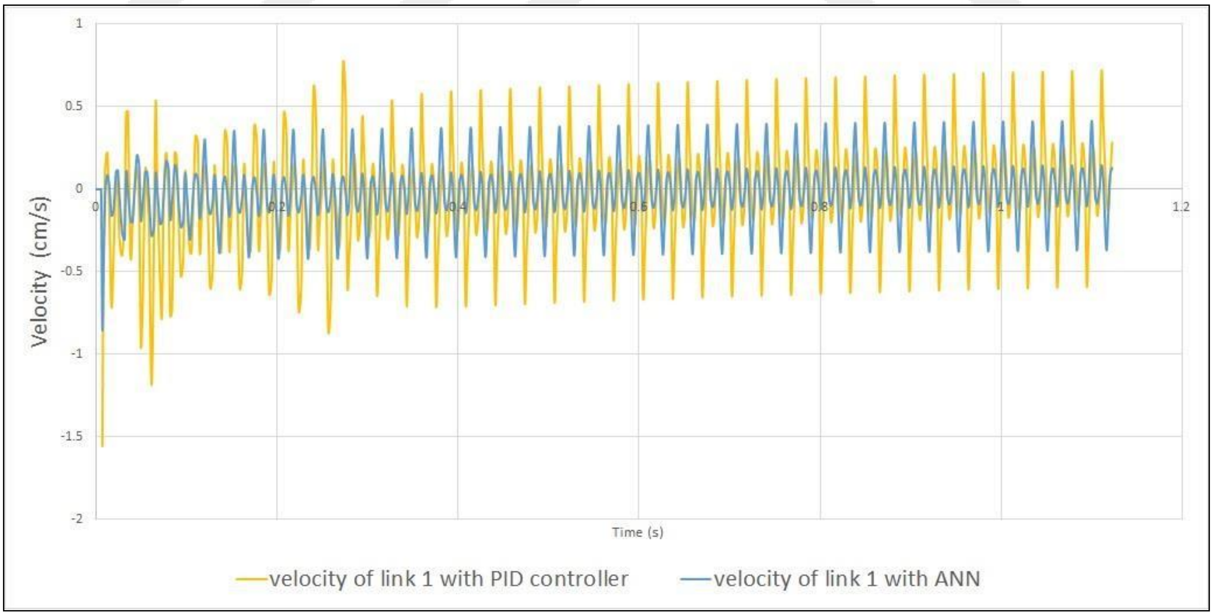


Figure 4.2: Velocity with Time at ANN-PID Controller for Link 1.

As for the second link, the amount of speed decreased significantly due to the precise configuration of the circle, as it can be seen from Figure 4.2 that the amount of speed in the presence of artificial intelligence reached 0.12 cm/s, while in PID controller it reached 0.57 cm/s.

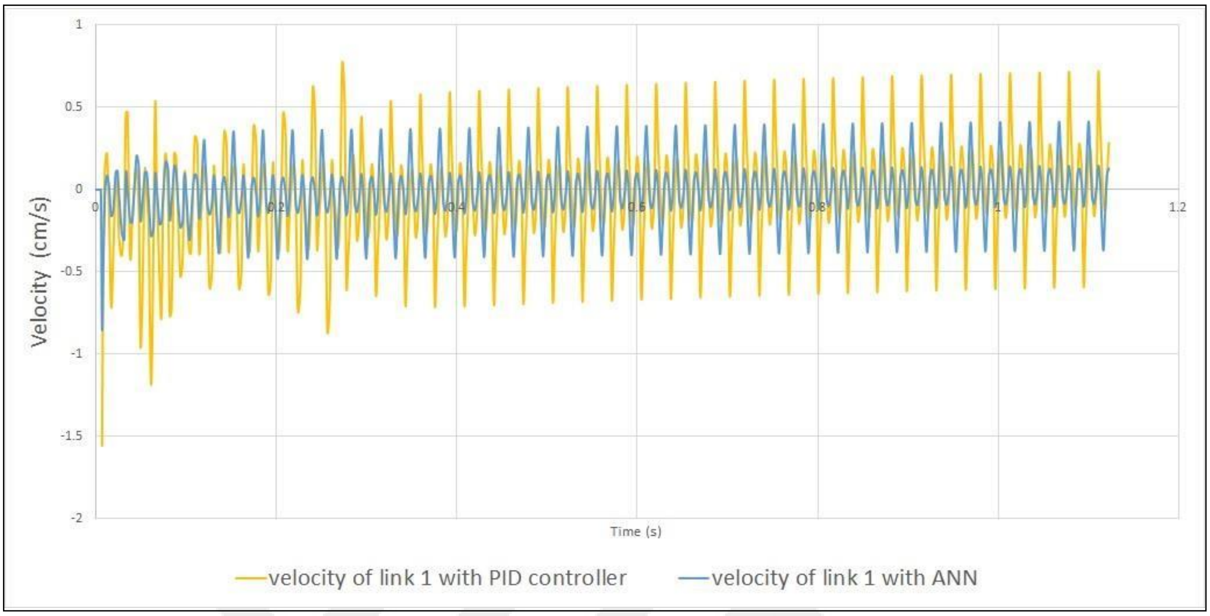


Figure 4.3: Velocity with Time at ANN-PID Controller for Link 2.

The speed also decreased in Figure 4.3 at the third link, which reached 0.5 cm/s in the presence of artificial intelligence or in the presence of PID controller, so the speed reached 0.82 cm/s.

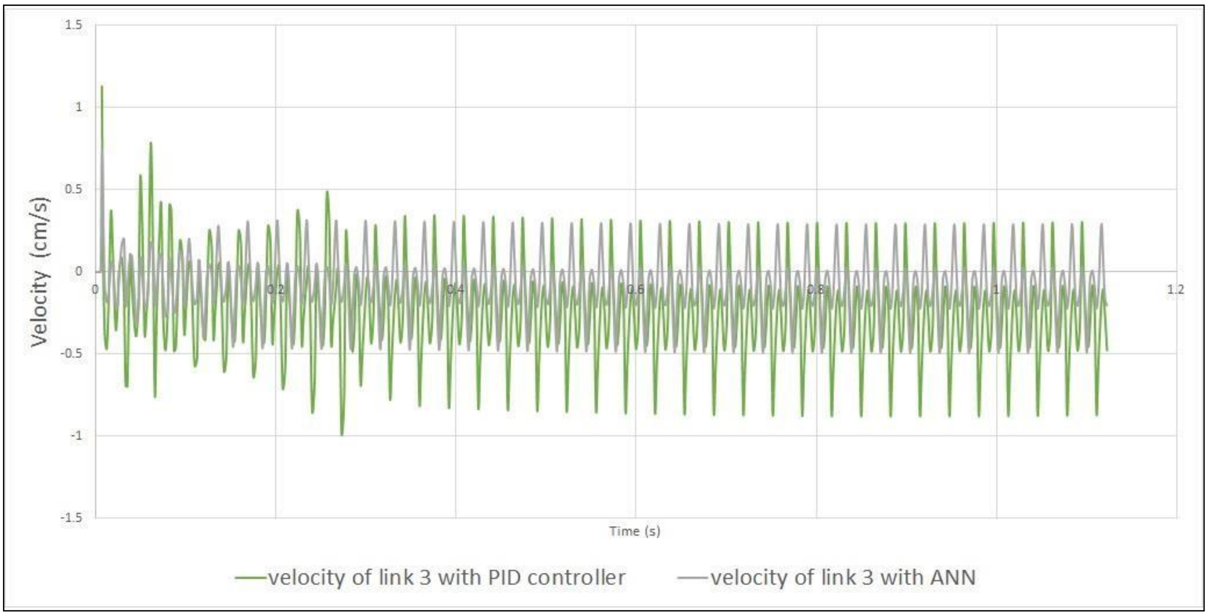


Figure 4.4: Velocity with Time at ANN-PID Controller for Link 3.

4.3 THE EFFECT OF METHOD ON ACCELERATION

Acceleration in a 3DOF robotic system can be controlled using PID controller or artificial neural networks (ANN). The control strategy affects the speed at which the robotic links can change their velocity. ANN management involves training the ANN to provide the desired acceleration profiles, with factors such as architecture, flexibility, and training data quality influencing its effectiveness. PID controller provides exact control over acceleration, but the precision of the control methods and mathematical models is crucial. Feedback control, kinematics, and mechanical design also play a role in achieving and maintaining the desired acceleration. The choice between these strategies depends on factors like task complexity, training data availability, computer resources, and desired control precision. Regardless of the approach, the robotic links must have precise kinematics, feedback control, and a well-thought-out mechanical system to achieve and sustain the desired accelerations.

Through Figure 4.4, which represents the change in acceleration with time in forming the circle through the robot with ANN and PID controller, and on the first link, it is observed that the acceleration of the ANN link increased compared to the PID controller, where it reached 600 cm/s^2, while with the ANN, it reached 250 cm/s^2, where an advantage is achieved. In terms of reducing acceleration and increase stability.

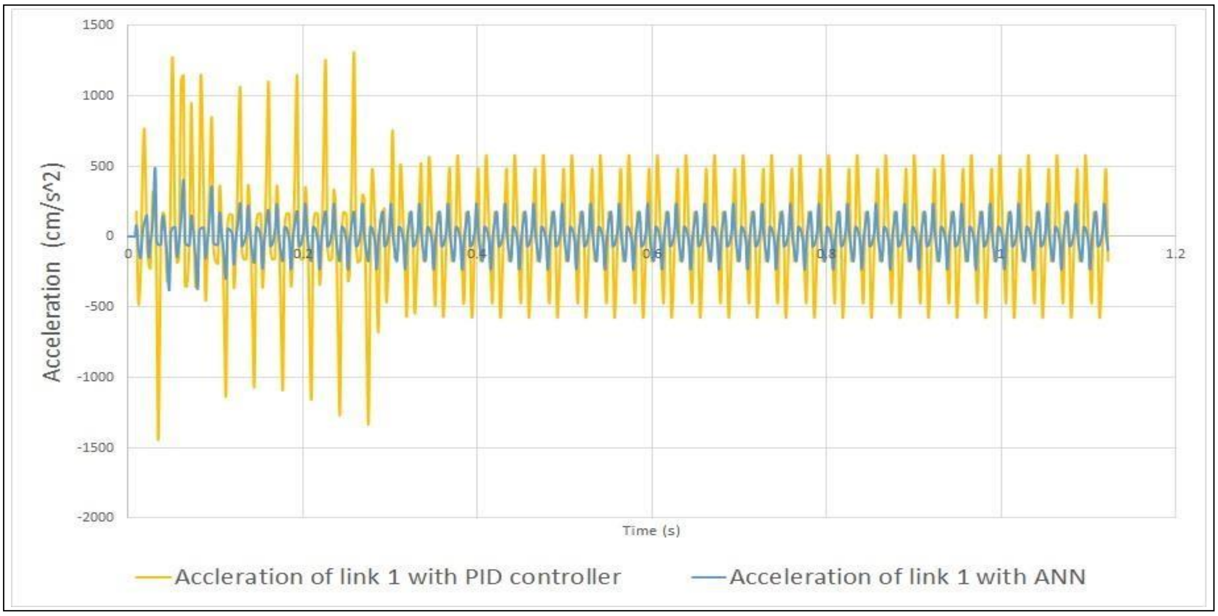


Figure 4.5: Acceleration with Time at ANN-PID Controller for Link 1.

Regarding the second link, the exact circular configuration resulted in a large drop in acceleration. Figure 4.5 illustrates that the acceleration reached 90 cm/s^2 when artificial intelligence was present, but it reached 250 cm/s^2 when using a PID controller.

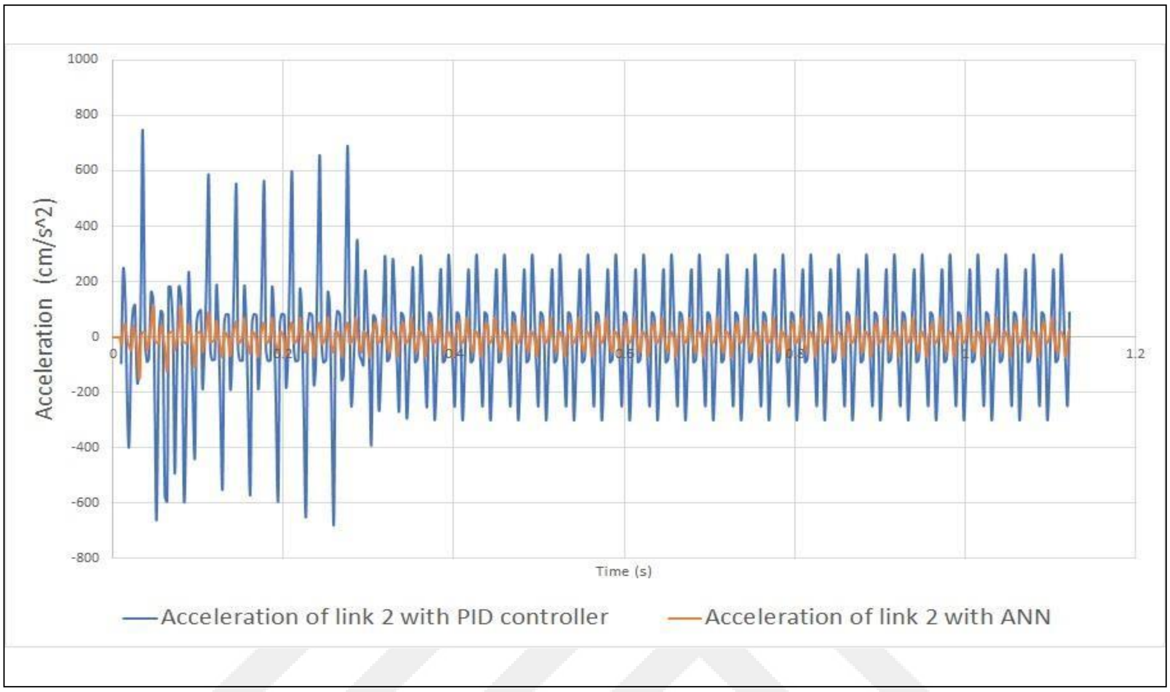


Figure 4.6: Acceleration with Time at ANN-PID Controller for Link 2.

The third link of Figure 4.6 is described in the same way as the first link. Where the acceleration when using PID controller is 520 cm/s^2, however the link acceleration when the ANN is moving has reached 200 cm/s^2. This has the benefit of increasing stability and decreasing acceleration while creating a circular shape.

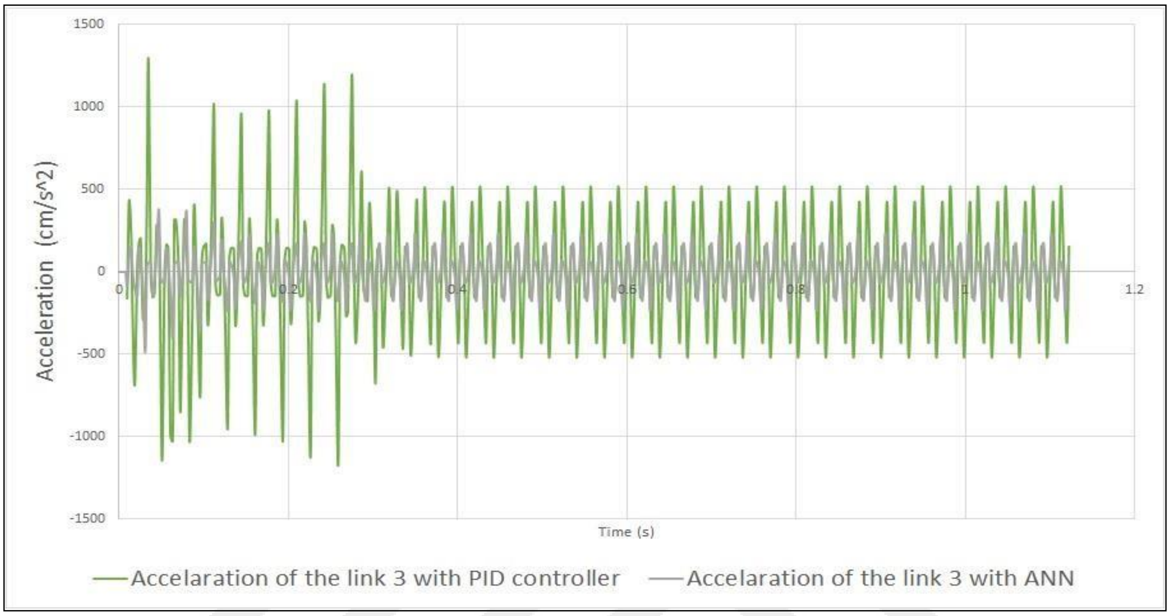


Figure 4.7: Acceleration with Time at ANN-PID Controller for Link 3.

5. CONCLUSION AND RECOMMENDATION

In conclusion, this study has made significant contributions to the field of tendon-driven robot arm design and simulation. Through the use of simulink by SOLIDWORK, a virtual model was built and simulations were carried out to test the feasibility and effectiveness of the design. The study demonstrates the effectiveness of artificial intelligence in obtaining approximate equations more accurately through trial and error, with ANN being more effective in achieving the desired circle shape. in conclusion, we note that when using the ANN there are changes in speed and acceleration for each link of the robotic arm, as the results indicate that in the first link the speed decreased from 0.76 cm/s when using a PID controller to 0.4 cm/s when using ANN, as for the second link, we notice a significant decrease in the speed, as it decreased from 0.57cm/s when using the PID controller to 0.12cm/s when using the ann. the same is true for the third link, and it was noted that the speed decreased from 0.82cm/s to 0.5cm/s. as for acceleration, it was observed that the acceleration in movement of the first link decreased from 600cm/s^2 when using the PID controller to 250 cm/s^2 when using the ann. as for the second link, the circular configuration led to a significant decrease in acceleration when using the ANN, as it reached 90 cm/s^2, while it was 250 cm/s^2 when using PID controller. Likewise, for the third link, a significant decrease in acceleration was observed, as it reached 200 cm/s^2 when using the ANN, after it was 520 cm/s^2 when using the PID controller. In general, it is worth noting that the decrease in acceleration and speed in execution has the benefit of increased stability and accuracy in execution while creating a circular shape. as for the recommendations, there are still areas for improvement, such as incorporating gravity effects, adding different end effects, and modeling the elastic properties of cables. Future work should focus on improving the motion accuracy of the model, especially for small-scale applications such as surgery and micro manufacturing. this can be achieved by developing better and more accurate models of the elastic properties of cables and incorporating them into the simscape model.

Additionally, the functionalities of the model can be expanded by including the effects of gravity and using different end effectors to perform various tasks. These advancements will help to further validate the viability of cable-driven robots as lighter and safer alternatives to traditional serial manipulators. The design presented in this thesis is a significant step towards developing a lightweight robot arm that can be used in various applications. The results obtained from the simulations suggest that this design is viable and can be improved further to meet the requirements of different applications.

For future work, the experimental setup of the robot arm can be built and the results from the simulation can be compared with the experimental results. This will help in identifying the deviations between the simulated and experimental results and will help in improving the design further. In addition to this, the design can be improved by incorporating more DOF to make it a more versatile robot arm. Also, the design presented in this thesis has a lot of potential for further improvement and development. The lightweight robot arm developed in this thesis can be used in various applications, such as pick and place tasks, material handling, and inspection tasks, among others. The results obtained from the simulations are encouraging, and the design can be further improved to meet the requirements of different applications. The objective of this thesis was to improving the motion and task efficiency of a 3-dof tendon-driven robotic arm using artificial neural network, which could provide a lighter and safer alternative to traditional serial manipulators. The thesis began with the conceptual design of a model with three degrees of freedom and an experimental model was built based on this design However, due to the very high cost and the scarcity of companies supporting the project, experimentation with this model was not possible and the approach was changed to use virtual models and simulations using SOLIDWORK and MATLAB\Simulink.

The virtual model was built in a gravity environment, making it easier to control and study the responses of the prototypes. The manipulator can also in future work seen to be easily controlled using a simple PID controller. The Simscape model was built with much smaller dimensions than a human arm, but it can still be used as a design tool to test the responses of prototypes, especially for microgravity environments. The model also helped in studying the influence of changing properties such as inertia, gear ratio, and the addition of a filter.

In the future, the functionalities of the cable-driven robot arm can be extended by incorporating the effects of gravity, using different end-effectors on the final link, and controlling them accurately to perform various tasks. One of the challenges that need to be addressed in the future is to improve the accuracy of the motion when performing micro-scale applications such as surgery or micro manufacturing. This requires not only better control strategies for the motors but also an accurate modeling of the elastic properties of the cables and the friction between the pulleys and cables. The elastic properties of cables play a crucial role in determining the accuracy of the motion of the robot arm. Developing an accurate modeling of the elastic properties of cables and integrating them into the Simscape model is the next scope of improvement for such models. The use of cable-driven robots has enormous potential, from assisting differently-abled people to performing household chores, and from aiding in surgery to micro-scale manufacturing. The simulation of a cable-driven robot arm using SOLIDWORK and Simulink has proven to be an effective method for designing and testing prototypes. The results obtained from the simulations have provided valuable insights into the behavior of cable-driven robots, and the findings of this thesis can be used as a foundation for future research in this field. With further advancements in control strategies and the modeling of the elastic properties of cables, cable-driven robots have the potential to revolutionize the way we interact with the world around us.

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APPENDIX A

-The Matlab function that draw a circle for both tendon driven robotic arm using PID controller and using ANN.

```
function [theta1, theta2, theta3] = f1 (u)
XC = -10;
yc = -20;
rc=5;
l1=14.1;
l2=17.4;
l3=18.05;
xd = xc + rc * cos((2*pi/5)*u+pi/2);
yd = yc + rc * sin((2*pi/5)*u+pi/2);
r = sqrt(xd^2 + yd^2)
theta1 = atan2(yd, xd)
cos_theta3 = (r^2 - l1^2 - l2^2) / (2 * l1 * l2);
sin_theta3 = sqrt(1 - cos_theta3^2);
theta3 = atan2(sin_theta3, cos_theta3);
sin_theta2 = (l2 * sin(theta3)) / r;
cos_theta2 = (l1 + l2 * cos(theta3)) / r;
theta2 = atan2(sin_theta2, cos_theta2);
```

− The MATLAB function of inverse kinematics

```
function [xa1,ya1]=f3 (q1  ,q2  ,q3, u)
l1=14.1
l2=17.4
l3=18.05
xa = l1 * cos(q1) + l2 * cos(q1 + q2) + l3 * cos(q1 + q2 + q3);
ya = l1 * sin(q1) + l2 * sin(q1 + q2) + l3 * sin(q1 + q2 + q3);
xc = 6;
yc = 6;
rc = 5;
xa1 = xc + rc * cos((2*pi/5)*u + pi/2)*1.02;
ya1 = yc + rc * sin((2*pi/5)*u + pi/2)*1.02;
```