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MODELLING AND CONTROL OF TENDON DRIVEN CONTINUUM ROBOT

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Abstract — This work is focused on the design, modelling, fabrication, and control of a tendon-driven continuum robot prototype. The TDCR arm developed in this work achieves the flexibility, mobility, compliant actuation and lightweight mechanical design. Interconnected segments that are actuated by tendons controlled by a motor-driven pulley system, allow movements more natural than traditional robots. The robot will be tested in a simulated environment, and its performance will be compared to existing devices. The robot movement was stable and showed no more than a 2% deviation from the simulated model's results.

Indexed terms **— Kinematic Modelling, Robotic Arm, Servo Control, Tendon Driven Continuum Robot**

I. INTRODUCTION

Robots are becoming an increasingly important part of everyday human lives. There is a rapidly growing necessity to automate tasks, improve production rates and perform precise inspection in the engineering industry. The necessity for robots in Biomimetic also remained ever rising.

Robotics is a multidisciplinary field that integrates engineering, computer science, physics, and mathematics to design, manufacture, and program devices capable of doing tasks independently or with minimum human interaction. The design and building of robots, also the development of algorithms, software, and systems that allow robots to sense their surroundings, make decisions, and complete tasks, are all part of the area of robotics.
There are various different types of robots, respectively with its own function.

One of the main obstacles in robotics is designing robots that can operate in unstructured environments and adapt to changing conditions. Another challenge in robotics is the improvement of robots that can work efficiently with humans. In order to overcome these challenges, researchers are working on developing robots that are designed to be intuitive and easy to use, as well as robots that can interconnect efficiently with humans.

Tendon Driven Continuum Robot

Tendon-driven continuum robots outperform rigid link serial manipulators with dexterity and manipulability. Because of their ability to adapt to complicated curves in 3D space, continuum robots are particularly effective for applications in limited and difficult-to-access settings. Unlike typical rigid robots that utilise joints and motors to move, continuum robots are made up of a sequence of flexible segments that resemble the body of a snake. These parts are often composed of soft materials like silicone, rubber, or polymers, allowing the robot to bend, twist, and contort into a variety of forms and sizes.

TDCRs move by using cables or tendons that are run across the span of the robot's segments. These tendons are attached to a motor at the base of the robot and may be pushed or released, causing the segments to bend and flex. The robot can move in a number of ways and execute a broad range of jobs by managing the tension and release of the tendons, from grabbing and manipulating things to conducting surgical operations.

These robots are ideal for inspection and maintenance of pipes, ducts, and other confined spaces. They can also be used in medical applications, such as minimally invasive surgeries, as their soft, flexible structure allows them to move and manipulate tissue without causing damage.

Additionally, their shape and size can be easily modified to suit the task at hand, reducing the need for multiple specialized robots.However, there are also some challenges associated with tendon-driven continuum robots. One of the main challenges is controlling the motion of the robot. Because the

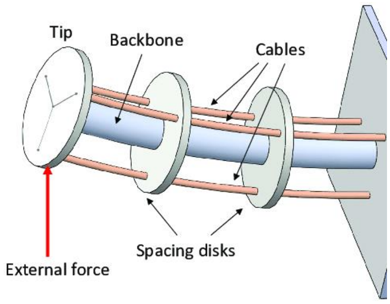

Fig. 1 - Tendon-Driven Continuum Robot

robot's segments are flexible, it can be difficult to accurately control its movement and position. Additionally, the tendons can experience wear and tear over time, which can affect the robot's accuracy and precision.

II. LITERATURE REVIEW

J. Wu, et al (1) presents a design and analysis of a TDCR actuated by servo motors. The proposed robot consists of three sections, each driven by a single servo motor. A dynamic model is developed to describe the behaviour of the robot, and simulations are conducted to evaluate the robot & performance. The results show that the proposed design can achieve a high precision and a large workspace.

Y. Sun et al (2) proposes a real-time control system for a TDCR actuated by servo motors. The proposed system includes a control algorithm and a hardware platform. The control algorithm is based on a dynamic model of the robot and can achieve accurate control of the robot position and force. The hardware platform includes a microcontroller and a motor driver, which can provide real-time control signals to the servo motors. The experimental results demonstrate the effectiveness of the proposed system.

M. Li, Y et al (3) presents the design and fabrication of a TDCR actuated by servo motors for endoscopic surgery. The robot consists of three segments, each actuated by a servo motor. The robot kinematics and dynamics are analysed, and a control algorithm is developed to achieve precise control of the robot position and force. The robot is fabricated using 3D printing technology, and experiments are conducted to evaluate the robot performance. The results demonstrate that the proposed design can achieve a high precision and can be used for endoscopic surgery applications.

N. Dehghani et al (4) proposes a design, modelling, and control approach for a TDCR. The robot consists of multiple segments connected by tendons, and the model takes into account the nonlinearities of the tendons and the backbone. A control algorithm based on feedback linearization is developed to achieve accurate control of the robot position and force. The experimental results demonstrate the effectiveness of the proposed approach.

III. DESIGN METHODOLGY

Continuum robots are constantly bending, eventually twisting and extending have no joints and hence are made of flexible, elastic, or soft materials. To have a continuum robot move along a predefined path, deploy into a cluttered environment, we must first describe the connection between joint space and task space. This kinematic mapping is critical for any robot's motion planning and control.

Mapping between Joint and Task Space

Continuum robots can be thought of as slender structures, that is, structures that are much longer in one direction than the other two. This slender structure bends continuously and is represented by a space curve. As a result, we model continuum kinematics using a frame that evolves along a continuous backbone that is parameterized by arc length. The backbone's local motion at a point is modelled in terms of the local frame. This strategy enables the computation of forward kinematics and the construction of continuum Jacobians, similar to rigid-link systems.

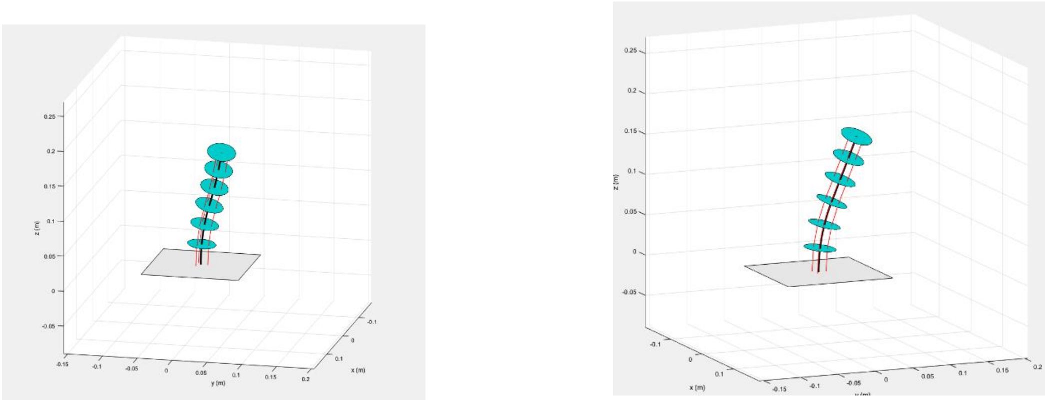

Fig. 2 (a) and (b) - Modelled TDCR using Constant curvature frame work

Constant Curvature Kinematic Framework Approach

The majority of continuum robots share the property that the resultant backbone can be approximated by a serially connected set of constant curvature sections.

This is due to the following:

1. All extrinsic and basically actuated continuum robots create a series of connected sections
2. Internal potential energy in every section is equally distributed; and thus, within every section, inner forces act to drive the un-actuated (passive) degrees of freedom to balance in value along the section.

Constant curvature Kinematic frameworks represent the configuration space of a continuum robot as a finite number of mutually tangent curved segments, each with a constant curvature along its length.

In this framework, the curvature, length, and angle of the bending plane of each segment - known as the arc parameters - form a set of configuration coordinates that completely describe the robot's shape. The position and orientation of the robot at any point can be expressed as a function of the arc parameters and the length of the arc along the backbone to that point.

Steps to Modelling

- Selecting the Backbone Parameterization.
- Deriving the Force and Moment Equilibrium Equations
- Formulating the Constitutive Equations

MATLAB Simulations

This code implements various approaches to modelling t
he kinematics/statics of a tendon-driven continuum robot that are currently available.

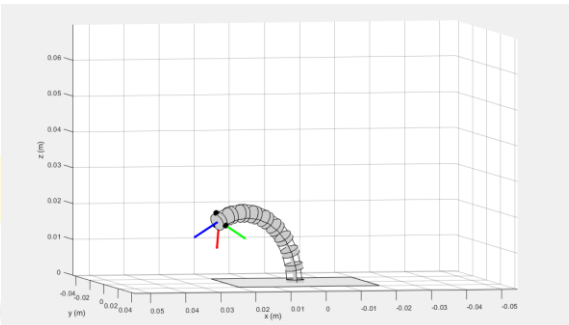

Fig. 3 - Externally loaded robot displacing

The implementation takes into account a two-segment TDCR with four tendons per segment that is subject to an external load at the robot's tip.

Parametric approach to choosing disc dimensions and backbone material

The size of the disc will directly affect the range of motion, precision, and force output of the robot, so it is important to choose the size that is best suited to the specific application. The most important details when choosing a disc size for a TDCR are the required range of motion, precision, and force output. Smaller discs provide greater precision, while larger discs provide greater force output due to the tendons being able to exert greater tension on the disc.Ultimately, the choice of disc size for a TDCR will depend on a range of factors and requires some experimentation and simulations to determine the optimal size for the specific application. Assuming a fixed robot length of 200mm, a single segment, and a range of disc diameters from 25mm to 55mm, with the backbone made of Nylon Polyamide. A maximum load of 3N or 300g was considered:

A parametric study was conducted using MATLAB modelling to evaluate the performance of a single-segment TDCR with different disc sizes. The simulation involved exerting a constant force on the tendons and measuring the resulting force output and precision. An evaluation of the TDCR performance with 7 different disc sizes, ranging from 25mm to 55mm in diameter, in 5mm increments.

The results of the parametric study are shown in the table below:

Disc Dia. (mm)	Maximum Force Output (N)	Precision (mm)
25	1.95	0.15
30	2.50	0.19
35	2.98	0.23
40	**3.66**	**0.28**
45	4.19	0.33
50	4.66	0.38
55	5.10	0.44

From the table, we can observe that as the disc size increases, the maximum load capacity of the TDCR also increases. The precision of the TDCR, however, decreases as the disc size increases. As a disc diameter of 40mm is optimal to bear a load of 300g, it was selected. The disc was 3D printed using PLA plastic to achieve accurate channels for tendons, durability, strength, and lightweight.

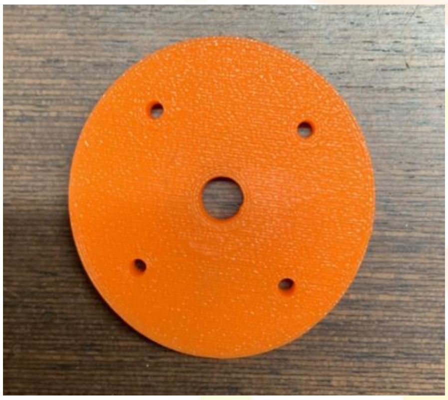

Fig. 4 - 3D printed TDCR disc

Fig. 5 - Assembled TDCR arm with backbone, discs and tendons

Additionally, the material used to create the backbone of the robot also impacts its performance. Nylon Polyamide is known for its high strength, stiffness, and durability. Thus, it is used as the material for the backbone of the robotic arm.

Actuators

Some of the possible actuators that can be used for tendon-driven continuum robots are:

- Servo motors
- Pneumatic actuators
- Shape memory alloys
- Electroactive polymers
- Magneto-rheological fluids

Thus, there are many possible actuators that can be used for tendon-driven continuum robots, each with its own advantages and disadvantages.

Servo Motors - Actuator choice

Servo motors are often considered the best alternative for tendon-driven continuum robots due to their precision and control. While traditional motors may be too large and heavy for use in tendon-driven robots, servo motors are small and lightweight, making them well-suited for this application. Servo motors can be controlled with great accuracy, this is important in high precision applications. In addition, servo motors are highly customizable, allowing them to be tailored to the specific needs of the robot. This means that the torque, speed, and other parameters of the servo motor can be adjusted to match the requirements of the robot's movement.

Another advantage of servo motor is their ability to provide feedback on their position and velocity. This feedback can be used to improve the accuracy of the robot's movements and to ensure that the robot is operating within safe parameters.Overall, servo motors are an excellent alternative for tendon-driven continuum robots due to their precision, control, and customization. Pulleys coupled with the motors are used to provide tension on the tendons to actuate the arm and bring about the motion on the TDCR arm. MATLAB is used to establish the maximum displacement of the tendon, and the pulley is designed to provide this displacement to the TDCR arm.

Fig. 6 - Servo motor with pulley

Control Methods

Automation

Automation plays a crucial role in the development and operation of any robot. It can be used in tendon-driven continuum robots in several ways, such as controlling the tension in the tendons, planning and execution of movements, and improving safety and reliability. Automation can be achieved through sensors and feedback mechanisms that monitor the tension in the tendons and adjust it as needed. It can also be achieved through algorithms and software that optimize the robot's movements based on the specific task at hand. Automation is a critical component of tendon-driven continuum robots, as it can greatly improve efficiency, accuracy, and safety.

Real-time control - Joystick

The team devised a method of controlling TDCRs through the use of a joystick interfaced with an Arduino microcontroller and Processing software. The Arduino receives signals from the joystick and then sends signals to the robot's motors, which adjust the tension in the tendons to achieve the desired movement. Processing software is a programming language and environment that is particularly well-suited for controlling robots, as it allows for the creation of graphical user interfaces (GUIs) that can be used to control the robot's movements

The use of a joystick interfaced with Arduino and Processing software provides an accessible and user-friendly interface for controlling the TDCR.

The joystick also enables fine control over the movement of the TDCR, allowing the operator to adjust the tension in the tendons and move the robot in various directions with a high degree of precision. Additionally, the use of Arduino and Processing software provides the TDCR with a level of automation that can enhance its efficiency and accuracy. Sensors and feedback mechanisms monitor the tension in the tendons and adjust it as needed, ensuring that the robot can achieve the desired movements

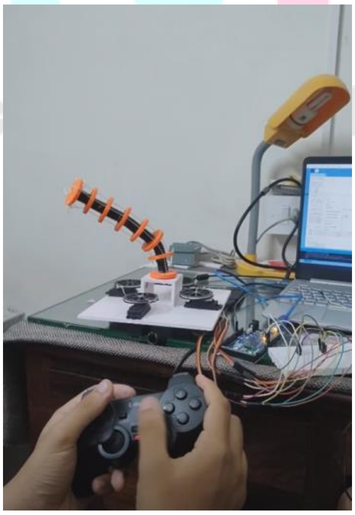

Fig. 7 - Using a joystick to control the robot in real-time

IV. CAD Modelling

Base Design

The design of the base for a Tendon-Driven Continuum Robot is essential for its functionality and effectiveness. It must be sturdy and durable enough to support the robot's weight and movement, with channels in the base to allow the motors to be mounted securely and in the correct position.

Slots for motors must be accurately placed and sized to ensure they can be mounted and aligned correctly, considering their dimensions and any mounting hardware. And they must be positioned in such a way that they can apply tension to the tendons in the correct direction and with the appropriate force.

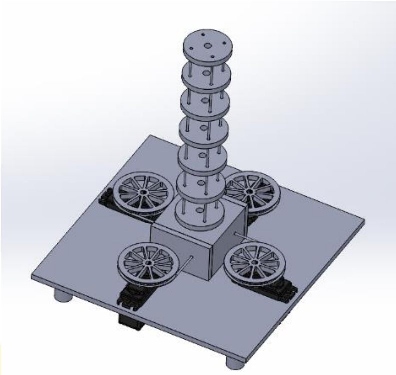

Fig. 8 - CAD Model of the base with the TDCR arm and actuators

The CAD model design for the base of a TDCR with holes for motors required careful consideration of structural integrity, the size and placement of the holes, and any additional features or components. This design was optimized for optimal performance and functionality, enabling the robot to achieve precise and accurate movements.

Pick and Place system

There are several options for pick and place mechanisms for Tendon-Driven Continuum Robots (TDCRs), including:

- **Gripper mechanism**
- **Suction cup mechanism**
- **Soft gripper mechanism**
- **Electromagnet mechanism**

The pick and place mechanism operate by an electromagnet. This system is simple to use and, most importantly, lightweight. An electromagnet is positioned above the object to be moved, and when the magnet is energized, it creates a magnetic field that attracts the object. The magnet can then be de-energized, causing the magnetic field to disappear and release the object. The electromagnet is then moved to the desired location, where it is energized again to pick up the object and transport it to its new location

Interchangeable End effector

A Tendon-Driven Continuum Robot (TDCR) can have different end effectors that are designed for specific tasks. The electromagnet pick-and-place mechanism of the TDCR is easily screwed in place. The flexibility to replace the end effector to execute different jobs at any moment makes the system modular.The electromagnetic mechanism can be easily detached and replaced with another end effector, say a hand drill to perform different tasks.

V. RESULTS AND DISCUSSION

It can be seen that both simulated and experimental methods give similar results to the position measurement. The error here is less than 2%. The developed system's performance was evaluated by testing the continuum robot with simple geometric trajectories and load at the tip. The robot is able to pick and place an object weighing 30N, i.e 300 grams approximately, from station A to B 300 mm apart. We were able to make the pick-and-place operation completely automated. The robot movement was stable and showed no more than a 2% deviation from the simulated results of the robot movement on MATLAB.

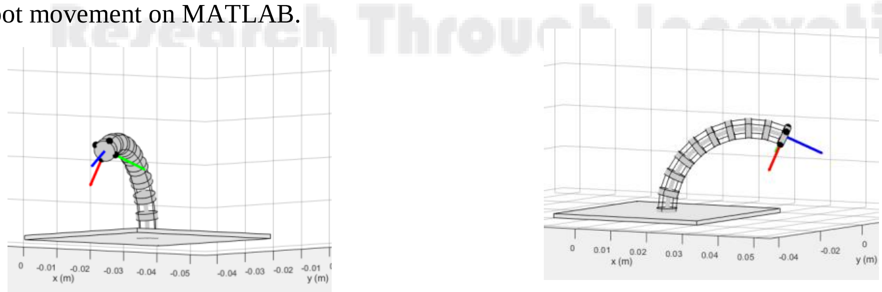

Fig. 9 (a) and (b) - Position measurements

MATLAB simulation are used to predict and analyse the position measurements of the Tendon Driven Continuum Robot (TDCR). The simulation incorporates a variety of parameters, such as the number and type of tendons, the shape of the robot, and the mechanical properties of the tendons and backbone as well as their dimensions. The simulation provides valuable information about the accuracy and precision of the TDCR's position measurements, as well as identify any potential sources of error or areas for improvement.

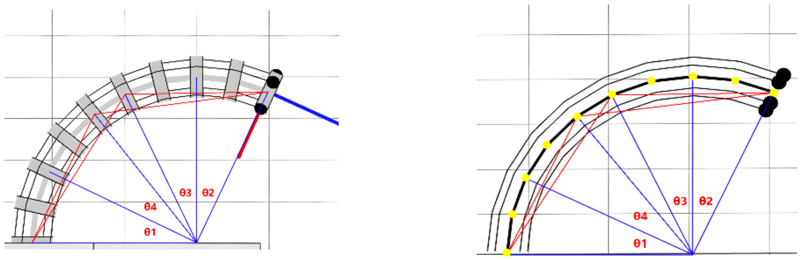

Fig. 10 - Position Measurements with Simulation Data

By analysing the simulation results, we can optimize the design of TDCRs and improve their overall performance in real-world applications.

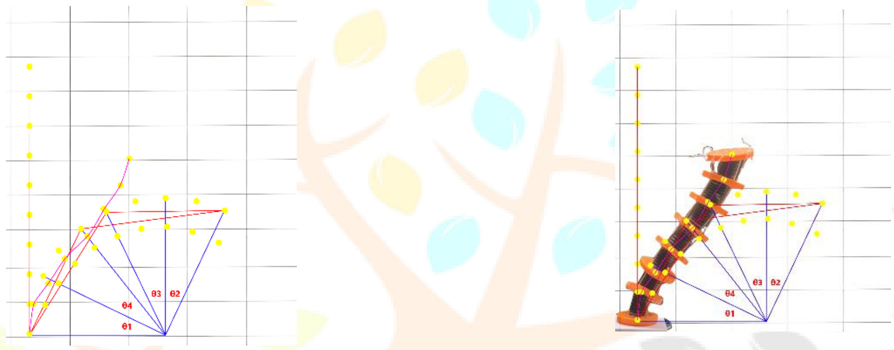

Fig. 11 - Experimental Data

The graph above (Fig. 11) demonstrates the bend angle of each discrete part of the robotic arm when bent at different angles. This was critical in selecting the materials for the backbone based on the loads the arm was required to withstand

Finally, positional measurements of a TDCR were compared with experimental data obtained from a TDCR arm. The simulation accurately predicted the position of the TDCR at various angles of bend, and the results were consistent with the experimental data obtained from the arm. This demonstrates the effectiveness of the TDCR model and the accuracy of the simulation. These simulation results can be used to optimize the design of TDCRs and further improve its performance in various applications.

VI **CONCLUSION**

The robot will be tested in a simulated environment, and its performance will be compared to existing devices. The robot movement was stable and showed no more than a 2% deviation from the simulated model's results.

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