A FIXED LENGTH SINGLE SEGMENT SOFT CONTINUUM MANIPULATOR FOR MULTI-ENVIRONMENTAL INSPECTION

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ABSTRACT

Inspection of structures is a regular practice in many industries to determine the condition of the structure in terms of safety and performance. Traditionally, inspection operations were performed by qualified personnel to evaluate the condition of the structure and to determine locations requiring maintenance. However, manual inspection is costly, time-consuming, and may endanger the lives of the inspectors especially in radioactive and poisonous environments. Alternatively, robotic inspection provides a faster, safer, and more cost-effective alternative to human inspection; however, robots are usually limited in their operational domains. Drones and other airborne vehicles are designed for aerial operation, while underwater robots are designed to inspect submerged structures. Additionally, drones, water-surface, and underwater robots are all constrained by their tether or onboard power source. In this work, a teleoperated soft continuum manipulator is implemented, capable of inspecting tall, submerged, and partially submerged structures for prolonged time periods. The manipulator consists of a suspended flexible arm, a part capable of sliding along the arm (referred to as an Arm Constrainer and Tendon Router 'ACTR'), and a rotatable upper base. Tendon actuation is used to provide high motion resolution as well as the ability to locate the driving motors remotely with respect to the actuated parts (arm and ACTR). Thus, allowing the manipulator arm to be placed in different environments without affecting the actuators or controlling circuitry. The results of the lab experiments illustrate the manipulator's ability to inspect tall structures with sub-millimeter vertical motion resolution. The experimental results also validated the manipulator's ability to inspect the different parts (above and below water) of a partially submerged tall structure, represented by an Aluminum pole. Additionally, the manipulator's modular design facilitates the replacement of its arm with another of different material and geometry, allowing it to be used in different environments. In comparison to soft continuum robots and manipulators (SCRaMs), this manipulator employs fewer actuators than multi-segment SCRaMs and covers a larger workspace than fixed-length single-segment SCRaMs.

ABSTRAK

Pemeriksaan struktur merupakan amalan biasa yang dilaksanakan di pelbagai industri bagi menentukan tahap keselamatan dan keupayaan struktur. Pemeriksaan robotik menyediakan kaedah yang lebih pantas, selamat dan menjimatkan kos sebagai alternatif kepada pemeriksaan yang dilakukan oleh individu; walau bagaimanapun, robot biasanya terhad kepada ruang domain operasi. Dron dan kenderaan udara direka untuk operasi pemeriksaan struktur tinggi, manakala robot bawah air direka untuk memeriksa struktur di dalam air. Selain itu, dron, robot terapung dan robot bawah air semuanya dikekang oleh penambat dan/ atau sumber kuasa dari kapal mereka. Dalam kajian ini, pemanipulasi kontinum lembut kawalan jauh digunakan, ianya mampu memeriksa struktur yang tinggi, kedalaman, struktur yang tenggelam dan separa tenggelam untuk tempoh masa yang panjang. Pemanipulasi ini terdiri daripada lengan fleksibel yang tergantung, bahagian yang mampu meluncur di sepanjang lengan (dirujuk sebagai ACTR), dan tapak atas yang boleh diputar. Sistem penggerakan tendon digunakan untuk memberikan resolusi gerakan yang tinggi serta kebolehan untuk menempatkan motor pemandu~~an~~ dari jauh berdasarkan dari bahagian yang digerakkan (lengan dan ACTR). Oleh itu, lengan pemanipulasi dapat diletakkan dalam persekitaran yang berbeza tanpa menjejaskan penggerak atau litar kawalan. Keputusan eksperimen makmal menggambarkan keupayaan pemanipulasi untuk memeriksa struktur tinggi dengan resolusi gerakan menegak dalam sub-milimeter. Keputusan eksperimen juga mengesahkan keupayaan pemanipulasi untuk memeriksa bahagian yang berbeza (di atas dan di bawah air) struktur tinggi separa tenggelam, yang diwakilkan oleh tiang Aluminium. Tambahan lagi, reka bentuk pemanipulasi secara modul memudahkan penggantian lengan dengan bahan dan geometri yang berlainan membolehkan ia digunakan dalam persekitaran yang berbeza. Berbanding dengan robot dan pemanipulasi kontinum lembut (SCRaM), pemanipulasi ini menggunakan sedikit penggerak berbanding SCRaM berbilang segmen dan mencakupi ruang kerja yang lebih besar berbanding SCRaM segmen tunggal dengan panjang yang tetap.

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	–	Three Dimensional
a	–	The minor radius *(width)* of the prolate spheroid.
ABS	–	Acrylonitrile Butadiene Styrene
ACTR	–	Arm Constrainer and Tendon Router
AMRRaMs	–	Aquatic Mobile Rigid Robots and Manipulators
A_{ps}	–	The surface area of the prolate spheroid.
AUV	–	Autonomous Underwater Vehicle
BRC	–	Bar Reinforced Concrete
c	–	The major radius *(height)* of the prolate spheroid.
CAD	–	Computer Aided Design
CCW	–	Counter-Clockwise
CW	–	Clockwise
DC	–	Direct Current
DEA	–	Dielectric Elastomer Actuators
EVLSS-SCRaMs	–	Extendable Variable-Length Single-Segment Soft Continuum Robots and Manipulators
FEA	–	Finite Element Analysis
FLSS SCRoM	–	Fixed-Length Single-Segment Soft Continuum Robots or Manipulators
FLSS-SCM	–	Fixed-Length, Single-Segment, Soft Continuum Manipulator
FLSS-SCRaMs	–	Fixed-Length Single-Segment Soft Continuum Robots and Manipulators
IDE	–	Integrated Development Environment
LED	–	Light Emitting Diode
MRRaMs	–	Mobile Rigid Robots and Manipulators

OTS	–	Off-The-Shelf
PC	–	Personal Computer
r_h	–	The height *(vertical radius)* of the workspace.
ROV	–	Remotely Operated Vehicle
RRaM	–	Rigid Robots and Manipulators
RVLSS-SCRaMs	–	Retractable Variable-Length Single-Segment Soft Continuum Robots and Manipulators
r_w	–	The width *(horizontal radius)* of the workspace.
SAP	–	Second Attachment Point
SCARA	–	Selective Compliance Assembly Robot Arm
SCR	–	Soft Continuum Robots
SCRaM	–	Soft Continuum Robots and Manipulators
SCRoM	–	Soft Continuum Robots or Manipulators
SMA	–	Shape Memory Alloy
SRaM	–	Soft Robots and Manipulators
SRRaMs	–	Stationary Rigid Robots and Manipulators
SS-SCRaMs	–	Single-Segment Soft Continuum Robots and Manipulators
USV	–	Unmanned Surface Vehicles
UUV	–	Unmanned Underwater Vehicle
VLSS-SCRaMs	–	Variable-Length Single-Segment Soft Continuum Robots and Manipulators
V_{ps}	–	The volume of the prolate spheroid.

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CHAPTER 1

INTRODUCTION

1.1. Background of the study

Inspection operations were conducted by humans since they started life on earth. From inspecting their early tools to ensure their effectiveness to the caves they used for shelter, inspection was part of the daily life activities of early humans.

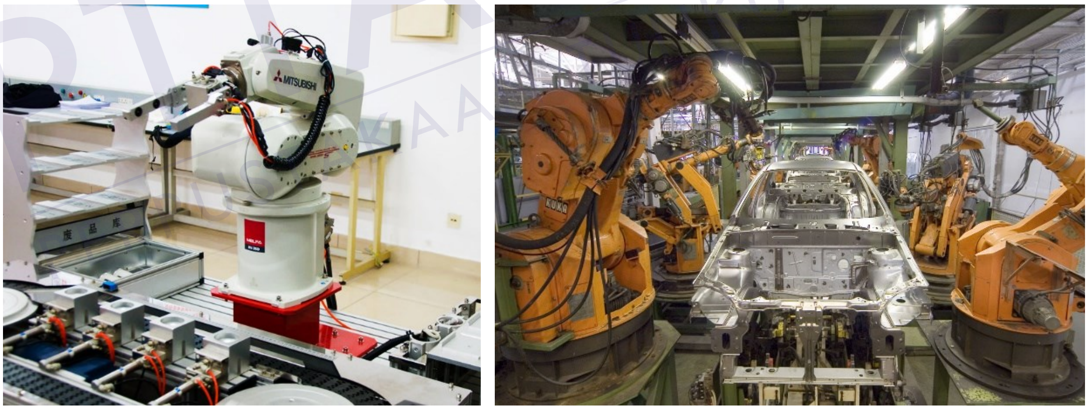
The operation of inspection continued throughout history, with the invention of new tools to better inspect the world around us. From early telescopes to microscopes, inspection devices, and tools helped humans in the discovery of new frontiers in science and technology. As humanity progressed and new tools were invented, the industry started an increasing trend of shifting from human-based to machine-based inspection. This shift is largely due to the ability of robots to reach difficult locations, or withstand extreme environmental conditions, thus relieving the stress and difficulty of conducting inspection operations by qualified personnel. In today's world, robots are used in architecture to inspect tall structures or used underwater for inspecting submerged objects. Figure 1.1 shows robots used for inspecting tall towers and underwater structures.

However, robotic inspection operations are limited by the ability of the machines performing these operations. Mobile robots inspecting tall structures are limited by their fuel or battery life, as well as surrounding conditions at the inspection site, such as extreme temperatures or excessive radiation. Additionally, robots inspecting underwater objects are limited by the depth they can reach, and the length of their operation time.

(a) (b)

Figure 1.1: Robots in inspection operations. a) Drone [1]. b) Underwater robot. [2].

Stationary robots and manipulators, such as the ones shown in Figure 1.2 do not use batteries, hence have an unlimited operation time. However, these robots and manipulators have a limited reach and are mostly suitable for inspecting objects in their vicinity. Scaling up rigid robots and manipulators to reach and inspect large structures increases their weight and energy requirements, making them costly, and difficult to relocate to different sites.



(a) (b)

Figure 1.2: Stationary robots and manipulators. a) A robot for inspecting items [3]. b) Industrial manipulators [4].

Soft continuum robots and manipulators (SCRaMs) have elongated flexible bodies and can extend to cover large areas as shown in Figure 1.3(a). However, these are suitable for the exploration and inspection of ground-based objects and landscapes. Vertically aligned SCRaMs, such as the one shown in Figure 1.3(b) can be used for inspecting tall structures. However, their body's thick cross-section limits their curvature angle and makes it difficult to reach and inspect all locations within a tall structure. Additionally, some of the actuators used by SCRaMs either have low accuracy, such as fluidic and shape memory alloy (SMA) actuators or employ high voltages to operate, such as dielectric elastomer actuators (DEA), making them impractical for field operations.

(a) (b)

Figure 1.3: Robots in exploration and inspection. a) An extendable soft continuum robot [5]. b) A soft continuum manipulator [6].

To solve these problems, an inspection robot or manipulator is required for the purpose of inspecting tall and partially submerged structures, as well as withstanding extreme conditions, such as radiation, pressure, and temperatures. The designed robot or manipulator should address the constraints of current systems in terms of tethering and on-board power limitations.

This work presents the design, fabrication, and testing of a teleoperated manipulator that can be easily rescaled to inspect taller structures, deeper waters, and withstand different environmental conditions while having a relatively high motion accuracy. Additionally, the manipulator has the ability to perform specific operations on any desired location through end effectors located at its tip.

1.2. Problem Statement

Teleoperated robots and manipulators are devices that are controlled by a human user to perform one or more tasks. Many types of teleoperated robots are used for inspection operations. Some are intended for land structures and others for underwater environments. Although all of these robots are designed to perform their tasks efficiently, each type has certain limitations making it unsuitable for inspecting tall and partially submerged structures for prolonged periods of time.

Teleoperated robots used for the inspection of tall structures on land conduct their operation by one of several methods, such as cable suspension, climbing the structure's walls, or flying about the structure [7]. However, these approaches are constrained by several factors, such as the limited operation time dictated by the robot's power source, as well as environmental conditions such as temperature and radiation. Teleoperated robots intended for underwater exploration are limited by the depth they can reach and the length of their operation time. These factors constrain their ability to perform inspection operations for prolonged periods or reach further and deeper locations [8]. Additionally, teleoperated robots designed for inspecting terrestrial structures are generally unsuitable for underwater operation, and vice versa. This results in requiring two robots or vehicles for inspecting partially submerged structures, such as offshore wind turbines, oil rigs, bridge pylons, and others.

Soft continuum robots and manipulators can be used to overcome the aforementioned constraints but suffer from different limitations. Horizontally aligned SCRaMs, such as [5] and [9] are suitable for exploring surface objects and structures but are unsuited for inspecting tall structures. SCRaMs, such as [6], [10], and [11] can be used for inspecting tall structures, however, the fluidic and SMA actuators used by [6] and [10] are difficult to achieve precise control, and the DEA actuator employed by [11] requires a high operating voltage making it dangerous to deploy in the field. SCRaMs employing tendon actuation, on the other hand, such as [12] and [13] have higher accuracy and are safe to be used in the field, however, the SCRaM's thick cross-section makes it difficult to reach and inspect all locations of the tall structure. Although SCRaMs, such as [14], [15], and [16] attempt to overcome this problem using a multi-segmented body, they employ numerous actuators, and are thus more costly and complicated to control.

To summarize, the problem is the absence of a robotic system that can be used to inspect tall and partially submerged structures for prolonged periods of time. Mobile robots suffer from the limitation of onboard power sources, stationary rigid manipulators are unsuitable for inspecting tall structures, while stationary soft robots and manipulators are not optimized for inspecting tall and partially submerged structures.

Thus, the aim of this work is to overcome the limitations of current robots and manipulators for structural inspection through the development of a robotic system capable of inspecting tall and partially submerged structures, with a relatively high motion resolution, and in different environmental conditions.

1.3. Research Objectives

Based on the research aims, this work seeks to accomplish the following objectives:

1. To design a teleoperated soft manipulator for inspecting tall and partially submerged structures (such as chimneys and offshore wind turbines).

2. To develop the manipulator through fabrication and assembly. Fabrication of the designed parts through 3D printing, and assembly of these parts with off-the-shelf components to produce the full manipulator.

3. To validate the manipulator's functionality through its ability to inspect tall structures and underwater objects.

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APPENDIX C

LIST OF PUBLICATIONS

[1] M. Shoani, M. N. Ribuan, A. A. Mohd Faudzi, and S. Mohamaddan, "Reducing Actuators in Soft Continuum Robots and Manipulators," *Appl. Sci.*, vol. 13, no. 1, p. 462, Dec. 2022, doi: 10.3390/app13010462.

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APPENDIX D

VITA

The author was born on September 14th, 1968, in Iraq. He pursued his degree at the University of Technology in Baghdad, Iraq, and graduated with B.Sc. in Computer Engineering in 1991, ranking 7th out of 46 graduates. In 1994, he travelled to Sana'a in Yemen and worked at several computer companies, before travelling to the United Arab Emirates in 1998, where he worked for a computer trading company in Jebel Ali, Dubai. In 2001, he started teaching in public schools, where he taught the subject of computers to middle and secondary school students. In 2007 he joined the American International School in Abu Dhabi (AISA) where he worked for four years. In 2012 he started his master's degree at Universiti Teknologi Malaysia (UTM) under the supervision of Prof. Shamsuddin bin Hj Mohd Amin, where he worked on an Autonomous Security Robot project. From the Autumn of 2015 to the summer of 2017, he worked as a part-time lecturer in three private universities in Erbil, Iraq: The University of Erbil, Cihan University, and The Lebanese French University. In the Autumn of 2017, He started his Ph.D. study, initially studying hybrid structures, but later focusing on soft continuum manipulators. During his Ph.D. course of study, Mr. Shoani authored several papers related to hybrid and soft robotics.