MODELLING AND ANGLE CONTROL OF FIBER BRAIDED BENDING ACTUATOR FOR FINGER REHABILITATION

MOHD NIZAR BIN MUHAMMAD NASIR ANNADURAI

A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Engineering Technology

Faculty of Engineering Technology
Universiti Tun Hussein Onn Malaysia

SEPTEMBER 2023

For my beloved mother and father, family, friends and lecturers.

ACKNOWLEDGEMENTS

I would like to extend my utmost appreciation and gratitude to all those who have extended their unwavering support and encouragement throughout my educational odyssey, a journey that spanned from the very inception of my academic pursuits to the culmination of my Master's degree. Despite the numerous challenges and vicissitudes that I encountered over the years, I am grateful to have persevered and successfully accomplished this momentous feat. My family, in particular, has been an invaluable source of inspiration and motivation, and I am indebted to their unrelenting love and support, without which I could not have attained this level of academic excellence.

Moreover, I would be remiss if I did not express my sincere appreciation and gratitude to my esteemed supervisor, Dr. Ili Najaa Aimi Binti Mohd Nordin, whose invaluable guidance and support had been critical to the successful completion of my Master's project. Dr. Ili Najaa Aimi Binti Mohd Nordin has been instrumental in providing me with an abundance of knowledge, inspiration, and ideas throughout the course of my study and even after the publication of my report. I would be remiss if I fail to acknowledge the invaluable contributions of my co-supervisor, Ts. Dr. Amirul Syafiq Bin Sadun, whose unwavering cooperation and dedication were essential to the completion of this project. Lastly, I would like to extend my heartfelt appreciation and gratitude to the esteemed collaborators from the Centre for Artificial Intelligence and Robotics (CAIRO), Universiti Teknologi Malaysia, namely, Prof. Ir. Ts. Dr. Ahmad 'Athif Bin Mohd Faudzi, Mr. Akmal, and Mr. Muftah. Their invaluable assistance and input were instrumental in the successful development of my research, and I am grateful for their unwavering support and guidance throughout this project.

ABSTRACT

Stroke is a prominent cause of disability on a global scale, often resulting in hand impairment that significantly hinders a person's ability to carry out daily activities. Soft actuators present a promising technology for addressing hand impairment in stroke patients, offering a more versatile and adaptable approach to actuation. Despite the benefits of soft actuators, their nonlinearity presents a challenge when it comes to modeling, controlling, and achieving swift response times. Due to the nonlinearity of the system, open-loop systems are not suitable for soft actuator applications. Open-loop controlled pneumatic actuator muscles often struggle with high precision control. The drawbacks can be addressed by implementing a closed-loop control system. The objective of a closed-loop control approach is to perform a dynamic task while enhancing precision, robustness, and actuator conformance to the environment. In this study, one approach to implementing closed-loop control is through system identification (SI), using a transfer function that simulates the actual actuator. The auto-regressive model structure was selected for this study. Pseudo-random binary sequences were employed as the input signal for the SI process. The implementation of a proportional-integral-derivative (PID) controller enabled the control of the angle of the Fiber Braided Bending Actuator (FBBA). Additionally, two tuning techniques were proposed for the PID controller, namely the auto-tuning method and the genetic algorithm method. Both controllers' real-time experiments and simulations are analyzed. The results indicate that, compared to PID tuned using the auto-tuning method, PID tuned using GA demonstrates a significant improvement in both simulation and real-time experiments.

ABSTRAK

Strok ialah punca utama kehilangan upaya seseorang pada skala global, selalunya mengakibatkan kecacatan tangan yang secara ketara menghalang keupayaan seseorang untuk menjalankan aktiviti harian. Penggerak lembut mempersembahkan teknologi yang menjanjikan untuk menangani kecacatan tangan pada pesakit strok, menawarkan pendekatan yang lebih serba boleh dan boleh disesuaikan untuk penggerak. Di sebalik faedah penggerak lembut, ketaklinearan penggerak lembut memberikan cabaran apabila melibatkan pemodelan, mengawal dan mencapai masa tindak balas yang pantas. Disebabkan oleh ketaklinearan sistem, sistem terbuka tidak sesuai untuk aplikasi penggerak lembut. Kawalan penggerak pneumatik gelung terbuka sering bergelut dengan kawalan ketepatan tinggi. Kelemahan boleh diatasi dengan melaksanakan sistem kawalan gelung tertutup. Objektif pendekatan kawalan gelung tertutup adalah untuk melaksanakan tugas dinamik sambil meningkatkan ketepatan, keteguhan dan pematuhan penggerak kepada persekitaran. Dalam kajian ini, satu pendekatan untuk melaksanakan kawalan gelung tertutup adalah melalui pengenalan sistem (SI), menggunakan fungsi pemindahan yang menyerupai penggerak sebenar. Struktur model auto-regresif telah dipilih untuk kajian ini. Urutan binari pseudo-rawak digunakan sebagai isyarat input untuk proses SI. Pelaksanaan pengawal terbitan-integral berkadar (PID) membolehkan kawalan sudut Penggerak Lentur Jalinan Fiber (FBBA). Selain itu, dua teknik penalaan telah dicadangkan untuk pengawal PID, iaitu kaedah penalaan automatik dan kaedah algoritma genetik. kedua-dua pengawal dianalisis dalam simulasi dan masa nyata. Keputusan menunjukkan bahawa, berbanding dengan PID yang ditala menggunakan kaedah auto-tala, PID yang ditala menggunakan GA menunjukkan peningkatan yang ketara dalam kedua-dua simulasi dan eksperimen masa nyata.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Ampere
AIC	-	Akaike's information criterion
ARC	-	Adaptive robust control
ARMAX	-	auto-regressive moving average with exogenous input
ARX	-	Auto-regressive exogenous
FBBA	-	Fiber braided bending actuator
FPE	-	Final prediction error
GA	-	Genetic algorithm
MPC	-	Model predictive control
NLARX	-	Non-Linear Auto-regressive exogenous
PID	-	Proportional-integral-derivative
PRBS	-	Pseudo random binary sequence
s	-	second
SI	-	System identification
SMC	-	Sliding mode control
u	-	Micro
V	-	Voltage

CHAPTER 1

INTRODUCTION

1.1 Project Background

The leading cause of death for Malaysians is cardiovascular and circulatory disorders, including cerebrovascular diseases (stroke), accounting for 21.65% of deaths in hospitals under the Ministry of Health (62,205), and 23.79% in private hospitals in 2018 [1]. The aforementioned risk factors have been implicated in the escalation of stroke incidence among individuals who are under the age of 65, whereby the male population experiences the greatest surge with a staggering increase of 53.3%, while the female demographic exhibits a significant augmentation of 50.4%, emanating from the age category of 35 to 39 years [2]. Traditional rehabilitation interventions are known to be insufficient in aiding stroke patients in regaining the capacity to lead an active lifestyle following their discharge. Moreover, such interventions do not effectively mitigate the risk of secondary stroke and other grave complications [3]. Results from the National Neurology Registry in Malaysia indicate that the majority of stroke patients, specifically 79.2%, experience their first-ever stroke. Conversely, a minority of patients, constituting 20.8%, suffer from a recurrent stroke [4].

Stroke can lead to various impairments, including finger impairments, based on stroke location and intensity. Motor area stroke results in one-sided body weakness or paralysis, including fingers. This is known as hemiparesis or hemiplegia, depending on the severity of the paralysis. The impairment of the fingers caused by stroke is known as hand function impairment, which can range from mild weakness to complete paralysis. A common type of finger impairment after a stroke is known as spasticity, which is a condition where the muscles become tight and stiff, making it difficult to move the fingers. This can lead to a decrease in fine motor control, making it challenging to perform daily tasks, such as grasping objects, writing, and typing. Another common type of finger impairment is weakness, which occurs when the muscles responsible for finger movement hardly receive enough stimulation from the brain. This can result in difficulty with gripping and manipulating objects as well as fine motor activities. The severity of finger paralysis can vary depending on the degree of brain damage and the individual's overall health. To address finger impairments caused by stroke, there are a variety of rehabilitation methods that can be used, including physical therapy [5], occupational therapy [6], and splinting [7]. These methods are designed to improve hand function, reduce pain, and help individuals regain as much independence as possible. Some specific techniques that can be used in rehabilitation include range-of-motion exercises, strengthening exercises, and sensory re-education [8]. In addition, various assistive devices, such as wrist braces and adaptive utensils, can be used to help individuals compensate for their impairments and improve their ability to perform daily activities.

Nevertheless, during inpatient recovery, patients experience time wastage that should be used profitably for successful rehabilitation. The insufficiency of therapy sessions in regards to metabolic stress calculation is a hindrance in inducing a cardiopulmonary training effect for patients in a post-stroke setting. Patients are inactive for 21% to 80% of the rehabilitation time [3]. The term rehabilitation process refers to a procedure that requires cooperation between various practitioners, the patient and family involved. With solid and meaningful objectives formulated along with the patient, this phase should be undertaken. The rehabilitation regimen may face limitations on occasion, due to the medical circumstances of individuals who have suffered a stroke; healthcare providers sometimes exhibit excessive vigilance. The physical and occupational therapists, for instance, may be afflicted with apprehension or worry about intensifying the degree of physical activity for these patient.

Stroke rehabilitation is targeted at two target behaviors that consistently work with a rehabilitative approach in all areas of patient care, and also work with the objectives of patients consciously and systematically. Approximately 66% of individuals who have experienced a stroke are confronted with enduring disability and limitations in upper limb mobility, posing a significant obstacle to their recovery. This dilemma is particularly prevalent in developing nations, where there is a pressing need for cost-effective rehabilitation interventions [9]. Therefore, rehabilitation robots have been recognised as productive and may be a cost-effective alternative to traditional rehabilitation facilities that offered highly rigorous and repetitive training [10]. Robot-assisted therapy represents a novel and auspicious strategy for rehabilitation that has demonstrated its efficacy in enhancing motor capacity, particularly in the context of finger rehabilitation following a stroke. The therapy involves the use of robotic devices to assist with rehabilitation exercises designed to improve range of motion, strength, and coordination. The utilization of soft actuators for finger rehabilitation is progressively becoming more prevalent, as they possess the capacity to replicate the innate movement of the human body and furnish particularized, delicate aid to the fingers.

In recent times, soft actuators have become more popular in research and industry because of their advantages over rigid actuators [11]. The incorporation of soft actuators has led to entertainment being integrated into the rehabilitation process, as noted in a study by [12]. The study designed a music rehabilitation glove and developed a mode of rehabilitation training that utilized multisensory interaction, encouraging users to complete hand rehabilitation exercises and aiding in their recovery preparation for hand functionality at home [13]. An alternative to motion recovery are robotic-based rehabilitation [14]. In the preceding decade, there has been considerable advancement in the realm of soft robotic gloves. These gloves possess an extraordinary aptitude to facilitate individuals in executing finger movements, which are indispensable in carrying out day-to-day routines (ADL) and auxiliary activities (iADL). The aforementioned activities necessitate the ability to clasp objects, and these gloves enable individuals to do so with ease and comfort [15]. Individuals who have experienced a stroke can harness the power of a soft robotic exosuit to assist their paretic plantar flexor muscles, resulting in remarkable improvements in both speed and distance that are clinically significant [16].

Soft actuators are typically composed of tremendously extensible elastomeric substances or silicone polymer making their operation safer than rigid actuators such as electric motors, and hydraulic and pneumatic cylinders [17]. The utilization of soft actuators has a diverse array of potential applications, encompassing manufacturing, manipulation, gripping, human-machine interaction, locomotion [18]. Soft actuators possess a high degree of compliance and are cost-effective to produce, rendering them suitable for use in both structured and unstructured environments [19], lightweight, high power-to-weight ratio, are safer to access than their counterparts [20]. Numerous methodologies have been formulated for the fabrication of soft actuators, including but not limited to the McKibben muscle, balloon-type, elastomeric-based, and a plethora of others.

McKibben's is a popular choice for soft actuators. It is a standard Pneumatic Muscle (PM) that has a double helical braid wrapped around an elastic cylindrical tube. It can produce large contraction strains, high blocked forces, and fast response time [21] making it suitable for rehabilitation purposes. The structural compliance of soft robots is another feature that might help to improve inherent safety. Due to its lightweight and compliant physical structure, McKibben's muscles are especially well suited to meeting these requirements [22]. Soft actuators typically have fewer sharp edges or pinch points, reducing the chances of entrapment or injury. The intricate motion patterns of the human hands coupled with their restricted joint range of motion render rigid accessory equipment capable of causing further injuries.

In light of this, the soft robot presents a promising avenue for exploration in the field of rehabilitation within the robotics industry. Notably, the Fiber Braided Bending Actuator (FBBA) represents a novel liquid silicone and thread-based invention that can be conveniently affixed to the dorsal aspect of the human hand [23]. When the soft actuator undergoes inflation or deflation, it concomitantly undergoes deformation and a consequential bending and stretching motion of the hand. This process occurs repeatedly with deformation. In the care of movement-disabled stroke patients, robot-assisted therapy has become a prevalent practice of late. Due to its inherent enforcement and safety characteristics, PM stands out as one of the most promising actuators for rehabilitation robots.

Despite the advantages of soft robots, they also pose several challenges as soft robots are made of compliant materials that exhibit nonlinear and time-varying behaviour, which can be difficult to model and control. Soft robots are a relatively new technology, and there are currently no standardized methods for controlling them. As a result, researchers and developers must often design custom control systems for each specific soft robot application. It is also challenging to obtain accurate measurements of the robot's position and movement, which can impact the effectiveness of the control system. Soft robots can be highly complex in their design, with many degrees of freedom and a high level of flexibility. Consequently, the process of designing and implementing an effective control system that can provide the necessary level of assistance and feedback is difficult. The design and control of soft robots require specialized knowledge and expertise in areas such as materials science, robotics, and control theory. Therefore, the number of researchers and developers who can work on soft robot applications is limited.

The FBBA utilised in this research was based on previous research by M. Nordin *et. Al.* [24]–[28]. The researchers have developed a single chamber actuator with two fiber braided angle reinforcements. A single-chamber soft actuator is a type of soft actuator that consists of a single inflatable chamber or compartment. It is designed to mimic the movement and functionality of natural muscles by utilizing the deformation of soft materials. The developed FBBA system was an open-loop without any control mechanism. Therefore, there is no feedback data for the bending position. This research focuses more on modelling and controlling the FBBA position.

1.2 Problem Statement

The previous project focuses on fabricating the FBBA. However, the implementation of a closed-loop control system is not present. Despite the numerous benefits that soft actuators offer, scholars encounter arduous obstacles when attempting to surmount the formidable non-linear characteristics of these devices. Such difficulties pose significant challenges for modeling, controlling, and achieving low response time [29] due to their materials, air compressibility, significant mechanical friction, poor damping ability, and valve dead zone issues. The uncertainties make the modelling and control of soft actuators more complex [30]. The implementation of a control system can be quite difficult as soft actuators are highly non-linear and have infinite parameters [31]. Therefore, numerous improvements are necessary to achieve the most optimum control capability.

1.3 Objectives

The followings are the objectives of this research:

i. To develop a mathematical model of FBBA based on Auto-regressive Exogenous (ARX) Model in Matlab System Identification Tool for FBBA.

ii. To construct an optimal PID controller for angle control of FBBA based on Genetic Algorithm and auto-tuning method.

iii. To evaluate the simulation and experimental results for the proposed optimized controller.

1.4 Scopes

The followings are the scopes of this research:

i. This study only focuses on actuating, controlling, and analysing one finger actuator in the FBBA system.

ii. The FBBA used in this study was based on previous work. PID controller design was tested on the obtained FBBA model.

iii. This research is not applied to humans as finger rehabilitation is taken as a case study for the implementation of FBBA position control development.

iv. Control system design development focuses on reducing error gain and increasing the reliability of the closed-loop system.

v. The system uses Arduino as Data Acquisition (DAQ) device that records input and output data for the system identification process.

vi. The sampling time of 0.005 s are used throughout the whole project.

vii. 7-bit pseudo-random binary sequences are used as the input signal for data acquisition.

viii. Electro-pneumatic regulators (SMC ITV003) are utilised in the project.

CHAPTER 2

LITERATURE REVIEW

The field of robotics has seen significant advancements in recent years, and one of the areas that have garnered particular attention is soft actuators. Soft actuators are a class of devices that can bend and flex, allowing them to mimic the movements of natural muscles. These actuators are more versatile than traditional rigid actuators, and have the potential to revolutionise the field of robotics. However, designing control systems for soft actuators can be a challenging task. The properties of soft materials can vary considerably, which makes it difficult to model and control the behaviour of these actuators. This is where the system identification technique comes in. Using this technique, it is possible to measure and model the dynamics of soft actuator systems, which is a crucial step in developing effective control strategies.

Robot rehabilitation involves restoring the functionality of damaged muscles of disabled patients, which can be achieved through the use of soft actuators [32]. These actuators can provide the necessary force and compliance to help restore the patient's range of motion, and control systems are used to manage the movement and angle of the actuators. This chapter explores the types of soft actuators, and discusses the development of control system designs for the actuators. The chapter also covers system identification techniques that can be used to model the dynamics of soft actuator systems. Finally, this chapter discusses the role of control systems in robot rehabilitation and the potential of soft actuators to improve the process.

2.1 Type of Soft Actuator

The McKibben muscle represents a typical example of a PM utilized in contemporary soft rehabilitation robotics. It features an elastic cylinder tube and a double helical braid that enwraps its exterior [33]. There is also a research paper that implemented Neo Hookean (hyper-elastic model) behaviour on soft actuator development [34]. The application of PM in rehabilitation robotics has significantly increased but only a limited number of review papers have focused on PM-powered rehab robots. When operating in the vicinity of human beings, robots designed for deployment in the domains of medical assistance and social welfare must ensure the safety of their human counterparts with whom they may occasionally interact. Consequently, a tendon-driven balloon actuator (balloon actuator) was developed for integration into a robotic hand specifically tailored for such environments, as shown in Figure 2.1. The pneumatic tendon-driven balloon actuator, or balloon actuator, boasts a number of distinct advantages, including a wide stroke and high capacity ratio [35].

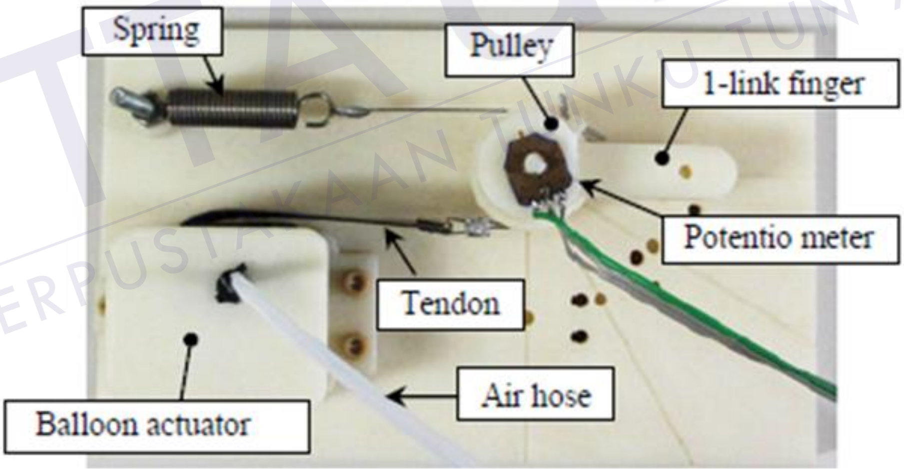

Figure 2.1: Tendon-driven Balloon Actuator [35]

There is also a soft actuator that uses fluid pressure in producing an elastomeric-based framework which can produce high deformation. Elastomeric configurations featuring integrated expandable chambers comprise of flexible fluidic actuators (FFAs) that exhibit alterations in their volume upon receipt of pressurized fluids. Consequently, contingent on the position of the chamber, the driver undergoes deformation, causing a displacement to occur [36]. FFAs that have antagonistic pairs will change shape and volume when a pressurised fluid flows into the chamber. The movement of FFAs depends on which chamber will be supplied with pressurised fluid. Therefore, displacement can be generated by the deformation of any chamber [37]. Figure 2.2 shows the FFAs developed by G. Gerboni *et. al*. [27].

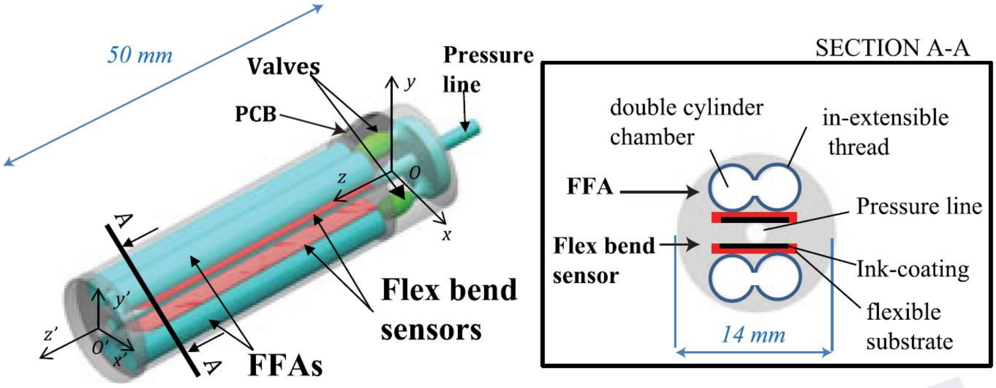

Figure 2.2: Flexible Fluidic Actuators (FFAs) [37]

Figure 2.3 depicts the dielectric elastomer actuators (DEAs). This particular variety of actuator is noteworthy amidst the diverse array of pliable actuators that have been scrutinized for employment in the realm of soft robotics, owing to its captivating benefits of substantial deformation, elevated energy density, rapid reaction time, and economical price point. W. Liang *et. al*. proposed an antagonistic actuation system for DEAs control [38]. The proposed system was stimulated by the resemblances discerned between DEAs and biological muscles with large deformations that may be found in animal bodies.

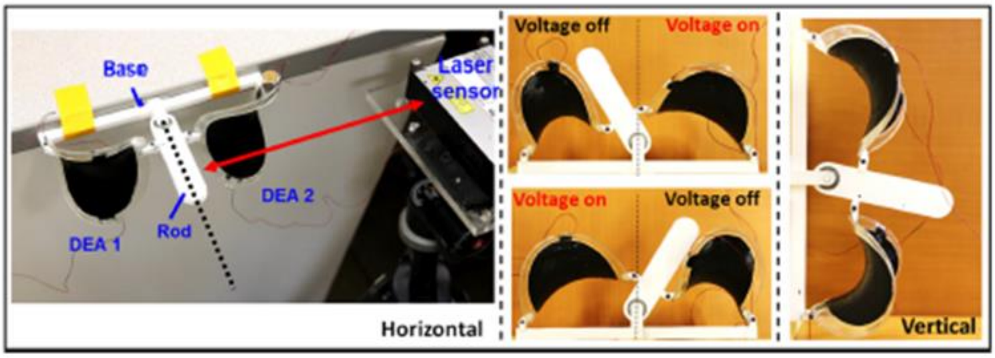

Figure 2.3: Dielectric Elastomer Actuators (DEAs) [38]

Diverse movements can be engendered by pliable actuators/robots, for example bending [39], rotary [40], contraction, and expansion [32], that have been studied and fabricated. The soft actuator has demonstrated its ability to perform tasks, such as gripping and grasping object [41]–[43], engendering crawling [44]–[46], and a range of gait movements [47]–[49]. V. Oguntosin *et. al.* directed their attention towards the pliable actuator that generated a rotary motion [50]. The expansion and contraction of the soft actuator caused clockwise and anti-clockwise rotary motions joined to a joint with opposing and protagonist pairs depicted in Figure 2.4. The mechanism consists of two pneumatic soft robots which are label R1 and R2. The direction of the joint will be determined by the state of the soft robots. The joint will rotate clockwise when R2 in expand state and R1 in contract state.

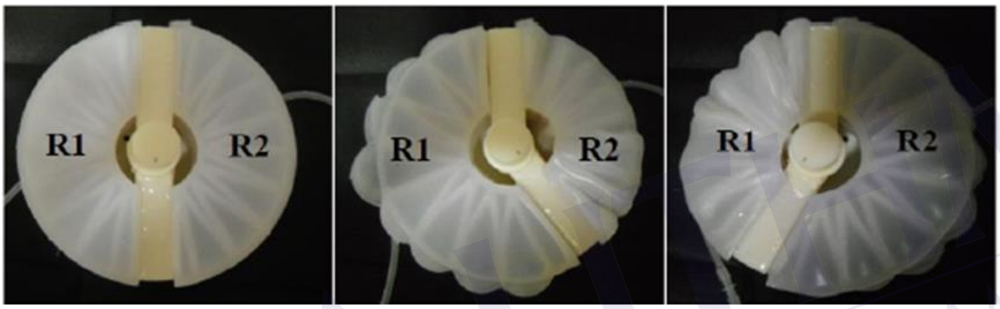

Figure 2.4: Gesture-Based Control of Rotary Pneumatic Soft Robot [50]

Hydraulically Amplified Self-Healing Electrostatic (HASEL) actuators consist of a soft or flexible pouch filled with a dielectric liquid. On either side of the pouch, a pair of electrodes are positioned as shown in Figure 2.5. Electrostatic forces displace the liquid dielectric as the voltage is applied to the electrodes, contributing to an overall shapeshift of the pouch. B. K. Johnson *et. al.* [51] employed a HASEL actuator in the system used, in which the actuators have 12 individual actuators in each foldable HASEL actuator stack. To be more specific, all 12 actuators were sealed in one strip. Vegetable-based transformer oil (Envirotemp FR3, Cargill) was used as the liquid dielectric to fill the pouches connected to a heat seal pattern.

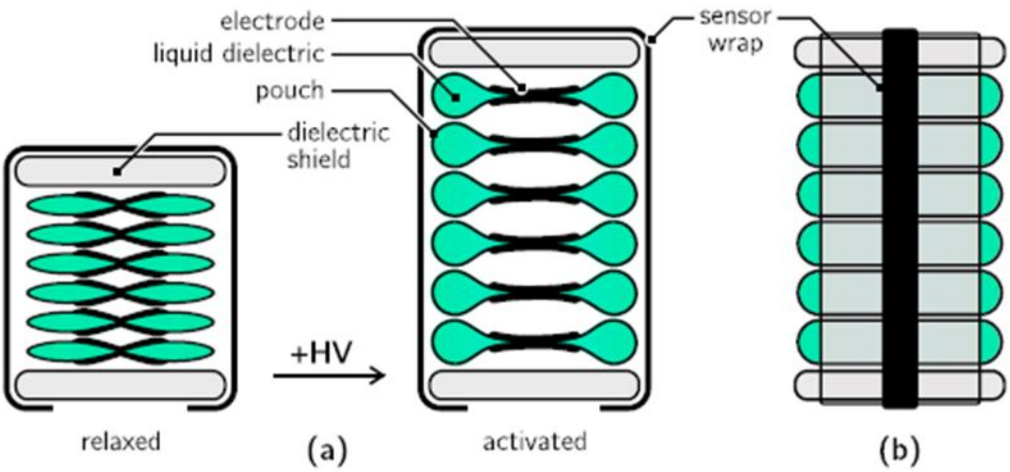

Figure 2.5: HASEL Actuators with Soft or Flexible Pouch [51]

Y. Li *et. al*. employed a pneumatic soft actuator furnished with a pre-charged mechanism in its design [52]. The design of the pre-charged actuator closely resembles that of a conventional bending pneumatic soft actuator. Systematically integrated one-way check valves were utilized in the system to encapsulate air inside the soft actuator, similar to the mechanism employed in air-filled balls and tires. Presently, the bending of the pre-charged pneumatic soft actuator can be regulated via a tendon. The bending angle and speed of the pre-charged pneumatic soft actuator can be manipulated by adjusting the tendon pulling speed and pulling distance. The act of pulling or releasing the tendon can create a bending motion of the pre-charged pneumatic soft actuators. Figure 2.6 shows the working concept of a pre-charged pneumatic soft gripper.

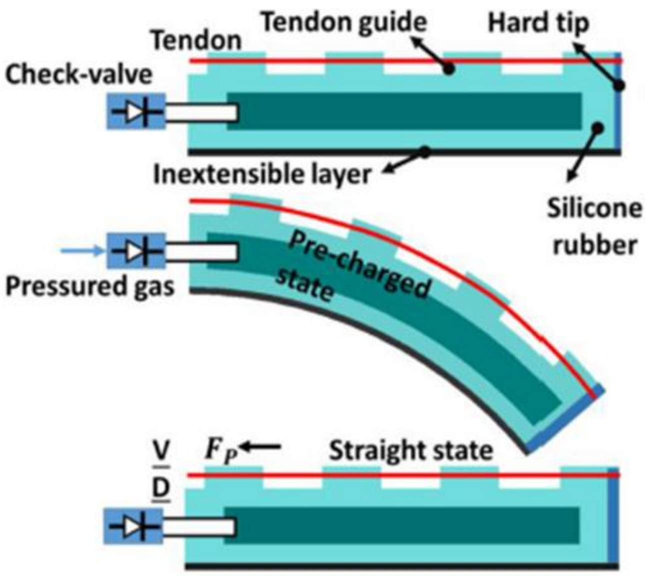

Figure 2.6: Pre-Charged Pneumatic Soft Gripper [52]

Soft electro-thermal actuators fall under the classification of thermally-driven actuators that are powered by electricity. These actuators typically consist of non-conductive elastomers or polymers as structural layers that undergo large deformations, and conductive pathways as resistive heaters. Generally, flexible electro-thermal actuators are formed in a biomorphic structure comprising of two layers with significantly different coefficients of thermal expansion. The mismatch in thermal expansion between the two layers induces bending in the bimorph structure when exposed to temperature fluctuations resulting from thermal energy [53]. he deformation of the actuator is self-sensed by monitoring the change in resistance of the microfilament heater that is embedded in the flexible electro-thermal actuator. Figure 2.7 shows the soft electro-thermal actuator.

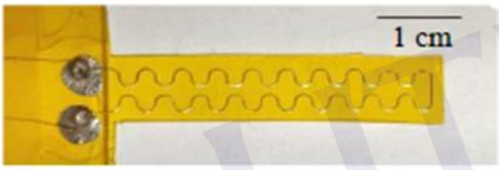

Figure 2.7: Soft Electro-Thermal Actuator [53]

2.1.1 Fiber Braided Bending actuator (FBBA)

FBBA is used in the development of the soft actuator. FBBA is capable of sustaining a bending motion when pneumatic air is supplied to the actuator. Fiber knitting with two different fiber angles in the bending actuator will directly reinforce the overall strength of the soft actuator at the same time reduces hysteresis to occur in the system [25]. Figure 2.8 shows the proposed bending actuator which consists of 3 cylindrical layers with an air hollow chamber located at the center of the FBBA [23]. Air will be flowed to the hollow chambers to create a bending motion. As we can see that the actuator inner layer and actuator outer layer will be reinforced with fiber knitting in an attempt of inducing the soft actuator bending motion.

REFERENCES

[1] Ministry of Health (Malaysia), "Malaysia Health Indicators," 2019. https://ghdx.healthdata.org/series/malaysia-health-indicators.

[2] K. S. Tan and N. Venketasubramanian, "Stroke Burden in Malaysia," *Cerebrovasc. Dis. Extra*, vol. 12, no. 2, pp. 58–62, Mar. 2022, doi: 10.1159/000524271.

[3] V. Girard *et al.*, "Cardiorespiratory strain during stroke rehabilitation: Are patients trained enough? A systematic review," *Ann. Phys. Rehabil. Med.*, no. xxxx, 2020, doi: 10.1016/j.rehab.2020.09.007.

[4] Z. A. Aziz *et al.*, "Acute Stroke Registry Malaysia, 2010-2014: Results from the National Neurology Registry," *J. Stroke Cerebrovasc. Dis.*, vol. 24, no. 12, pp. 2701–2709, 2015, doi: 10.1016/j.jstrokecerebrovasdis.2015.07.025.

[5] L. Moggio, A. de Sire, N. Marotta, A. Demeco, and A. Ammendolia, "Exoskeleton versus end-effector robot-assisted therapy for finger-hand motor recovery in stroke survivors: systematic review and meta-analysis," *Top. Stroke Rehabil.*, vol. 29, no. 8, pp. 539–550, Nov. 2022, doi: 10.1080/10749357.2021.1967657.

[6] W. Li and D. Xu, "Application of intelligent rehabilitation equipment in occupational therapy for enhancing upper limb function of patients in the whole phase of stroke," *Med. Nov. Technol. Devices*, vol. 12, p. 100097, 2021, doi: https://doi.org/10.1016/j.medntd.2021.100097.

[7] L. Kerr, V. D. Jewell, and L. Jensen, "Stretching and Splinting Interventions for Poststroke Spasticity, Hand Function, and Functional Tasks: A Systematic Review," *Am. J. Occup. Ther.*, vol. 74, no. 5, pp. 7405205050p1-7405205050p15, Jul. 2020, doi: 10.5014/ajot.2020.029454.

[8] A. C. de Santana Chagas *et al.*, “Physical therapeutic treatment for traumatic brachial plexus injury in adults: A scoping review,” *PM&R*, vol. 14, no. 1, pp. 120–150, Jan. 2022, doi: https://doi.org/10.1002/pmrj.12566.

[9] D. D. Niama Natta *et al.*, “Effectiveness of a self-rehabilitation program to improve upper-extremity function after stroke in developing countries: A randomized controlled trial,” *Ann. Phys. Rehabil. Med.*, 2020, doi: 10.1016/j.rehab.2020.03.017.

[10] Y. Huang *et al.*, “A comparison of the rehabilitation effectiveness of neuromuscular electrical stimulation robotic hand training and pure robotic hand training after stroke: A randomized controlled trial,” *Biomed. Signal Process. Control*, vol. 56, 2020, doi: 10.1016/j.bspc.2019.101723.

[11] Y. Takishima, K. Yoshida, A. Khosla, M. Kawakami, and H. Furukawa, “Fully 3D-Printed Hydrogel Actuator for Jellyfish Soft Robots,” *ECS J. Solid State Sci. Technol.*, vol. 10, no. 3, p. 037002, 2021, doi: 10.1149/2162-8777/abea5f.

[12] Q. Li *et al.*, “Effects of the multisensory rehabilitation product for home-based hand training after stroke on cortical activation by using NIRS methods,” *Neurosci. Lett.*, vol. 717, no. August 2019, 2020, doi: 10.1016/j.neulet.2019.134682.

[13] Q. Li *et al.*, “Effects of the multisensory rehabilitation product for home-based hand training after stroke on cortical activation by using NIRS methods,” *Neurosci. Lett.*, vol. 717, p. 134682, 2020, doi: https://doi.org/10.1016/j.neulet.2019.134682.

[14] J. C. Castiblanco, S. Ortmann, I. F. Mondragon, C. Alvarado-rojas, M. Jöbges, and J. D. Colorado, “Biomedical Signal Processing and Control Myoelectric pattern recognition of hand motions for stroke rehabilitation,” vol. 57, 2020.

[15] C. E. Proulx *et al.*, “Review of the effects of soft robotic gloves for activity-based rehabilitation in individuals with reduced hand function and manual dexterity following a neurological event,” *J. Rehabil. Assist. Technol. Eng.*, vol. 7, p. 2055668320918130, Jan. 2020, doi: 10.1177/2055668320918130.

[16] L. N. Awad, P. Kudzia, D. A. Revi, T. D. Ellis, and C. J. Walsh, “Walking Faster and Farther With a Soft Robotic Exosuit: Implications for Post-Stroke Gait Assistance and Rehabilitation,” *IEEE Open J. Eng. Med. Biol.*, vol. 1, pp. 108–115, 2020, doi: 10.1109/OJEMB.2020.2984429.

[17] T. Hainsworth, L. Smith, S. Alexander, and R. MacCurdy, “A Fabrication Free,

3D Printed, Multi-Material, Self-Sensing Soft Actuator," *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 4118–4125, 2020, doi: 10.1109/LRA.2020.2986760.

[18] N. El-Atab *et al.*, "Soft Actuators for Soft Robotic Applications: A Review," *Adv. Intell. Syst.*, vol. 2, no. 10, p. 2000128, 2020, doi: 10.1002/aisy.202000128.

[19] Y. Zhao, Y. Chi, Y. Hong, Y. Li, S. Yang, and J. Yin, "Twisting for soft intelligent autonomous robot in unstructured environments," *Proc. Natl. Acad. Sci.*, vol. 119, no. 22, p. e2200265119, May 2022, doi: 10.1073/pnas.2200265119.

[20] A. D. D. R. Carvalho, N. Karanth P, and V. Desai, "Characterization of pneumatic muscle actuators and their implementation on an elbow exoskeleton with a novel hinge design," *Sensors and Actuators Reports*, vol. 4, no. May, p. 100109, 2022, doi: 10.1016/j.snr.2022.100109.

[21] D. Sangian, "'From Traditional Braiding Methods to Additive Manufacturing for Fabricating Mckibben Artificial Muscles,'" *Biomed. J. Sci. Tech. Res.*, vol. 38, no. 5, 2021, doi: 10.26717/bjstr.2021.38.006211.

[22] C. Xiang, M. E. Giannaccini, T. Theodoridis, L. Hao, S. Nefti-Meziani, and S. Davis, "Variable stiffness Mckibben muscles with hydraulic and pneumatic operating modes," *Adv. Robot.*, vol. 30, no. 13, pp. 889–899, Jul. 2016, doi: 10.1080/01691864.2016.1154801.

[23] I. N. A. M. Nordin, "A New Fiber Braided Soft Bending Actuator," Universiti Teknologi Malaysia, 2016.

[24] I. N. A. M. Nordin, A. A. M. Faudzi, M. Z. Kamarudin, D. E. Octorina Dewi, T. Rehman, and M. R. M. Razif, "GRIP FORCE MEASUREMENT OF SOFT-ACTUATED FINGER EXOSKELETON," *J. Teknol.*, vol. 78, no. 6-13 SE-, Jun. 2016, doi: 10.11113/jt.v78.9268.

[25] A. A. M. Faudzi, M. R. M. Razif, I. N. A. M. Nordin, K. Suzumori, S. Wakimoto, and D. Hirooka, "Development of bending soft actuator with different braided angles," *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM*, pp. 1093–1098, 2012, doi: 10.1109/AIM.2012.6266037.

[26] I. N. A. Mohd Nordin, M. R. Muhammad Razif, A. M. Faudzi, E. Natarajan, K. Iwata, and K. Suzumori, "3-D finite-element analysis of fiber-reinforced soft bending actuator for finger flexion," *2013 IEEE/ASME Int. Conf. Adv. Intell. Mechatronics Mechatronics Hum. Wellbeing, AIM 2013*, pp. 128–133, 2013, doi: 10.1109/AIM.2013.6584080.

[27] I. N. A. M. Nordin, A. A. M. Faudzi, M. R. M. Razif, E. Natarajan, S. Wakimoto, and K. Suzumori, “Simulations of two patterns fiber weaves reinforced in rubber actuator,” *J. Teknol. (Sciences Eng.*, vol. 69, no. 3, pp. 133–138, 2014, doi: 10.11113/jt.v69.3315.

[28] I. N. A. M. Nordin, A. ’. M. Faudzi, S. Wakimoto, and K. Suzumori, “Simulations of fiber braided bending actuator: Investigation on position of fiber layer placement and air chamber diameter,” in *2015 10th Asian Control Conference (ASCC)*, 2015, pp. 1–5, doi: 10.1109/ASCC.2015.7244886.

[29] J. Kim, J. W. Kim, H. C. Kim, L. Zhai, H. U. Ko, and R. M. Muthoka, “Review of Soft Actuator Materials,” *Int. J. Precis. Eng. Manuf.*, vol. 20, no. 12, pp. 2221–2241, 2019, doi: 10.1007/s12541-019-00255-1.

[30] K. Osman, M. F. Rahmat, and K. Suzumori, “Intelligent Pneumatic Assisted Therapy on Ankle Rehabilitation,” pp. 107–112, 2015.

[31] M. Trumić, K. Jovanović, and A. Fagiolini, “Decoupled nonlinear adaptive control of position and stiffness for pneumatic soft robots,” *Int. J. Rob. Res.*, vol. 40, no. 1, pp. 277–295, 2021, doi: 10.1177/0278364920903787.

[32] M. Li, A. Pal, A. Aghakhani, A. Pena-francesch, and M. Sitti, “Soft actuators for real-world applications,” *Eur. PMC Funders Gr.*, pp. 235–249, 2022, doi: 10.1038/s41578-021-00389-7.Soft.

[33] Q. Liu, J. Zuo, C. Zhu, and S. Quan, “Design and control of soft rehabilitation robots actuated by pneumatic muscles : State of the art ☆,” vol. 113, pp. 620–634, 2020.

[34] P. D. S. H. Gunawardane, R. E. A. Pallewela, and N. T. Medagedara, “Tele-operable controlling system for hand gesture controlled soft robot actuator,” *RoboSoft 2019 - 2019 IEEE Int. Conf. Soft Robot.*, pp. 656–662, 2019, doi: 10.1109/ROBOSOFT.2019.8722756.

[35] J. Y. Nagase, K. Hamada, T. Satoh, N. Saga, and K. Suzumori, “Comparison between PFC and PID control system for tendon-driven balloon actuator,” *IECON Proc. (Industrial Electron. Conf.*, pp. 3398–3403, 2013, doi: 10.1109/IECON.2013.6699674.

[36] E. Sun, T. Wang, and Z. Zhu, “Design and Control of an Electrohydraulic Soft Actuator System for Robotic Grippers,” in *2019 IEEE 8th International Conference on Fluid Power and Mechatronics (FPM)*, 2019, pp. 327–333, doi: 10.1109/FPM45753.2019.9035816.

[37] G. Gerboni, A. Diodato, G. Ciuti, M. Cianchetti, and A. Menciassi, “Feedback Control of Soft Robot Actuators via Commercial Flex Bend Sensors,” *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 4, pp. 1881–1888, 2017, doi: 10.1109/TMECH.2017.2699677.

[38] W. Liang, J. Cao, Q. Ren, and J. X. Xu, “Control of Dielectric Elastomer Soft Actuators Using Antagonistic Pairs,” *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 6, pp. 2862–2872, 2019, doi: 10.1109/TMECH.2019.2945518.

[39] A. Zolfagharian, M. A. P. Mahmud, S. Gharaie, M. Bodaghi, A. Z. Kouzani, and A. Kaynak, “3D/4D-printed bending-type soft pneumatic actuators: fabrication, modelling, and control,” *Virtual Phys. Prototyp.*, vol. 15, no. 4, pp. 373–402, Oct. 2020, doi: 10.1080/17452759.2020.1795209.

[40] J. Fras, Y. Noh, H. Wurdemann, and K. Althoefer, “Soft fluidic rotary actuator with improved actuation properties,” in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 5610–5615, doi: 10.1109/IROS.2017.8206448.

[41] D. Herrero-Pérez and H. Martínez-Barberá, “Soft Gripper Design and Fabrication for Underwater Grasping,” *Appl. Sci.*, vol. 12, no. 21, pp. 1–14, 2022, doi: 10.3390/app122110694.

[42] Y. Haibin, K. Cheng, L. Junfeng, and Y. Guilin, “Modeling of grasping force for a soft robotic gripper with variable stiffness,” *Mech. Mach. Theory*, vol. 128, pp.254–274,2018, doi: https://doi.org/10.1016/j.mechmachtheory.2018.05.005.

[43] P. Cheng, J. Jia, Y. Ye, and C. Wu, “Modeling of a Soft-Rigid Gripper Actuated by a Linear-Extension Soft Pneumatic Actuator,” *Sensors*, vol. 21, no. 2. 2021, doi: 10.3390/s21020493.

[44] T. Du, L. Sun, and J. Wan, “A Worm-like Crawling Soft Robot with Pneumatic Actuators Based on Selective Laser Sintering of TPU Powder,” *Biomimetics*, vol. 7, no. 4. 2022, doi: 10.3390/biomimetics7040205.

[45] J. Li, S. Chen, and M. Sun, “Design and fabrication of a crawling robot based on a soft actuator,” *Smart Mater. Struct.*, vol. 30, no. 12, p. 125018, 2021, doi: 10.1088/1361-665X/ac2e1b.

[46] Q. Tan *et al.*, “Underwater Crawling Robot With Hydraulic Soft Actuators,” *Front. Robot. AI*, vol. 8, no. August, pp. 1–13, 2021, doi: 10.3389/frobt.2021.688697.

[47] A. F. Pérez Vidal *et al.*, “Soft exoskeletons: Development, requirements, and

challenges of the last decade," *Actuators*, vol. 10, no. 7, pp. 1–26, 2021, doi: 10.3390/act10070166.

[48] P. Ramasamy, E. Calderon-Sastre, G. Renganathan, S. Das, and Y. Kurita, "Soft actuators-based skill training wearables: a review on the interaction modes, feedback types, VR scenarios, sensors utilization and applications," *ROBOMECH J.*, vol. 10, no. 1, pp. 1–15, 2023, doi: 10.1186/s40648-023-00239-x.

[49] M.-H. Hsieh, Y. H. Huang, C.-L. Chao, C.-H. Liu, W.-L. Hsu, and W.-P. Shih, "Single-Actuator-Based Lower-Limb Soft Exoskeleton for Preswing Gait Assistance," *Appl. Bionics Biomech.*, vol. 2020, p. 5927657, 2020, doi: 10.1155/2020/5927657.

[50] V. Oguntosin, A. Akindele, and E. Oladimeji, "Gesture-based control of rotary pneumatic soft robot using leap motion controller," *2019 6th Int. Conf. Soft Comput. Mach. Intell. ISCMI 2019*, pp. 169–174, 2019, doi: 10.1109/ISCMI47871.2019.9004295.

[51] B. K. Johnson *et al.*, "Identification and Control of a Nonlinear Soft Actuator and Sensor System," *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 3783–3790, 2020, doi: 10.1109/LRA.2020.2982056.

[52] Y. Li, Y. Chen, and Y. Li, "Pre-charged pneumatic soft gripper with closed-loop control," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1402–1408, 2019, doi: 10.1109/LRA.2019.2895877.

[53] Y. Cao and J. Dong, "Self-Sensing and Control of Soft Electrothermal Actuator," vol. 4435, no. c, 2020, doi: 10.1109/TMECH.2020.3009237.

[54] A. Das, M. Nabi, and F. Chinesta, "Modeling soft robotic actuators using data-driven model reduction," in *2020 28th Mediterranean Conference on Control and Automation (MED)*, 2020, pp. 490–495, doi: 10.1109/MED48518.2020.9182978.

[55] P. Abbasi, M. A. Nekoui, M. Zareinejad, P. Abbasi, and Z. Azhang, "Position and Force Control of a Soft Pneumatic Actuator," *Soft Robot.*, vol. 7, no. 5, pp. 550–563, Apr. 2020, doi: 10.1089/soro.2019.0065.

[56] Z. Zhang, X. Wang, S. Wang, D. Meng, and B. Liang, "Design and Modeling of a Parallel-Pipe-Crawling Pneumatic Soft Robot," *IEEE Access*, vol. 7, pp. 134301–134317, 2019, doi: 10.1109/ACCESS.2019.2941502.

[57] G. Mengaldo *et al.*, "A concise guide to modelling the physics of embodied

intelligence in soft robotics," *Nat. Rev. Phys.*, vol. 4, no. 9, pp. 595–610, 2022, doi: 10.1038/s42254-022-00481-z.

[58] Z. Wang, J. B. Estrada, E. M. Arruda, and K. Garikipati, "Inference of deformation mechanisms and constitutive response of soft material surrogates of biological tissue by full-field characterization and data-driven variational system identification," *J. Mech. Phys. Solids*, vol. 153, p. 104474, 2021, doi: https://doi.org/10.1016/j.jmps.2021.104474.

[59] F. Quevedo, J. Muñoz, J. A. Castano Pena, and C. A. Monje, "3D Model Identification of a Soft Robotic Neck," *Mathematics*, vol. 9, no. 14. 2021, doi: 10.3390/math9141652.

[60] X. Wang, T. Geng, Y. Elsayed, C. Saaj, and C. Lekakou, "A unified system identification approach for a class of pneumatically-driven soft actuators," *Rob. Auton. Syst.*, vol. 63, no. P1, pp. 136–149, 2015, doi: 10.1016/j.robot.2014.08.017.

[61] F. Quevedo, J. Mu, J. A. Castano, A. Monje, and C. Balaguer, "Model Identification of a Soft Robotic Neck," pp. 8640–8645, 2020.

[62] A. A. M. Faudzi, N. H. I. Mat Lazim, and K. Suzumori, "Modeling and force control of thin soft McKibben actuator," *Int. J. Autom. Technol.*, vol. 10, no. 4, pp. 487–493, 2016, doi: 10.20965/ijat.2016.p0487.

[63] X. Luo, M. B. Xiao, Y. Ding, and H. Ding, "Hysteresis modeling and compensation of a pneumatic end-effector based on Gaussian process regression," *Sensors Actuators, A Phys.*, vol. 315, 2020, doi: 10.1016/j.sna.2020.112227.

[64] J. Y. Loo, K. C. Kong, C. P. Tan, and S. G. Nurzaman, "Non-linear System Identification and State Estimation in a Pneumatic Based Soft Continuum Robot," pp. 1–8, 2019.

[65] H. A. Ibrahim, H. H. Ammar, and R. Shalaby, "Modeling and Control of a Novel Design of Series Elastic Actuator for Upper Limb Rehabilitation," *Math. Model. Eng. Probl.*, vol. 9, no. 1, pp. 85–93, 2022, doi: 10.18280/mmep.090111.

[66] K. Elgeneidy, N. Lohse, and M. Jackson, "Bending angle prediction and control of soft pneumatic actuators with embedded flex sensors – A data-driven approach," *Mechatronics*, vol. 50, no. October 2017, pp. 234–247, 2018, doi: 10.1016/j.mechatronics.2017.10.005.

[67] A. H. Khan, Z. Shao, S. Li, Q. Wang, and N. Guan, “Which is the best PID variant for pneumatic soft robots? an experimental study,” *IEEE/CAA J. Autom. Sin.*, vol. 7, no. 2, pp. 451–460, 2020, doi: 10.1109/JAS.2020.1003045.

[68] M. Hassan, M. I. Awad, and S. A. Maged, “Develop Control Architectures to Enhance Soft Actuator Motion and Force,” *Computation*, vol. 10, no. 10, 2022, doi: 10.3390/computation10100178.

[69] Q. Ji, X. Zhang, M. Chen, X. V. Wang, L. Wang, and L. Feng, “Design and closed loop control of a 3D printed soft actuator,” *IEEE Int. Conf. Autom. Sci. Eng.*, vol. 2020-Augus, pp. 842–848, 2020, doi: 10.1109/CASE48305.2020.9216946.

[70] J. Morrow *et al.*, “Improving Soft Pneumatic Actuator fingers through integration of soft sensors, position and force control, and rigid fingernails,” *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 2016-June, pp. 5024–5031, 2016, doi: 10.1109/ICRA.2016.7487707.

[71] M. S. Xavier, A. J. Fleming, and Y. K. Yong, “Design and Control of Pneumatic Systems for Soft Robotics: A Simulation Approach,” *IEEE Robot. Autom. Lett.*, vol. 6, no. 3, pp. 5800–5807, 2021, doi: 10.1109/LRA.2021.3086425.

[72] T. Lyu, “A Control Method for SMA Robotic Actuators,” *J. Comput. Commun.*, vol. 10, no. 05, pp. 103–112, 2022, doi: 10.4236/jcc.2022.105007.

[73] A. Khan and S. Li, “Sliding Mode Control With PID Sliding Surface for Active Vibration Damping of Pneumatically Actuated Soft Robots,” *IEEE Access*, vol. PP, p. 1, May 2020, doi: 10.1109/ACCESS.2020.2992997.

[74] E. H. Skorina, M. Luo, S. Ozel, F. Chen, W. Tao, and C. D. Onal, “Feedforward augmented sliding mode motion control of antagonistic soft pneumatic actuators,” *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 2015-June, no. June, pp. 2544–2549, 2015, doi: 10.1109/ICRA.2015.7139540.

[75] G. Cao, Y. Liu, Y. Jiang, F. Zhang, G. Bian, and D. H. Owens, “Observer-based continuous adaptive sliding mode control for soft actuators,” *Nonlinear Dyn.*, vol. 105, no. 1, pp. 371–386, 2021, doi: 10.1007/s11071-021-06606-w.

[76] Y. Li, Y. Cao, and F. Jia, “A neural network based dynamic control method for soft pneumatic actuator with symmetrical chambers,” *Actuators*, vol. 10, no. 6, 2021, doi: 10.3390/act10060112.

[77] C. Nicholson-smith, V. Mehrabi, S. F. Atashzar, R. V Patel, and L. Fellow, “A Multi-Functional Lower- and Upper-Limb Stroke Rehabilitation Robot,” vol. 2,

no. 4, pp. 549–552, 2020.

[78] F. Gao, L. Wang, and T. Lin, “Intelligent wearable rehabilitation robot control system based on mobile communication network,” vol. 153, no. December 2019, pp. 286–293, 2020.

[79] S. J. Bae, S. H. Jang, J. P. Seo, and P. H. Chang, “A pilot study on the optimal speeds for passive wrist movements by a rehabilitation robot of stroke patients : A functional NIRS study,” pp. 7–12, 2017.

[80] C. Luca, D. Andriġoi, and C. Corciovǎ, “Intelligent Glove for Rehabilitation of Hand Movement in Stroke Survivor,” no. Epe, pp. 546–549, 2020.

[81] K. X. Khor *et al.*, “Portable and Reconfigurable Wrist Robot Improves Hand Function for Post-Stroke Subjects,” vol. 25, no. 10, pp. 1864–1873, 2017.

[82] C. Yokota *et al.*, “Acute stroke rehabilitation for gait training with cyborg type robot Hybrid Assistive Limb: A pilot study,” *J. Neurol. Sci.*, vol. 404, no. April, pp. 11–15, 2019, doi: 10.1016/j.jns.2019.07.012.

[83] Z. Zhou, Y. Zhou, N. Wang, F. Gao, K. Wei, and Q. Wang, “A proprioceptive neuromuscular facilitation integrated robotic ankle-foot system for post stroke rehabilitation,” *Rob. Auton. Syst.*, vol. 73, pp. 111–122, 2015, doi: 10.1016/j.robot.2014.09.023.

[84] H. Eschmann, M. E. Héroux, J. H. Cheetham, S. Potts, and J. Diong, “Thumb and finger movement is reduced after stroke: An observational study,” *PLoS One*, vol. 14, no. 6, pp. 1–14, 2019, doi: 10.1371/journal.pone.0217969.

[85] C. Y. Chu and R. M. Patterson, “Soft robotic devices for hand rehabilitation and assistance: A narrative review,” *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–14, 2018, doi: 10.1186/s12984-018-0350-6.

[86] A. Borboni *et al.*, “Robot-Assisted Rehabilitation of Hand Paralysis After Stroke Reduces Wrist Edema and Pain: A Prospective Clinical Trial,” *J. Manipulative Physiol. Ther.*, vol. 40, no. 1, pp. 21–30, 2017, doi: 10.1016/j.jmpt.2016.10.003.

[87] X. Q. Shi, H. L. Heung, Z. Q. Tang, Z. Li, and K. Y. Tong, “Effects of a Soft Robotic Hand for Hand Rehabilitation in Chronic Stroke Survivors,” *J. Stroke Cerebrovasc. Dis.*, vol. 30, no. 7, p. 105812, 2021, doi: 10.1016/j.jstrokecerebrovasdis.2021.105812.

[88] J. Lee, W. Park, S. Kim, and J. Bae, “Design of a Wearable Hand Rehabilitation System for Quantitative Evaluation of the Stroke Hand,” no. Iccas, pp. 419–

422, 2016.

[89] A. Yurkewich, S. Member, D. Hebert, R. H. Wang, and A. Mihailidis, "Hand Extension Robot Orthosis (HERO) Glove : Development and Testing With Stroke Survivors With Severe Hand Impairment," vol. 27, no. 5, pp. 916–926, 2019.

[90] K. Anam, "The Design of a Low-Cost Therapy Robot for Hand Rehabilitation of a Post-Stroke Patient," pp. 0–3, 2021.

[91] M. Runciman, J. Avery, A. Darzi, and G. Mylonas, "Open Loop Position Control of Soft Hydraulic Actuators for Minimally Invasive Surgery," *Applied Sciences*, vol. 11, no. 16. 2021, doi: 10.3390/app11167391.

[92] Mouser electronics, "FS-L-095-103-ST Datasheet." https://www.mouser.com/ProductDetail/Spectra-Symbol/FS-L-095-103-ST?qs=PqoDHHvF64%2Feuno7kpu37A%3D%3D.

[93] Nitto Bend Technologies, "1-Axis Soft Flex Sensor." https://www.nitto.com/sea/en/nbt/products/1-axis-soft-flex-sensor/.

[94] SMC Pneumatics, "SMC ITV0030-3BL regulator, electro-pneumatic, IT/ITV0000/1000 E/P REGULATOR." https://www.smcpneumatics.com/ITV0030-3BL.html.

[95] S. Davarzani, M. A. Ahmadi-Pajouh, and H. Ghafarirad, "Design of sensing system for experimental modeling of soft actuator applied for finger rehabilitation," *Robotica*, vol. 40, no. 7, pp. 2091–2111, 2022, doi: DOI: 10.1017/S0263574721001533.

[96] J. Cao, W. Liang, J. Zhu, and Q. Ren, "Control of a muscle-like soft actuator via a bioinspired approach," *Bioinspir. Biomim.*, vol. 13, no. 6, p. 66005, 2018, doi: 10.1088/1748-3190/aae1be.

[97] P. Abbasi, M. A. Nekoui, M. Zareinejad, P. Abbasi, and Z. Azhang, "Position and Force Control of a Soft Pneumatic Actuator," *Soft Robot.*, vol. 7, no. 5, pp. 550–563, 2020, doi: 10.1089/soro.2019.0065.

[98] M. Li, Q. Wang, Y. Li, and Z. Jiang, "Modeling and Discrete-Time Terminal Sliding Mode Control of a DEAP Actuator with Rate-Dependent Hysteresis Nonlinearity," *Applied Sciences*, vol. 9, no. 13. 2019, doi: 10.3390/app9132625.

[99] A. Zolfagharian, A. Kaynak, A. Noshadi, and A. Z. Kouzani, "System identification and robust tracking of a 3D printed soft actuator," *Smart Mater. Struct.*, vol. 28, no. 7, p. 75025, 2019, doi: 10.1088/1361-665X/ab1cce.

[100] Y. Huang, M. Hofer, and R. D'Andrea, "Offset-free Model Predictive Control: A Ball Catching Application with a Spherical Soft Robotic Arm," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021, pp. 563–570, doi: 10.1109/IROS51168.2021.9636608.

VITA

The author was born on 1st of September, 1997, in Kedah Malaysia. For his secondary education, he attended Sekolah Menengah Kebangsaan Jati in Ipoh, Perak, Malaysia. At the Universiti Tun Hussein Onn Malaysia (UTHM), where he pursued his education, he received a Bachelor of Electronic Engineering Technology (Industrial Automation) with Honours in 2020. He directly further his master studies after receiving his degree in the same university because of his passion in gaining knowledge.