# Development of a Continuum Manipulator with Integrated TENG sensor for Enhanced Control and Feedback

by

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## Abstract

The integration of continuum manipulators into mobile robotic systems for pipe inspection represents a significant advancement in navigating confined environments. These manipulators demonstrate exceptional flexibility and smooth movement, enabled by individually controlled motors that manage cable tension, allowing for complex tasks such as defect detection and object manipulation. The lightweight yet robust design, achieved through 3D-printed trimmed-helicoid structures, effectively addresses mechanical wear and environmental challenges encountered in pipelines. Enhanced real-time feedback is provided by sensor technologies, particularly triboelectric nanogenerator (TENG)-wire sensors, which improve operational precision and support adaptive manipulation strategies. By addressing the unique challenges of pipeline inspection, including navigation through complex geometries and hazardous environments, advanced control strategies and the synergistic integration of design methodologies, sensor technologies, and interdisciplinary advancements are employed. This comprehensive approach establishes a foundation for reliable and efficient mobile robotic systems tailored for critical inspection tasks.

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# Contents

# List of Figures

# Chapter 1

# Introduction

The development of mobile robotic systems tailored for pipe inspection presents a significant advancement in the field of robotics, particularly with the integration of continuum manipulators designed for operation in constrained environments. Continuum manipulators, characterized by their flexibility and smooth movement capabilities, play a vital role in ensuring the effective navigation and manipulation within confined spaces. The use of individually controlled motors to manage cable tension enhances the dexterity of such manipulators, allowing movement in multiple directions and facilitating intricate tasks such as defect detection and object manipulation. Firstly, 3D printed trimmed helicoid structures are also incorporated, which contribute a lightweight, but robust design framework, necessary for operations in pipelines subject to mechanical wear, and environmental constraints [1]–[3].

Further sensor technologies are used to enhance the functionality of these robotic systems. Specifically, the TENG (triobelectric nanogenerator) integrated in the manipulator sensor wire allows contact detection to pipeline surfaces or objects with. Dual benefit to these sensors is that they produce instantaneous feedback to the control system improving operational accuracy and they are adaptive manipulation strategies using dynamic responses to the environmental stimuli. Reliable interaction with surfaces and objects requires such feedback mechanisms particularly in situations where interaction with defect or in cases of sensitive handling of objects [1], [4], [5].

Understanding and optimization of manipulator behavior is a result of the backbone mathematics in mathematical modeling. Through the use of continuum mechanics based models containing their principles as well as cable driven actuation, workspace, movement trajectories and force distributions can be predicted accurately. These models are part of a complete manipulation methodology, where the operational parameters of the manipulator are in agreement with the limited operation environment of confined pipe lines. A complementary role of finite element analysis (FEA) simulations is to validate the manipulator's workspace and stress distribution [5], [6].

Prototype development, in bridging theoretical modeling with practical implementation, minimizes developments such as build and test and characterizes the performance of lifetimes and technologies. Fabrication of manipulators with 3D printed components not only reduces the production time but also allows for subsequent testing and optimization of the design through manufactured based on experimental feedback. This method follows the setup of hybrid rigid-soft manipulator systems, i.e., soft robotics with rigidity of rigid mechanism. However, hybrid systems of such kind clash with conventional robotic categorisations and provide versatile solutions tailored for application-specific needs as in pipe inspection task, for instance [1], [2], [5], [7].

It is not feasible to inspect the inner surfaces of the pipelines due to the lack of direct out and lack of visibility inside pipelines and hence require special tools to inspect the surfaces of the pipelines. Features for increase in mobileability and adaptability are designed in to the mobile robotic systems so as to address these challenges. Rather, all these components, including robotic arms, actuation boxes, dedicated end effectors operate in a seamless manner. Additionally, the manipulator's capacity to enter in narrow gaps and maneuverable around obstacles provides evident suitability for a sort of pipeline inspection scenario [7], [8].

Additional capabilities of the system are the integration of advanced control strategies, including the incorporation of force control mechanisms. Precise manipulation is possible with force control, especially when there are errors in lighting or spatial constraints of visible systems. These approaches maintain consistent contact, pressure in the case of pipeline interaction to ensure accurate detection of defects and safe operation [1], [7].

Finally, mobile robotic systems for pipe inspection on Figure 1.0.1 are shown to be overall consisting of pipe inspection robot mounted on the tracked chassis with continuum manipulator and its onboard Actuation box [1], [2], [4].

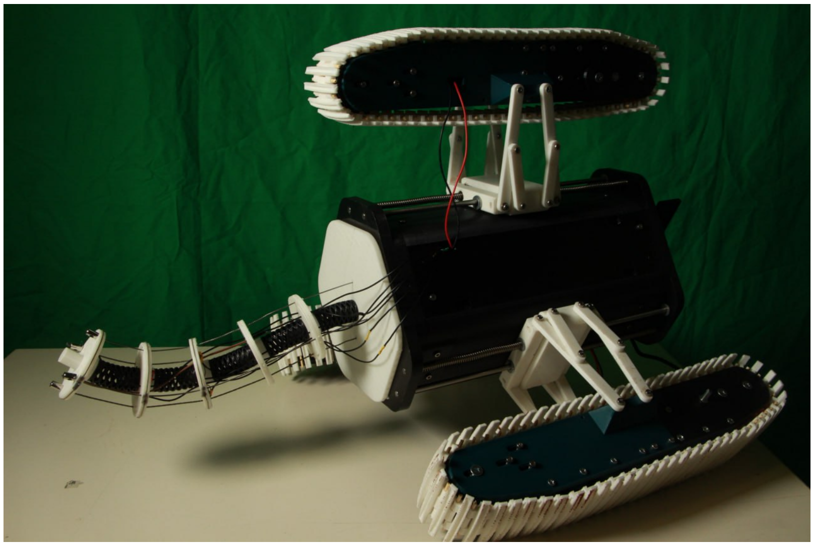

Figure 1.0.1: Complete mobile pipe–inspection robot with integrated continuum manipulator.

## 1.1 Literature Review

### 1.1.1 Development History

The incremental innovations of structural design, actuation mechanisms, and functional adaptations in continuum manipulators were to create continuum manipulators that can meet diverse application needs including industrial inspection, medical interventions, as well as robotics for environments of constraints. Early designs were influenced predominately by the fact that artificial systems to emulate the flexibility or adaptability of such natural systems as tentacles or vertebrate spines were desired. Improvements in the materials, the actuation methods, as well as the control strategies in turn shaped evolution of these robots and therefore, we acquired sophisticated systems for specialized tasks.

Notable in this development as one trajectory was the incorporation of concentric tube mechanisms with multiple precurved nested tubes to achieve high flexibility, compactness. Continuum robots that used passive arm discs, however, proved such designs very reliable in environments with small gravity; where the continuum robot can continuously deform without compromising its structural integrity. [9], [10].

Secondly, cable driven systems were introduced with individually actuated motors controlling cable tensions to drive the robot. In particular, this principle had good value in attaining very high dexterity and redundancy in motion. For example, TakoBot 2 featured sliding disc and backbone mechanism for improved bending and unique helical motion with motion accuracy at while showing how wire driven discrete continuum robots have the potential for complex maneuvers [8], [11].

At the same time researchers investigated the use of soft robots for continuum manipulators considering the link between geometry and mechanical properties. Here we exemplified this approach at the trimmed helicoid structure to maximize axial and bending stiffness for tendon driven soft robotic arms. The proposed design framework that helped with the development of manipulators capable of operating in confined spaces as in pipelines, balancing flexibility with structural rigidit [12]. This showed that the adaptability of these systems had rendered them suitable for the task of intricate manipulation in constrained environments.

Second, sensor technologies have been integrated into continuum manipulator systems to further improve their utility. Real time feedback about contacting objects was incorporated using TENG wire sensors, which allowed much more reliable control and defect detection of the manipulators as well as interaction with their environment. Optical feedback systems also witnessed similar advancements, and they were able to provide precise bending and orientation angles information, which were then used for closed loop control to achieve more accurate and responsive operations [13].

Other efforts were made to miniaturize and refine the construction of continuum manipulators in order to validate workspace and the distribution of mechanical strain. In multi-section designs, variable segment contributions made it possible to distribute strain more efficiently along the manipulator's length providing a better reach and accuracy in experimental models. Moreover, these advancements guaranteed that the simulated performance brought the simulated positions as close as possible to the actual performance in the industrial and academic applications [1].

If structural innovations alone took the continuum manipulator from the sketch pad to its present, the actuation mechanisms would have been vital contributors to the progress. An alternative method of actuation was achieved through magnetic soft robots and MR guided piezoelectric concentric tube devices in medical domains where accuracy and compactness are the main concerns. The solutions discussed provide into how magnetic actuation can overcome the miniaturization challenges in continuum robot designs [3], [6].

A big optimization of the slenderness ratio of continuum manipulators, a key design metric, also took place. For industrial end effectors, robots with extremely high diameter to length ratios such as robots with compliant and rigid joint combinations were developed to enable structural integrity and full actuation of multiple degrees of freedom. Through these advancements it was shown that manipulators could, in fact, be designed for application to specific problems: defect detection within pipelines and industrial settings that constrained the abilities of manipulation [14].

Further methodological refinements in continuum manipulator model were outlined, such as use of generalized coordinates for rotation and sliding motion [15]. Thus, we were able to derive closed form algebraic equations for shape variables, actuation forces and torques, which simplified the computational tasks needed for precise control as well as simulation. This therefore portrayed the importance of mathematical modelling in mainstreaming theoretical designs in accordance with practical implementations.

### 1.1.2 Cable-Driven Type of Continuum Robots

Well known in the field of continuum manipulators, cable driven continuum manipulators can provide flexible and precise motions and well suited for such type of application in confined environments. The cables are typically fabricated as nitinol and transmit forces for actuation through these systems. Cable driven design has been popular because nitinol combines flexibility, strength and biocompatibility. The manipulation of the manipulator itself is improved with the use of nitinol, while keeping it light. As an example, segmented cable driven systems using nitinol backbones, have shown good movement a description and control [3]. One of the innovative feature of cable-driven manipulators is that they can perform hyper redundant motion. It works by using strategically routed tendons to allow the parts to work like a complex combination of axial extension, tangential bending, and torsion. As an example of this, the composite tendon and pneumatically driven components cable-pneumatic hybrid structure given in [16] forms a structure. Such designs greatly increase operational reliability by increasing stiffness and resisting external forces.

In the static modeling of cable driven continuum manipulators, it is often taken into account several forces of tension, friction, gravity, elasticity loading. These forces act on the manipulator's backbone structure as well as driving cables and thus affect the manipulator's shape and functionality. Section shapes under a variety of loading conditions are understood in the context of models based on such principles as principle of virtual work and the theory of Cosserat rods. This however, will encounter difficulties such as tendon slacking during quick accelerations, whereby the control accuracy is reduced. .Refined control algorithms and design optimizations are needed in order to minimize the unwanted behavior.

Success of the cable driven manipulator to adapt its shape in different applications is mainly dependent on the actuation mechanisms. For example, linear stage or screw carriage mechanisms combined with concentric tube designs provide ability to vary length of individual sections with high precision [10]. For tasks in need of a high number of DOF, these configurations are especially desirable. This is demonstrated in [9] through nine degrees of freedom of bending and telescopic motion in the concentric tubular structures shown. It allows improving maneuverability in dwellings, such as pipes. Since cable driven manipulators hold the key to the systems where the emphasis is on the flexibility, payload capacity, and accuracy in industrial applications, they are crucial. It is composed of these features and are ideal for tasks that involve delicate movements and consistent object handling. These applications are illustrated by the cable driven hyper redundant robot described in [17] in which the design analysis and experimental validation are integrated in an effective manner.

Finally, errors of shape prediction are also introduced from the cables and guiding elements due to their friction [14]; this is particularly true if the curvature is constant. More accurate alternatives to the above modeling approaches, e.g. variable curvature models, acknowledge these effects. Furthermore, designs taking benefit from guiding arms and optimal routing of the tendon as discussed in [1] improve the operation of the cable driven manipulators. Continuum robots made with integrated cable driven systems embody this versatility and should be considered an advanced robotic solution for constrained environments. These systems taking advantage of materials, such as nitinol, sophisticated modeling techniques, and new design approaches meet the requirements of adaptability, precision and robustness required in modern robotics [3], [14].

### 1.1.3 Research Gap and Objectives

Conventional in-pipe inspection robots are not known to have reliable direct contact sensors or are constrained by the use of rigid sensors which may not give useful feedback. Tactile sensing using triboelectric nanogenerators (TENG) has been overlooked in prior studies on continuum robots for use in flexible manipulators. This thesis uses a continuum manipulator with embedded TENG sensors in order to solve these problems- this contributes to improved collision detection, as well as feedback control in closed-in pipeline environments.

The main objectives of this research are described below:

- Create a new continuum manipulator for the inspection of pipelines, with a flexible backbone like trimmed-helicoid design, and embedded TENG sensors for contact detection metric.
- Place the triboelectric sensor wires in the manipulator and calibrate them to determine the sensitivity so as to able to measure the contact events or defor-

mation in order to have accurate correlation of the sensor signals and actual interactions.

- The design of a control algorithm optimized for data processing from the TENG sensors will enhance the ability of the robot to navigate safely. For instance, the robot can be programmed to stop or withdraw, if the sensors show that it has hit the pipe wall or another body.
- Test system performance with experiments, monitoring how accurate sensor feed is received and how well the manipulator responds in real-time and keeps position. Show that the integrated system is able to maneuver easily in confined spaces, and respond quickly to collisions or contacts.

# Chapter 2

# Kinematic Modeling

## 2.1 Dynamic and Static Modeling

### 2.1.1 Dynamic Analysis

Dynamic analysis has fundamental importance for continuum manipulator behavior, especially in those regimes needing high precision motion, high stability, and high responsiveness, like with pipe inspection. These manipulators are performance dynamically controlled by the interaction of internal forces, cable tension, and external forces contact with pipe walls or with obstacles. We require mathematical models of this behavior that can be used to accurately analyze and predict it, and that integrate the unusual structural, material and actuation properties of the manipulator.

Because they are able to be slender and fit in cramped spaces, the dynamics of the tendon-driven mechanism, as a primary mechanism in continuum manipulators, is essential in dynamic modeling. By utilizing cables and guide disks as the backbone structure, tension forces along the manipulator are distributed along the manipulator both in elongation as well as in bending. Yet, owing to friction, cable elongation, and non-linear dynamics among segments, there are additional complexities to this design that must be accounted for in dynamic models [2], [13]. In addition, the use of tension optimization algorithms helps performance by minimizing unnecessary forces within the performed movement trajectory.

A multi body approach is frequently implemented to describe the dynamic behavior, because each segment is viewed as a discretized substructure with its own dynamics. The equations of motion include interactions between adjacent segments, e.g. contact force and friction. Finally, this framework allows inclusion of external disturbances (pipe irregularity), as well as internal constraints (cable forces and joint flexibility) in a comprehensive study of the manipulator stability and response [7]. Secondly, the control of dynamics is further enhanced with feedback from contact sensors such as TENG-wire sensors on the body of the manipulator, by supplying real time feedback on environmental interaction.

By adding in the actuation strategy which involves the individually controlled motors to modulate the cable tension, the dynamic system is further complicated. Coordination of these motors is therefore precise for smooth and accurate motion. The process can be simplified by the utilization of kinetic decoupling methods [2] which isolate the effect of each cable, providing for greater control of bending and elongation actions. By using optical or other types of sensors, closed loop control systems further enhance the dynamic accuracy and can compensate for errors induced by cable elongation or misalignment.

The dynamic analysis in pipe inspection applications must also take into consideration the pipeline's topology which the manipulator is interacting with. The manipulator has to overcome bends, changes in diameter, and even obstructions, all without eating itself alive. In most of its applications such as inspection tasks, mathematical models incorporating constraints are usually used to simulate the conditions of these tasks, so the manipulator remains inside the operational limits. Furthermore, the theoretical framework is refined and the system performance optimized through experimental validation of dynamic models e.g., through prototype testing or teleoperation systems [2], [18].

The second important aspect of dynamic analysis is the effect of payload capacity on actuation efficiency. The trade off between compactness and the ability to support external loads has been known to exist with tendon driven manipulators. The tradeoff is related to the material properties of the backbone and the tension limits of the cables. Thus, researchers strive to optimize these aspects to produce the functional range of the manipulator without degrading the stability [2], [7], [18]. In some designs, some designs have further increased distal dexterity and payload capacity, and adopted rolling joint mechanisms, which are especially suited to also tasks that require a high degree of precision and adaptability [13].

On the whole, the dynamic analysis of continuum manipulators for pipe inspection is in the realm of structural mechanics, actuation optimization, and environmental interaction modeling. The control and operation in these highly constrained environments are made possible because it is possible to achieve robust control and reliable operation by exploiting advanced mathematical formulations as well as real time sensor feedback. These analyses provide the insights needed for the iterative design and refinement of such systems, such that they do well in modern robotic applications [2], [7], [13].

### 2.1.2 Static Equilibrium

The forces and moments applied to the structure of a continuum manipulator are balanced, i.e. forces and moments are in static equilibrium. Achieving stationary configurations in such an environment, namely pipelines with stability and precision requirements for inspection and defect detection, requires this equilibrium state. Since the manipulator's design includes 3D printed trimmed helicoid structure and tendon driven actuation, it is necessary to understand the detailed force interactions to meet the reliability requirement of its static performance.

Newton's laws are used to find the static equilibrium of each segment of the manipulator. There are also external and internal forces involved in the forces acting on the manipulator such as forces due to pipeline walls contact (external force), forces due to r tendons tensions (tendon tension force), and forces due to gravitational orientation (gravitational force). This helicoidal structure of the manipulator introduces geometric constraints that relate these forces through relationships based on the curvature and torsion of the continuum limb. A single-segment arm with its trimmed helicoid lattice backbone for axial compliance is shown in Figure 2.1.1. A possible way to model these forces is by taking into account the manipulator's material properties and its geometric configuration [4], [13].

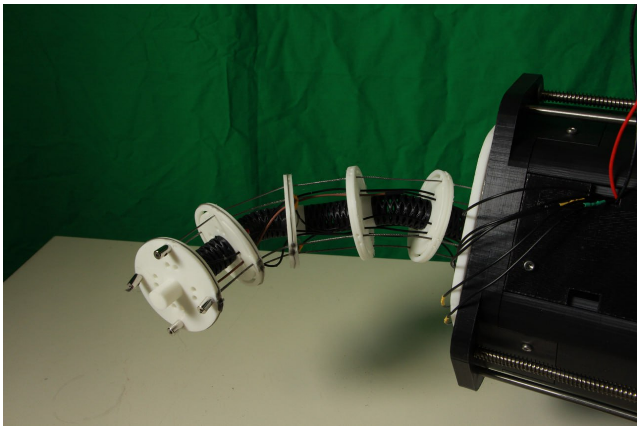

Figure 2.1.1: Single-segment continuum arm built from a 3-D-printed trimmed-helicoid backbone providing axial compliance and torsional stiffness.

A mathematical framework for analyzing static equilibrium begins with the equilibrium equations for a differential segment of the manipulator. Considering a segment of length d$s$, the sum of forces $F$ and the sum of moments $M$ in equilibrium are given by:

$$\frac{\mathrm{d}F}{\mathrm{d}s} + f_{\text{ext}} = 0,$$

$$\frac{\mathrm{d}M}{\mathrm{d}s} + r \times F + m_{\text{ext}} = 0,$$

where $f_{\text{ext}}$ and $m_{\text{ext}}$ are the external force and moment per unit length, respectively, and $r$ is the position vector of the segment. In this case, tension within the cables is a critical internal force. The geometry of the trimmed-helicoid structure ensures that cable displacements induce corresponding deformations, governed by the manipulator's stiffness matrix [4], [15].

The integration of the above equilibrium equations over the manipulator's length provides the global force and moment balance. Tendon-driven actuation introduces boundary conditions at the base and tip of the manipulator, where motor-driven tensions at one end interact with contact forces at the other. To prevent slack in the tendons, which can destabilize equilibrium, a minimal pretension is maintained. This pretension is crucial in multi-tendon systems to avoid issues such as wire slack, a phenomenon noted to arise in wire-driven actuation systems [4]. It is also well known that contact forces, sensed by the TENG-wire sensors, are largely responsible for equilibrium. The feedback from these sensors is used to make real-time adaptations in the tendon tension such that the manipulator deformation matches the prescribed static configuration. The feedback loop allows the system to cope with external disturbances, e.g. with contact of irregular pipeline surfaces, and keeps the system in equilibrium [1], [13]. Modeling the manipulator in its trimmed helicoid design simplifies the motion degrees of freedom and make the manipulator easier to model. Consequently, the continuum manipulator can be considered to be made up of a number of rigid segments, each having its local equilibrium equations. Nevertheless, introduction of the 3D printed structure's compliance introduces nonlinearity in the equilibrium conditions. Because of this nonlinearity, advanced numerical techniques such as finite element analysis have to be used to address it, which was validated through experimental trials on similar tendon-driven manipulators [1]. Quantifying the manipulator's response to static forces and incorporation of sensor feedback permit prediction of the manipulator's behavior under changeable load conditions needed for robust operation in confined pipeline environment [1], [10], [13].

# Chapter 3

# Control Systems

## 3.1 Motor Control

### 3.1.1 Servo Mechanisms

For continuum manipulations that need precise movement or adaptability in confined spaces, servo mechanisms are played an important role in the motor control of continuum manipulators. The use of these mechanisms is crucial in enabling actuators in the manipulator segments to accurately drive the ends of the manipulator cable. In its typical specification, a servo system comprises a number of individually controlled motors that are responsible for maintaining the level of tension applied to the cables routed through the manipulator's structure. Dynamic adjustments of the manipulator's shape and position are possible through this design, so it may navigate complex shapes, perform object manipulation and defect detection tasks.

The servos are used as actuator by the manipulator, with their actuation governed by the interplay between the servos and the cable driven mechanism. The actuator for each DoF is dedicated and uses pulleys and Bowden tubes to route cables along the manipulator's arm. Pistone et al. [7] also noted that this configuration minimizes slack and has consistent tension during operation. This is further enhanced by the implementation of the pretensioning mechanism that is introduced near the base of the manipulator, as preventing cable slack is a major problem with wire driven systems yet in [11]. Figure 3.1.1 shows the compact actuation plate with four Dynamixel MX - 28 servos and her cable spools attached. We shall demonstrate that this approach is advantageous in maintaining the accuracy of the end effector's motion as the motion of the other segments relies on the motion of the manipulator's distal end [19].

Figure 3.1.1: Four Dynamixel MX-28 servos are used to actuation plate, which provide independently tension to the left, right, up, and down tendons.

As Guan et al. mention, the manipulator is in a trimmed-helicoid structure which is a robust environment for the servo mechanisms to operate well. The design allows for various actuation modes (axial, lateral and side), thus allowing the manipulator to work the contraction, bending and gripping moves. Sensors in the form of TENG wires can be integrated with the manipulator's structure to further enhance the servo system with real time feedback in object contact. This feedback loop accommodates the adaptive control, which can make a small error to a precise manipulation and not to commit errors during operation [12].

For continuum manipulators, the servo mechanisms are optimized by way of mathematical modeling. Wei et al. [20] have demonstrated that kinematics of the manipulator under various movement modes can be analyzed using position based finite element method (FEM). This modeling approach allows the predicting its behavior namely the 90 degree bending angle and contraction ratio 40

The servo mechanisms also support the functionality as described by Blanco et al. [21], the modular design of the manipulator. The manipulator achieves the required adaptability in order to navigate complex pipe geometries by connecting independent modules to a central contraction element. It also allows for integration of soft elements that increase the manipulator compliance and its interaction with the environment. It is possible due to the combination of servo mechanisms and a modular design, that the manipulator has the ability to perform high precision and reliability for the tasks.

Another important aspect of servo controls in continuum manipulators is evolution of control curvature radius, evaluated byDragone et al. [13]. The manipulator embeds permanent magnets within the robot body to change shape that causes its motion to rede. This capability is especially beneficial for scenarios in which disposability, an MRI-compatible package, and a small package size are highly constrained. Such integrated advanced sensing formulation to the servo system further improves the performance and adaptability of the manipulator.

Overall, these servo mechanisms are critical to control the motor of continuum manipulators to provide precise actuation and accommodation in the confined environments. Individual motors with their own control can be combined with very advanced modeling and unprecedented structural designs such that these systems are very reliable and efficient in such pipe inspection and defect detection applications.

### 3.1.2 TTL Bus Communication

The motor control systems of mobile robots rely heavily on TTL (Transistor-Transistor Logic) bus communication for precesison manipulation and feedback in those systems specifically. The digital signals with high reliability and low power consumption characteristic of TTL communication enables it to be used to control the individually actuated motors in the continuum manipulator. Since cable driven actuation is included in the design of the manipulator, a robust communication protocol that guarantees accurate motor adjustment in real time is necessary.

TTL bus works by transmitting binary signals on the bus where logical high and low states are represented by voltage levels normally lying between 0 and 5 V. The values in this voltage range nicely fit with the motor controllers' need for discrete signals to control cable tension and direction of motion. While the authors of [22] note that precise motor control is required through feedback mechanisms, such as inertial measurement units (IMUs) embedded into the system to track angular velocity and acceleration. This allows for the data to be passed from the IMU sensors to the motor controllers without any interruption, thus making for an easy and unbroken data relationship. For continuum manipulator, the modular design presents the need of synchronization of multiple motors while operating to maintain shape equilibrium, and reduce cable friction. ccording to Bai et al. [9], actuation redundancy and control accuracy are the challenges of cable driven systems. TTL bus communication is addressing the issues of motor actions coordination with a reliable interface which allows the decrease of error when adjusting the cable tension. In fact, the TTL signals also have a low latency, which enables real-time control, which is indispensable for keeping the structural integrity and operational efficiency of the manipulator.

# Chapter 4

# Sensor Technology

## 4.1 TENG Sensor Design

### 4.1.1 Principles of TENG

The triboelectric effect, which is the basis of the principles of TENG (Triboelectric Nanogenerator) sensor, is the process for two materials to come into contact and then apart from each other generating an electrical charge change. It is used to capture electrical signals which can be utilized for sensing purposes. The material properties such as electron affinity, surface roughness, and dielectric constant shape the working of triboelectric effect that govern the efficiency of charge transfer during contact and separation.

There are four fundamental modes of TENG sensors working mechanism: vertical contact separation, lateral sliding, single electrode and freestanding triboelectric layer modes. In particular, the vertical mode of contact separation is of interest as it includes the dynamics of periodically compressing and releasing two triboelectric layers. The generated charge density modulation due to this mode is an alternating current (AC) signal arising from dynamic changes in the contact area and separation distance.

The output voltage $V$ and current $I$ from a TENG sensor both mathematically can be modeled in terms of charge density $\sigma$, separation distance $d$, and capacitance $C$.

This is, for example, the case where $V = \frac{\sigma d}{\epsilon_0}$. In the same way, the current is obtained from the time derivative of the charge $I = \frac{dQ}{dt}$, where $Q$ is the total charge that accumulates on the electrodes. The dependence of the electrical output of the sensor is emphasized on the mechanical motion and material properties in these equations.

The TENG sensors can instead be integrated into continuum manipulators, such as the one in this project, whose use of them enables detection of contact with objects within confined spaces. In the embedded sensors, there exist real time feedback for interactions with the environment. Such feedback is critical for increasing the control and accuracy of the manipulator in tasks such as object manipulation and pipeline defects finding (e.g. cracks, bulged walls, etc.). Moreover, as the closing function of a helical tendon routing of the manipulator complements the functionality of TENG sensors, sensor organ placement can be stable on the platform and contact dynamics can be stable.

In addition, the advantages of high sensitivity, lightweight construction, and ability to harvest energy has made the use of TENG wires sensors more useful. They transmit the mechanical energy of the manipulator's movements into electric signals in such a way to reduce dependence on external power sources. Furthermore, this feature is especially useful for applications in remote or indisposed areas that require high energy efficiency.

For this application of the TENG sensors, the design of TENG sensors relies on optimizing the triboelectric materials and electrode configuration to yield TENG sensors that are reliable under changed operational conditions. Geometry of sensor, selection of triboelectric pairs, and integration method within the manipulator are evaluated carefully to make sure that it is compatible with manipulator's mechanical and electrical system. Testing the response of the sensor to various contacting scenarios and evaluating its durability in pipeline environments is done as experimental validation of the sensor design.

### 4.1.2 Voltage Generation

One of the key aspects of TENG (Triboelectric Nanogenerator) sensor functionality is the voltage generation, specifically for applications where it is important to have highly precise feedback, eg, for use in a continuum manipulator for pipe inspection. TENG sensors are fundamentally based on the generation of voltage from triboelectric effect and electrostatic induction. As a result, when two materials with different triboelectric properties come into contact and are separated, a charge transfer occurs, and opposite charges are accumulated on the surfaces of the materials. Electric potential difference is formed due to charge separation which can be utilized as a voltage output.

TENG sensors use triboelectric layer and electrode to interact with each other to work. For example, a negative triboelectric layer has been made of a flexible PDMSFDT film and positive triboelectric layer materials are PET, et cetera. The system is enhanced by integrating copper nanowires and reduced graphene oxide (CuNWs/RGO) electrodes as electrodes for improved conductivity and efficiency. These materials ensure that we have a robust and consistent voltage output that is required to detect contact and feedback in confined environments like pipelines [23].

A number of factors, including the material properties, surface area, as well as the relative motion between the triboelectric layers, can change the voltage output of TENG sensors. For instance, a 3D printed trimmed helicoid structure of the manipulator offers mechanical flexibility and also facilitates to optimize contact area for the triboelectric interaction. This kind of structural design will maximize the generated voltage when working on the manipulator, so that the objects or defects in the pipeline can be reliably detected.

Moreover, the simplicity and potential in various applications of the single electrode mode of TENG has attracted a lot of attention. In this mode, the output voltage is formed by inductive charges appearing on the lower electrode when negatively charged object (in hand or other surface) gets close to the sensor. However, such a mechanism permits not only accurate measurement of distance and contact but is also useful in human computer interaction and intelligent sensing field. This mode is capable of being fitted into the continuum manipulator, owing to the ability to adapt to its needs and the real time feedback is critical in case of effective operation [24].

Its ability to respond to such mechanical stimuli as bending or stretching enhances TENG sensor for dynamic properties. The structural sine wave shape integrated into the manipulator structure helps to distribute the stress more smoothly and reduce stress concentrations so that the mechanical integrity of the sensor is maintained. However, to guarantee that the manipulator can achieve consistent voltage generation regardless of changing mechanical loads [12] is critical to meet the performance demands in complex and confined environments.

In addition, the TENG-wire sensors integrated in the manipulator offer the contact detection ability, which is important information for controlling the manipulator. These sensors generate voltage which is an input to the control algorithms, such that the manipulator can move and stabilize. The high motion accuracy required for tasks such as defect detection and object manipulation within the pipeline is key, however, to enable this, the feedback loop in Eq. (2) is essential. Experimental results in similar systems have shown that TENG sensors are effective in maintaining controller stability and confident human-robot interaction, and thus their possibility in Collaborative and Assistive Robotic Systems [16].

Lastly, with structural design and the choice of materials, the voltage produced in TENG sensors exists by way of the triboelectric effect and electrostatic induction. Incorporating these sensors into the continuum manipulator improves its functionality, and ensures reliable performance in harsh environment. The significance of TENG in the applications of modern sensing and robotics is emphasized by the improvements in TENG technology such as single-electrode modes and optimized structural designs [12], [23], [24].

## 4.2 Sensor Placement

### 4.2.1 Disk Integration

For purposes of placing and functioning of the continuum manipulator's sensors in precise control and feedback during pipe inspection tasks, disk integration is important. Integration of disks is necessary not only for the purpose of structural support, but also for accurate routing and placement of driving cables and sensors. These disks have to be designed to meet both the mechanical and the sensing requirements, such that they balance rigidity and flexibility properly to maintain the manipulator's operational efficiency.

Driving cables are able to pass through evenly spaced holes of structural design of the disks. As an example, the first metal disk of the manipulator has a total of eight holes evenly distributed on said metal disk, four for the drives of the first segment and four for the second segment. The cables are routed this way so as to securely route the cables and provide proper separation between cables to prevent interference. The pair of adjacent cables have 90° spaced and the pair of the same spool cable is 180° spaced, with the intent to reduce the mechanical stress during the operation and maximize the actuation of the manipulator [25].

The disks are designed with certain features such that the integration of tension sensors and similar components could help enhance the manipulator's flexibility and control. For example, after the driving cable bypasses the pulley block, one end is fixed on a tension sensor and the other end goes through the holes of the disk cable to be connected with the last disk of the corresponding section. Thus, this arrangement can be used to measure the force exerted by the cable so that it always keeps up the consistently tension and never becomes slack. Furthermore, the pulley block serves to lengthen the stroke of the driving cable, which is important for providing the desired working range with as compact a control box as possible as stated in [26].

Inclusion of TENG-wire sensors into the disk body enables additional functionality for the manipulator. These sensors are strategically placed to detect contact with objects, providing real-time feedback for improved control and adaptability. Figure

4.2.1 highlights the three terminal disks carrying colour-coded TENG-wire electrodes. The placement of TENG-based sensors within the manipulator's disks allows for the monitoring of local bending angles and other critical parameters. Figure 5.2.1 visualises how each of the three instrumented disks reports contact events through the TENG-wire voltage. This integration not only supports the manipulator's ability to navigate confined pipelines but also contributes to its effectiveness in detecting defects and manipulating objects. The use of TENG sensors within the disks demonstrates their potential for multifunctional sensing, combining mechanical motion detection with other sensory inputs to achieve a comprehensive feedback system [23], [27].

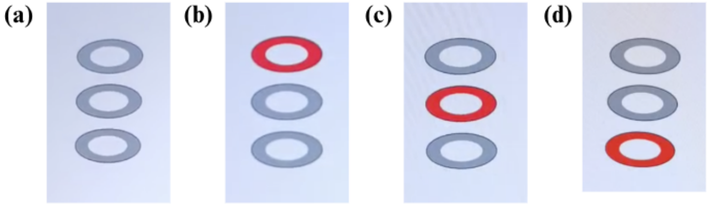

Figure 4.2.1: TENG-wire contact states for the three instrumented disks. Grey rings denote idle sensors; red rings indicate the disk whose TENG wire is generating a voltage spike. (a) baseline with no external contact, (b) contact on the upper disk, (c) contact on the middle disk, and (d) contact on the lower disk.

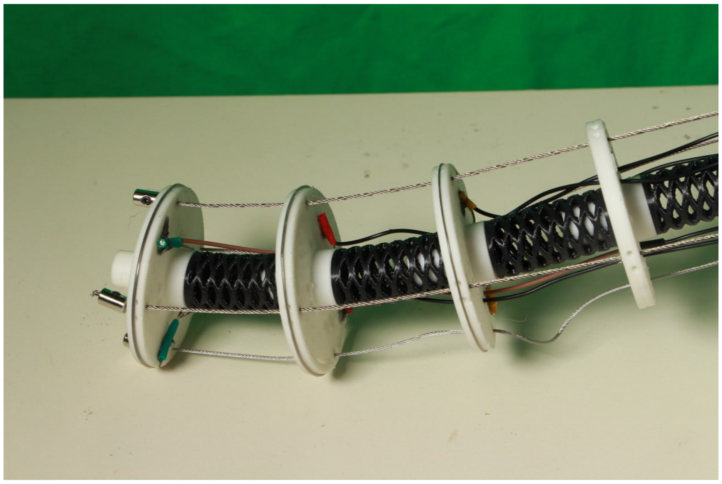

Figure 4.2.2: Terminal disks instrumented with TENG-wire sensors for contact detection and voltage feedback.

The disks also play a significant role in maintaining the structural integrity of the manipulator. The tendons used for actuation are symmetrically distributed along the main axis at 120° intervals, a design that ensures uniform force distribution and minimizes the risk of structural deformation. This symmetry, combined with the compact arrangement of the flexible arm structure and its associated driving components, results in a robust and efficient manipulator design. The integration of these elements into the disk structure highlights the importance of precise engineering in achieving the desired performance characteristics [16].

It should also be noted that the selection of materials and the geometric design of the disks are important for their suitability with the overall manipulator architecture. The rotational stiffness of the disks needs to be sufficient so as to prevent twisting, but at the same time they need to provide enough bending flexibility. This is achieved by carefully choosing the materials and optimising the disk's pitch, such that points of disk attachment to support disks are smaller and other areas are larger. In this paper, such design considerations are important to ensure the functionality and reliability of the manipulator during operation [10].

By integrating disks into the continuum manipulator, there is an interplay between mechanical design and sensor technology. The disks allow for accommodating driving cables, tension sensors, and sensors based on TENG, and provide a basis supporting advancing capabilities of the manipulator. Moreover, this integration is presented to provide manipulator performance improvement in confined pipelines and also highlights the significance of the exact engineering in the creation of the novel robotics system.

### 4.2.2 Sensor Calibration and Error Analysis

Calibration of the TENG sensor was carried out using a controlled test environment where certain input parameters (for instance forces or displacements) changed the output voltage. During calibration, the voltage exhibited on this sensor ranged from almost zero volts (no contact) to tens of volts at the maximum contact or deformation and all in between. For example the Figure 4.2.3 presents an ordinary sensor output response trace recorded when measuring sensor during calibration that illustrates the spectrum of reaction to repeated stimulus inputs.

The raw signals exhibited an amplitude jitter that corresponded to a few millivolts, the usually dominant cause of which was ambient vibrations and electronic interference. With time, a clear shift in the baseline voltage was observed as the materials of the sensor equilibrated. Without correction, these factors may lead to false data readings.

In order to address such concerns, we implemented a variety of signal processing strategies on the data collected by the sensors. In order to reduce false readings due to insignificant vibrations, a threshold was established, so that any voltage fluctuations below 0.5 V were marked as noise. Additionally, the application of a low-pass filter reduced the high frequency noise and the moving average filter was used to reduce the variability of the read outs over time. The use of these techniques combined dramatically reduced erratic signals and increased the consistency of the reports made by the sensor. Insights gained from a histogram of baseline output noise as illustrated in Figure 4.2.4 were used to determine the optimum noise threshold.

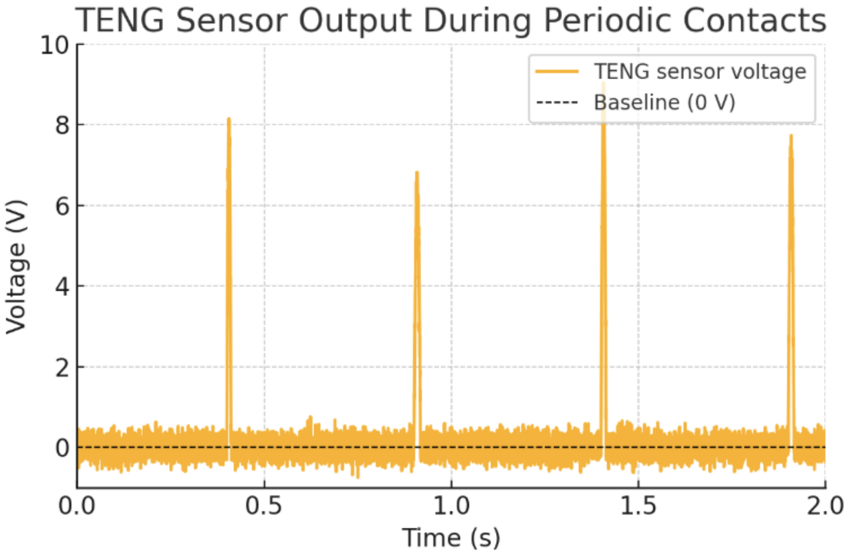

Figure 4.2.3: The sensor's voltage output over time during a calibration test

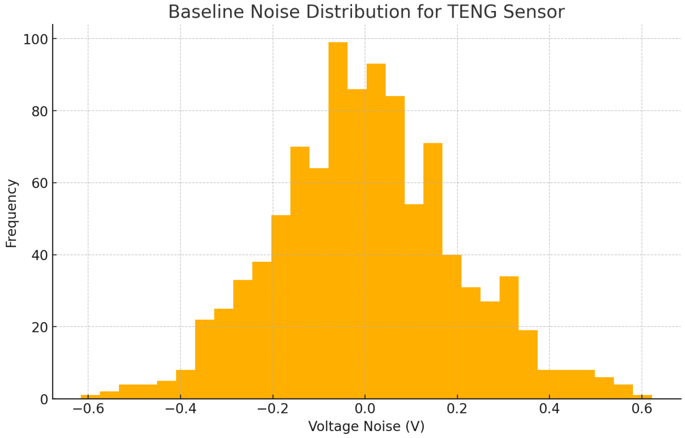

Figure 4.2.4: A histogram of the TENG sensor's output voltage.

# Chapter 5

# Performance Evaluation

## 5.1 Simulation Techniques

### 5.1.1 Model Validation

It is necessary to validate the model of the continuum manipulator designed for pipe inspection on its way to the continuum manipulator in order to validate the model, as it employs mathematical models which simulate continuum manipulator behavior. Fidelity of the model is validated by comparing with experimental data or theoretical predictions which in turn evaluates how well the model simulated results.

Design of the continuum manipulator based on a 3D printed trimmed helicoid structure and motors individually controlled to adjust cable tension leads to unique modelling problems. To control the movement of the manipulator in the confined pipelines, precise control mechanisms are required and this is supported with TENG-wire sensors that feed information about contacts with objects. Due to the fact that the manipulator system is nonlinear, it is necessary to include the nonlinear dynamics that are necessary in the manipulator system in order to validate the model. The cable tensioning system is nonlinear, as is the interaction between the manipulator and the pipeline walls, and the helicoid deformation during maneuvering. However, these factors demand advanced simulation techniques that can predict the manipulator's behaviour with sufficient accuracy.

[9] states that for effective control, the authors outline that model based control methods require mapping actuation space, joint space, and task space. This mapping must be enhanced for its accuracy, for this will help in the validation process since it will ensure that the simulated manipulator's movements correspond with its physical counterpart. Furthermore, the feedback provided by the TENGwire sensors can be integrated into the model for real time adaptation because the feedback is integrated in real time into the model to make it better capable to adapt to changing environments. This is important in detecting defects in pipelines because the manipulator can react to changes in its environment.

Interpretability of models is very important for applications such as medical surgery where insight into how the model works, i.e., what is the logic behind predicting 1 versus 0, increases trust of the user and mitigates operational risk. In the second case, interpretation and reliability of the model predictions are ensured in the validation process in the pipe inspection context. This entails studying how the model behaves in reaction to several input situations including modifications in cable tension or contact forces and contrasting that behavior to those obtained in experiments. Assessing the model's ability to replicate the manipulator's behaviour under these different scenarios (based on the parameters given) can thus be done by doing so.

In the authors describe testing of the controllers for continuum manipulators in synthetic simulation environments. The interaction with obstacles of the manipulator was modeled using splines whose axes are defined with control points. By adapting such techniques for the pipe inspection manipulator, one can simulate its motion in confined space and validate its ability to go around obstacles. Comparison of simulation results with the data from the prototype tests can confirm that the model reflects the actual physical behaviour of the manipulator.

Also, hybrid modeling approaches, as mentioned in [6] provide a means to better validate the model by creating a hybrid of a theoretical model and a data–driven model. This allows horizontal integration of various degrees of motion and sensory feedback into the model from the complex dynamics of the manipulator. The accuracy of defect detection and object manipulation using the manipulator can be validated against experimental data by using the hybrid model.

As the authors in [15] state, solving the optimization problems helps obtain task specific equilibrium configurations of the continuum manipulators. With respect to the validation of the model, optimization techniques can be used to tune the model parameters so that the simulated manipulator has these desired equilibrium states during operation. Since this approach can be useful in verifying if the manipulator has enough stability to reach and pass through the pipelines, the task is designed to be rigidly intuitive.

Finally, the validation process requires considering the model's robustness to the variations of hyperparameters and tuning, as it is mentioned in [25]. The DDPG algorithm is effective in continuous spaces, however, due to irrelevant errors in the Q function, it experiences end up in policy collapse. And to address this, the validation process should be performed through running sensitivity analyses to check how the model performs with different parameter settings. This way, the model is made reliable and robust enough to be applied under different operating conditions.

## 5.2 Experimental Setup

### 5.2.1 Test Environment

A range of test environment was meticulously designed to simulate real world confined pipeline situation for the evaluation of the performance of mobile robot designed for pipe inspection. The continuum manipulator incorporated in the experimental setup consisted of individually controlled motors to offer adjustments of cable tensions for movement in multiple directions. A 3D-printed trimmed-helicoid manipulator was integrated with TENG wire sensors, which were used to detect contact with objects to provide crucial feedback for more efficient and enhanced control during operation.

Experimental layout included a controlled pipeline simulation platform that was necessary to ensure assessment of maneuverability and object manipulation capabilities of the robot. Under different conditions, the capability of the manipulator to navigate through the narrow and curved sections of the pipeline was tested. Disturbances experiments were executed to prove the robustness of the system, modifying the stability and precision of the manipulator when 1 kg of weight was applied to test it [16]. Furthermore, the experimental design involved using a VICON® system to measure the motion and orientation of the robot as it moved, in order to track the performance of the robot [14].

After this, experiments were carried out using various magnitudes of weights, in order to evaluate the manipulator's payload capacity and rigidity. For example, it was evaluated on a 175 g weight to determine whether the manipulator could lift and manipulate objects effectively. From these tests, it was shown that the PTM manipulator dominated other prototypes, achieving higher lifting weight and better rigidity in the slack wire conditions [11]. In addition, challenging conditions for measurement performance are included in the experimental setup, the case where the manipulator is bent along the coordinated axes. As a reference, ground-truth data measured by the IMU was used to calculate errors of an optical module with error metrics, such as root mean square error (RMSE) and mean error [13].

The experimental test environment also included a multistage inspection platform in order to validate the manipulator's capabilities in typical aeroengine inspection scenarios. A platform built from real data using this challenge (like confined pipelines) was used to evaluate kinematic decoupling control method of the manipulator and the described tendon driven mechanism [2]. Additionally, the experimental tests analyzed soft joints of the manipulator with the different inputs and the movements and pointed out that the tendon length ratios and the workspace constraint are essential in achieving optimal performance [28]. Another focal point of the test environment was results of real time manipulator configuration. Actuated lengths, bending angles and estimated end disk attitudes were measured and compared to measurements from the IMU. The robustness and utility of manipulator in real time application was shown through the average attitude error over different sections of manipulator which was as low as 1.6 degrees for certain sections. Additionally, it demonstrated that the manipulator was able to carry out the smooth transition within 25 seconds, achieving higher manipulator capabilities for aerial manipulation tasks compared to that of manual operations (reaching more than 60 seconds for one task in [29]). The reachable workspace acquired during free space tele operation trials is shown in Figure 5.2.1.

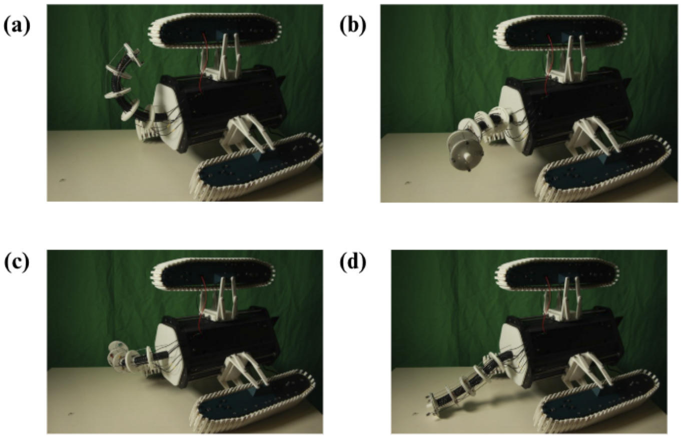

Figure 5.2.1: Furthermore, the reachable workspace of the continuum manipulator during free-space tele-operation was demonstrated: (a) Up (b) Left (c) Right (d) Down

To assess performance metrics for a manipulator, including stiffness ratio $\lambda_{\text{stiff}}$, varying tendon actuation modes should be considered in the test environment. Coupled tendons between adjoining sections and the separation created by routing the tendons with Bowden cables were two of the modes used to understand the manipulator's adaptability and structural integrity [12]. We also highlighted the necessity of anchor blocks in acquiring features and creating output vector of bounding box coordinates along with forecast confidence scores [4] for detecting defect in the pipelines.

### 5.2.2 Dynamic Response and Actuation Performance

We ran a variety of motion instructions to observe how the system responds, using VICON motion capture to analyze it and evaluate the manipulator's dynamic performance. The system's efficiency is characterised by a critical metric called the *rise time*, which is the time that manipulator requires to get close to about 90% of its position. Our tests required 0.5 s for the system to reach 90% of the commanded position in standard step input, although the magnitude of the motion affected this. One of the parameter characteristics of the system's performance displays a reduced *steady-state error*: Once the system had stabilized the error between the desired and the actual position had been minimal, most of the time it was simply a fraction of the full motion range. The manipulator had slight overshoot in step responses, which indicates that the actuation and control system can drive the system to the desired position but not with large oscillatory behavior.

The system not only demonstrates its accuracy but also it is clear that the system is also responsive from its ability to comply time-varying commands. When required to exhibit sinusoidal movements or step instructions, the continuum robot proved to have tight tracking of the desired path with only a minimal delay in response.

Accompanied by the qualitative plots, the numerical ones are offered in Table 5.1, showing performance. The results of various test-cases are tabulated in the detailed form displaying both commanded target positions and final steady-state positions achieved. Once the system reaches steady state, steady-state error has been defined as the difference between the actual position and the commanded target. A look at the example values in the table proves that the deviations from the target positions are small with consistent and accurate positioning from the system.

Table 5.1: Comparison of commanded vs. actual positions for the continuum manipulator.

| **Commanded Position** | **Achieved Position** | **Steady-State Error** |
|---|---|---|
| 30° | 28.5° | 1.5° |
| 45° | 44.2° | 0.8° |
| 60° | 59.0° | 1.0° |

# Chapter 6

# Future Directions

## 6.1 Technological Advancements

### 6.1.1 Sensor Improvements

Improvements to the sensors in the context of pipeline inspection robots are a key means to increase the accuracy, efficiency, and versatility of these systems. This will be a major advancing step to manufacturing reliable object manipulation within confined spaces combined with defect detection for the integration of more advanced sensing technologies such as TENG wire sensors. These triboelectric nanogenerator (TENG) sensors are able to output specific voltage signals for contact with different materials and structures. With this capability, feedback can be provided in an exact manner which is vital for optimization control mechanisms and successful navigation and manipulation of complex pipeline environment [27].

TENG-wire sensors have advantages that include the capability of differentiating between the target materials glass, PTFE, PMMA, nylon, Kapton, paper, and skin. They differentiate through variations in the voltage signal due to contact between the materials and are a result of the triboelectric properties of the materials. Additionally, the sensors can learn to new possible configurations of the structure considering that the contact situation may change with changes in the target structure. This makes the sensor adaptation necessary for the producers to maintain usable, consistent sensing performance in constantly changing, unpredictable pipeline environments [24], [27].

Shape sensing as another step of sensor technology consists of methods which are insensitive to positional errors. These methods require less sensors, yet have great accuracy with high resolution, which reduce cost and enhance the efficiency. For example, closed loop control systems based on sliding mode were utilized for the improvement of the precision of shape sensing models that aid continuum manipulators working in small environments. Improvements in sensor design and calibration work as a whole to enhance the overall reliability and functionality of the pipeline inspection robots [30].

Continuum manipulators further testify the progress achieved in the sensor technology by the integration of fiber Bragg grating (FBG) sensors. One can control these sensors to detect bending and curvature with high sensitivity and obtain real time shape detection and tracking of large deformations. For deploying soft robotic systems on pipelines accurately (to navigate and manipulate objects), this capability is most advantageous. Optic fiber arrays coupled to FGB sensors increase precision of shape detection and improve the robotic system as a whole [3], [9]

Advancements of sensor capabilities are in turn supported by multi sensor fusion systems. Various techniques including artificial landmark generating and moving average filter have been investigated to improve the performance of SLAM (Simultaneous Localization and Mapping) in pipeline environments. With these advancements, robots can better explore pipelines to inspect them with greater accuracy and efficiency especially when Pipeline inspection is a function that robots must execute in confined complex spaces [22].

It has further been determined to optimize structural designs in continuum manipulators as a way to enhance bending measurement performance. Researchers adjust the number of elements and directions of the rotation axes of rolling-joint kinematics to decrease mechanical compliance and tendon slackness. The structural enhancements contribute to the overall accuracy and reliability of sensor systems, where the sensor systems allow pipeline inspection robots to perform under the highly variable operating environment [13].

The use of NC-TENG systems also further reveals the possibility of gaining from sensor improvements. While these devices are still infantile, they are highly promising devices intended to be used in sensing field. Researchers hope to realize the sensitive and efficient sensing effects by connecting multiple non-contact devices to establish high performance sensing network. Such networks help to assure individual sensors are running independent from each other and thereby enhance overall functionality of the robotic system [24].

Finally, actuator reduction methods such as helical and polynomial tendon routing are examined in achieving precise positional and shape accuracy with the inclusion of sensor integration. They give parallel tip orientation at various positions to provide consistent sensor feedback and control. Researching actuating loading, power consumption and friction allows to optimize sensor performance and make sure robust operation of pipeline inspection robots becomes possible as stated in [10].

Based on the above sensor technologic advancements, it shows about the existing attempts to enhance the capabilities of pipeline inspection robots.

### 6.1.2 Integration with AI

The introduction of artificial intelligence (AI) in the development of mobile robots for pipe inspection is a major technological progress, which can improve the ability and adaptability of continuum manipulators. This allows for the control of the cable tension in the manipulator to be optimized by AI driven systems, such that precise movement can be achieved in extreme and complex environments. The robot uses machine learning (ML) algorithms to dynamically change its behavior as a result of real time feedback from TENG –wire sensors that sense contact with objects, and provide key data for navigation and manipulation tasks [27], [29]. Considering that feedback, this loop helps the robot to refine its movement making defect detection accurate and object manipulation reliable in pipelines.

AI techniques such as artificial neural networks (ANNs) can be applied to extend the capabilities of the mathematical modeling of the manipulator's motion by being able to emulate the forward and inverse robot models. These models allow for the validation of control hypotheses and increase the robot's capability of performing intricate tasks (tracking and reaching in confined spaces) [15]. Also, reinforcement learning (RL) methods can be used to train the robot when supervised data collection is difficult, for example, in physical interaction tasks in unstructured environments. With RL, the robot can learn the optimal ways to navigate through pipelines and to interact with objects overcoming the constraints of the traditional control approaches work [1], [15].

Furthermore, the design and optimization of control algorithms are also made using AI. For example, in interdisciplinary decision making processes appropriate orientation representation methods can be selected, which considerably increase accuracy and complexity of manipulator's control system. This way, the robot movements are synchronized with the desired path and therefore, the efficiency of the robot for inspection and maintenance applications [6] increases. Besides that, AI is also helpful in creating teleoperation interfaces that allow the operators to control the robot remotely with ease and precision. Some of these interfaces can contain predictive models that predict what the operator will tell the machine to do and make the human machine interaction more efficient.

Extending these capabilities, the AI is incorporated into the manipulation fabrication process of the manipulator. These structures make the manipulator more flexible and durable to be better suited for navigating through pipelines of various shapes and sizes. Furthermore, the development of manipulators that can adapt to varying environment conditions can be explored using the concept of 4D printing where the material possesses the ability to change properties over time [24].

For autonomous aerial manipulation tasks (robot requires navigating through cluttered and unstructured environment), AI driven whole body planning techniques are of particular use. Using these techniques, the robot is able to effectively plan their movements to avoid obstacles and to perform complex things such as contend objects and return to their initial position. Through incorporating AI in the planning stage, the robot is able to gain an elevated amount of autonomy and in adaptability, enabling it for inspection and maintenance purposes in pipeline [29].

The use of AI for providing an insight to sensor fusion algorithms helps the robot's localization and navigation. AI can utilize data from multiple sensors to create a complete image of its surroundings and the movements to take based on the data they have collected. In challenging environments for operations, such as pipelines, accurate positioning and navigation are particularly critical to be able to achieve completion of a task. Furthermore, AI can enhance the path planning algorithms to allow the robot to reach the desired position as efficiently as possible and reduce energy consumption as well as avoid risky situations [7].

Authors of outline continuum robots as continuum based robots which have infinite theoretical degrees of freedom, thus giving a way to design a highly dexterous tool responsive to bending and kinding at certain points. These capabilities can be improved further using AI, to allow the robot to change its shape and position in accordance with changes in the environment. The flexibility is the key feature to several acts like defect detection and object manipulation that need to be precise and flexible [3].

The designed manipulator can further optimize the integration of TENG wire sensors into the manipulator through AI leveraging. Because they can detect structural and material types and are known for flexibility, high accuracy, and self-powered nature, these sensors can be used in pipelines. The data collected by these sensors can be analyzed by AI algorithms for finding the patterns and anomalies and help in defect detection and maintenance planning [27]. In addition to improving the robot's function, this integration also aids the development of more intelligent and autonomous inspection systems.

This is a huge leap for mobile robotics in combining AI into design and operation of the continuum manipulator. AI combined advanced control strategies, with machine learning techniques and novel fabrication methods which make it possible for the robot to attain extraordinary levels of precision, adaptability, and efficiency in task of pipeline inspection and maintenance.

# Chapter 7

# Conclusion

The latest developments of mobile robotic systems for pipe inspection highlight the great potential of continuum manipulators as effective mean of navigating confined and dynamic environments. The demand for integrating cutting–edge mechanical designs, robust tension control mechanisms and sophisticated modeling techniques when building these systems has emerged through the necessity to increase the operational capabilities of these systems. Using 3D printed trimmed helicoid structures demonstrates how innovative design can produce lightweight lightweight framework that is durable and wear resistant of mechanical wear and environmental stressors.

Flexibility and resistance to various conditions of the manipulators are mostly achieved by the strategic arrangement of components, especially of those using superelastic NiTi alloy. This design approach serves to enhance such intricate movements that may be required for tasks such as detecting defects and manipulating objects, as well as provide structural stability through methods such as magnetic repulsion, which helps to achieve a uniform spacing of the disks. To further improve on the dexterity and responsiveness of such manipulators, individually controlled motors are incorporated for cable tension management.

Moreover, the integration of advanced sensor technologies, such as triboelectric nanogenerator (TENG)-wire sensors, elevates the operational capabilities of these robotic systems. These sensors provide real time feedback about contact with the surface and thus they allow for an adaptive manipulation strategy, without which the interaction with the environment is not effective. As a foundational tool, mathematical modeling and finite element analysis simulations provide the application through which manipulator behavior may be dictated towards the design of optimal manipulator systems, that is, in compliance with the specificities of a given problem such as pipeline inspection.

With the benefits of variable flexibility, force output, and adaptability form different deployment of mechanics, continuum manipulators have been evolved through innovations in actuation mechanisms, such as the cable driven, hydraulic, and pneumatic systems.

The outcome will be to further develop the Biophysical Cobot through interdisciplinary sprit between Material Science, Robotics, and Control Engineering as the field progresses in order to address the multidimensional hurdles that the confined environments will pose. These robotic systems can navigate complex geometries and hazardous environments and the advantages are the reason that they can be deployed in several industrial applications. Future exploration of innovative designs, more sophisticated control strategies, and integration of more sensors will make some contribution to the future development and trajectory of mobile robotic systems for pipe inspection. The confluence of technology and engineering will result in more bled and versatile solutions to robotic inspection and manipulation, thus the new solutions created here will have a significant influence on industries who rely on pipeline integrity and maintenance.

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