

DESIGN OF BIOMIMICRY ROBOTIC EYE USING THIN MCKIBBEN
ACTUATORS WITH AGONIST-ANTAGONIST MUSCLES

HONG WIN SOON

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechatronics and Automatic Control)

School of Electrical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JULY 2020

DEDICATION

This project report is dedicated to my parents, who always provided me with the love and support to always strive on and move forward in life. It is also dedicated to my sister, who have always help and support me from behind the scenes. I would not have been able to do this without any of them by my side.

ACKNOWLEDGEMENT

In preparing this project report, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Associate Professor Ir. Ts. Dr. Ahmad 'Athif Bin Mohd Faudzi, for encouragement, support, guidance, critics and friendship. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for supporting my research in this study. I would also like to thank the various lecturers from the Electrical Faculty on their advice on my project.

I would also like to thank my fellow postgraduate student for their support. My sincere appreciation extends to all my colleagues from the Actuator and Automation Lab (A2 Lab) and others who have aided at various occasions. Without their help, support and feedback, I would not have been able to accomplish this.

ABSTRACT

The human eye is important to the survival and evolution of humanity. Thus, we look to it for inspiration in designing and translating its design into a robotic system that can be actuated by soft actuators. The purpose of this study is to investigate and implement biomimicry of the human eye through a 3D printed robotic eye based on a ball joint system that is actuated by thin McKibben actuators with agonist and antagonist muscles. This study proposes the implementation of the agonist-antagonistic as well as neutralizer muscles pairs to actuate the robotic eye through the control of air pressure at 200 kPa and 420 kPa investigate the behaviour of the thin McKibben actuators during the implementation of the agonist-antagonist muscles as well as the assessment of its performance via the laser pointer experiment and Tracker application. The solution is based on the advantage gained through the implementation of the thin McKibben actuators as well as 3D printing during the robotic eye design, which grants an improved, simpler design to the robotic eye. The approach has several notable merits, namely a reduction in design complexity and reduction in size. A comprehensive verification via experimentation was carried out to determine the effectiveness of the concept and design. The result confirms that the method can produce a robotic eye design that works well through the use of agonist-antagonist muscles pairs and neutralizer muscle pairs. From the experimentation works, it was found that the 3D printed robotic eye can be actuated via the Thin McKibben actuator with the angular movement of around 20 degrees and with two Degrees of Freedom via Agonist-Antagonist muscle pairing. The results also show the high repeatability of the robot while operating under hysteresis mode, with a standard deviation of 0.1 to 0.54 after repeated testing. Furthermore, the behaviour of the thin McKibben actuators during the implementation of agonist-antagonist muscle action was successfully identified and categorized as contraction, relaxation and re-contraction behaviours. The method proposed in this paper can be implemented in other types of robots with thin McKibben muscles as actuators as well.

ABSTRAK

Sistem visual manusia adalah amat penting kepada survival dan evolusi manusia. Oleh itu, kita merujuk kepadanya untuk inspirasi dalam mereka cipta sistem visual robotik yang boleh disesuaikan dalam sistem robot yang menggunakan penggerak lembut dengan otot agonis-antagonis. Kajian ini dijalankan dengan tujuan implementasi biomimikri kepada sistem pergerakan mata manusia dengan penggunaan robot mata berdasarkan sendi mata yang dihasilkan melalui percetakan 3D dan manipulasi penggerak nipis McKibben. Kajian ini mencadangkan kaedah implementasi otot agonis dan antagonis serta otot peneutralan untuk menggerakkan system robot mata melalui kawalan tekanan udara dalam 200 kPa dan 420 kPa, dan juga menyiasat tingkah laku penggerak McKibben nipis semasa implementasi otot agonis-antagonis serta menilai prestasi robot mata dengan menggunakan kaedah eksperimen penunjuk laser dan applikasi Tracker . Keupayaan robot ini dapat dicapai hasil daripada implementasi penggerak McKibben nipis dan percetakan 3D dalam process reka cipta robot yang mengizinkan reka cipta yang lebih baik dan mudah kepada mata robotik ini. Pendekatan ini mempunyai beberapa merit yang ketara, iaitu pengurangan kerumitan reka bentuk dan pengurangan saiz. Pengesahan menyeluruh melalui eksperimen dijalankan untuk menentukan keberkesanan konsep dan reka bentuk. Hasil eksperimen mengesahkan bahawa konsep pasangan otot agonis-antagonis serta otot peneutralan berjaya dilaksanakan. Dari hasil eksperimen, didapati bahawa robot mata yang dicetak 3D dapat digerakkan melalui penggerak McKibben nipis dengan pergerakan sudut sekitar 20 darjah dan dengan dua Darjah Kebebasan menggunakan pasangan otot agonist dan antagonist. Tambahan lagi, tingkah laku penggerak nipis McKibben semasa operasi pasangan otot agonis-antagonis juga berjaya dikenal pasti dan dikategorikan sebagai pengecutan, kelonggaran dan pengecutan semula. Kaedah yang dicadangkan dalam kajian ini juga boleh dilaksanakan dalam jenis robot yang menggunakan penggerak nipis McKibben juga.

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	iii
	DEDICATION	iv
	ACKNOWLEDGEMENT	v
	ABSTRACT	ii
	ABSTRAK	iii
	TABLE OF CONTENTS	iv
	LIST OF TABLES	viii
	LIST OF FIGURES	ix
	LIST OF ABBREVIATIONS	xiv
	LIST OF SYMBOLS	xv
	LIST OF APPENDICES	xvi
CHAPTER 1	INTRODUCTION	1
	1.1 Problem Background	1
	1.2 Problem Statement	2
	1.3 Research Objectives	3
	1.4 Research Scope	4
	1.5 Operational Definition	4
CHAPTER 2	LITERATURE REVIEW	7
	2.1 Introduction	7
	2.2 The Human Eye and Extraocular Muscles	7
	2.3 Agonist- Antagonist Muscles and Neutralizer Muscles	8
	2.4 Biomimicry	9
	2.5 Soft Robotics	11
	2.6 The Thin McKibben actuator	12
	2.7 Implementation of Agonist and Antagonist Muscle via Pneumatic Artificial Muscle	17

2.8	Similar Works Related to Robotic Eye Actuated by Soft Actuator	20
CHAPTER 3	RESEARCH METHODOLOGY	23
3.1	Introduction	23
3.2	Phase one - 3D printed Robotic Eye Design	25
3.2.1	Identification of the Anatomy of the Human Eye	27
3.2.2	3D Printed Robotic Eye Prototype Design and Actuation	27
3.2.2.1	Frontal Sphere	28
3.2.2.2	Rear Sphere	29
3.2.2.3	Ball Joint	30
3.2.2.4	Actuator Ring	31
3.2.2.5	Cradle	32
3.2.3	3D Printed Robotic Eye Prototype Actuation and Testing	32
3.2.3.1	Dimensions and Actuators of the 3D printed Robotic Eye	33
3.2.3.2	3D Printed Prototype Robotic Eye Assembly and Integration with Thin McKibben Actuators	37
3.2.3.3	3D Printed Robotic Eye Actuation Testing	39
3.2.4	3D Printed Robotic Eye Redesign	40
3.2.4.1	Cradle Base	41
3.2.4.2	Middle Support Column	42
3.2.4.3	End Support Column	43
3.2.4.4	Central Rod	44
3.2.5	Implementation of the Agonist-Antagonist & Neutralizer Muscles	48
3.2.5.1	Agonist- Antagonist muscles	48
3.2.5.2	Neutralizer Muscles	50
3.2.6	Functional Test	53

3.3	Phase two - McKibben Actuator Fabrication, Testing, Behavior Profiling	54
3.3.1	The Fabrication of Thin McKibben Actuators	54
3.3.1.1	Fabrication Process	55
3.3.1.2	Leak Seal Test	58
3.3.1.3	Reseal Process	60
3.3.2	The Testing of the Thin McKibben Actuator and Behavior Profiling	61
3.3.2.1	Contraction Test	63
3.3.2.2	Relaxation Test	64
3.3.2.3	Re-Contraction Test	65
3.4	Phase 3 - Pneumatic System and Open Loop Control Design	66
3.5	Phase 4 – Testing and Validation	68
3.5.1	Laser Pointer Experiment	68
3.5.1.1	Laser Module and Calibration	71
3.5.1.2	Max actuation check	72
3.5.2	Tracker Software Verification	73
3.6	Chapter Summary	74
CHAPTER 4	RESULTS AND DISCUSSION	77
4.1	Introduction	77
4.2	3D Printed Robotic Eye Fabrication	77
4.2.1	Prototype 3D Printing Fabrication	77
4.2.2	Final Robotic Eye 3D Printing Fabrication	80
4.3	3D Printed Robotic Eye Assembly with Actuators	83
4.4	Thin McKibben Actuator Test Results	88
4.4.1	Thin McKibben with Leak vs Thin McKibben without Leak	88
4.4.2	Improper Test Procedures Vs Proper Test Procedures	89
4.4.3	Contraction Test Result	91
4.4.4	Relaxation Test Data	92
4.4.5	Re-Contraction Test Data	94

4.4.6	The Averaged McKibben Test Data	96
4.5	Robotic Eye Actuation Functionality Check	98
4.6	Laser Pointer Experiment Results	99
4.6.1	Initialization Data	99
4.6.2	Robotic Eye Directional Laser Experiment Data	100
4.7	Laser Experiment Vs Tracker Data	103
4.8	Troubleshooting and Analysis	105
4.9	Hysteresis Mode Operation	107
CHAPTER 5	CONCLUSION AND RECOMMENDATIONS	109
5.1	Introduction	109
5.2	Conclusion	109
5.3	Future Works	110
	REFERENCES	113
	LIST OF PUBLICATIONS	121

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 4.1	3D Printer Configuration and Settings	82
Table 4.2	Initialization Test Data with Laser Pointer	100
Table 4.3	Directional Laser Experimental Data	101
Table 4.4	Laser Vs Tracker Comparison	104
Table 4.5	Hysteresis Performance of the Robotic Eye	108

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Lateral and Anterior View of the Right Eye [16]	8
Figure 2.2	Biceps and Triceps Muscle Pairs [20]	9
Figure 2.3	Octopus-like Robot Arm [22]	10
Figure 2.4	Human-like Robotic Hand [27]	10
Figure 2.5	Elastomeric Gripper under Mechanical Stress Test [30]	11
Figure 2.6	The Fabricated Thin McKibben Artificial Muscle [11]	13
Figure 2.7	Breakdown of a thin McKibben Actuator [33]	14
Figure 2.8	Bundled Thin McKibben Actuators [33]	14
Figure 2.9	Octopus Arm using Thin McKibben Actuators [13]	15
Figure 2.10	Long-Legged Hexapod Giacometti Robot [14]	15
Figure 2.11	Soft Manipulator using Thin McKibben Actuator [23]	16
Figure 2.12	Graph of Contraction Ratio Against Input Air Pressure of the 1.3 mm Thin McKibben Actuator [23]	16
Figure 2.13	Graph of Pulling Force Against Input Air Pressure of the 1.3 mm Thin McKibben Actuator [23]	17
Figure 2.14	Schematic Diagram of Wrist Joint Arrangement [37]	18
Figure 2.15	Model Equilibrium-Point Control of Agonist-Antagonist System [38]	19
Figure 2.16	Configuration of Robot Arm System Using Intelligent McKibben Actuator [39]	19
Figure 2.17	Prototype Humanoid Robotic Eye by X.wang <i>et. al</i> [7]	21
Figure 2.18	Pneumatically Actuated Robotic Eye by A.Lenz <i>et.al</i> [6]	21
Figure 2.19	Artificial Eyeball With Three Spring Roll Dielectric Elastomer [9]	22
Figure 2.20	Image of the Eye for Rotational Measurements [8]	22
Figure 3.1	Overall Phase Summary of the Project	23

Figure 3.2	Process Flow Chart for the Project	24
Figure 3.3	Flow Chart for Phase 1	25
Figure 3.4	Front View of 3D Render of Frontal Sphere of the Robotic Eye	28
Figure 3.5	Back View of 3D Render of the Prototype Robotic Eye	29
Figure 3.6	Render of Rear Sphere of the Robotic Eye A) Top B) Side C) Bottom	30
Figure 3.7	3D Render of Ball Joint	31
Figure 3.8	3D Render of the Actuator Ring of the Robotic Eye	31
Figure 3.9	3D Render of the Cradle of the Robotic Eye	32
Figure 3.10	Circle Diameter and Radius	33
Figure 3.11	Diameter and Radius of the Spherical Structure of the Robotic Eye	33
Figure 3.12	Half Actuation from The Centre of the Robotic Eye To The Right	35
Figure 3.13	Half Actuation from The Centre of the Robotic Eye to The Left	35
Figure 3.14	Assembled 3D Printed Prototype with Thin McKibben Actuators	38
Figure 3.15	Breakdown of Assembled 3D Printed Prototype	38
Figure 3.16	Prototype Robotic Eye Half Actuation Results at 400 kPa	39
Figure 3.17	Design of the Base for the Cradle of the 3D Printed Robotic Eye	41
Figure 3.18	Middle Support Colum A) Front View B) 30 Degree Side View C) Bottom Side View	42
Figure 3.19	End Support Colum A) Front View B) 30 Degree Side View C) Bottom Side View	43
Figure 3.20	First Central Rod Design A) 45 degrees view B) Top-Down view	45
Figure 3.21	Upper Half of the Central Rod A) Side View B) Top View C) Slanted Bottom View	46
Figure 3.22	Lower Half of the Central Rod A) Side View B) Top View C) Slanted Top View	46

Figure 3.23	Revised Upper Half of the Central Rod A) Side View B) Slanted Top View C) Top View	47
Figure 3.24	Up and Down thin McKibben Muscles on the Robotic Eye in the un-initialized state	49
Figure 3.25	Up and Down thin McKibben Muscles on the Robotic Eye at 200 kPa	49
Figure 3.26	Up and Down thin McKibben Muscles on the Robotic Eye When Moving Upwards	50
Figure 3.27	Frontal View of the Robotic Eye When Performing Up- Down Motion	51
Figure 3.28	Frontal View of the Robotic Eye When Performing Left-Right Motion	52
Figure 3.29	Frontal View of the Robotic Eye When in Neutral State	53
Figure 3.30	The Thin McKibben Manufacturing Process Flow Chart	55
Figure 3.31	Tools and Materials for Thin McKibben Actuator Fabrication	56
Figure 3.32	Leak Seal Test Setup for Thin McKibben Actuator	58
Figure 3.33	Results of the Leak-Seal Test a) Failing with Leakage b) Passing without Leakage	60
Figure 3.34	Thin McKibben Actuation Test Setup	62
Figure 3.35	Pneumatic Setup for Individual Thin McKibben Actuator	66
Figure 3.36	Individual McKibben Control a) Normal b) Simplified	67
Figure 3.37	Overall McKibben Valve Control Diagram	68
Figure 3.38	Laser Pointer Experiment Setup	69
Figure 3.39	Diagram of the Laser Experiment Setup	70
Figure 3.40	A) Laser Module B) Calibration Block with Laser Module Inserted C) Laser Calibration	71
Figure 3.41	Laser Module When Installed on the Robotic Eye	72
Figure 3.42	Manual Laser Verification of the Max Actuation	72
Figure 3.43	Tracker Video Capture Setup	73
Figure 3.44	Example of Tracker Software Being Used in Verification	74

Figure 4.1	Prototype Robotic Eye Part Fabrication in Progress	78
Figure 4.2	The Fabricated Prototype 3D Printed Parts	78
Figure 4.3	The Front Sphere and Rear Sphere Structure After Clean Up	79
Figure 4.4	The Assembled 3D Printed Robotic Eye	80
Figure 4.5	A) Printer Calibration B) Temperature Bridge C) Centre Rod Printed with Custom Supports	80
Figure 4.6	Printed Laser Module for the Robotic Eye with Experimental Tree Support	81
Figure 4.7	3D Printed Cradle Base A) Normal Position B) Stressed in Curve	83
Figure 4.8	Assembled 3D Printed Robotic Eye	84
Figure 4.9	The Eyeball Structure of the 3D Printed Robotic Eye	85
Figure 4.10	The Cradle Structure of the 3D Printed Robot	86
Figure 4.11	Breakdown of Backup Central Rod Reinforced with Iron Rod	86
Figure 4.12	Broken Centre Rod Without Iron Rod	87
Figure 4.13	End Support Column with Additional Screw-Clamp	87
Figure 4.14	Graph of Thin McKibben with Leak vs Thin McKibben without Leak	89
Figure 4.15	Result for O1 Not Following Methodology Vs O1 Result Following Methodology	90
Figure 4.16	Contraction Data of 10 thin McKibben Actuators with Averaged Reading	92
Figure 4.17	Relaxation Test Data of 10 thin McKibben Actuators with Averaged Reading	93
Figure 4.18	Re-Contraction Test Data of 10 thin McKibben Actuators with Averaged Reading	94
Figure 4.19	Test Data of Thin McKibben Actuator O9	95
Figure 4.20	The Averaged Test Data of 10 Thin McKibben Actuators	96
Figure 4.21	Focused View of Average Test Data From 200 kPa to 420 kPa	97
Figure 4.22	Average Test Data Comparison with Literature Review Data[23]	97

Figure 4.23	The Eye Robot Actuation A) Up B) Down	98
Figure 4.24	The Eye Robot Actuation A) Left B) Right	99
Figure 4.25	Troubleshooting via Pressure Sensor Setup at Initialization	105
Figure 4.26	Troubleshooting via Pressure Sensor Setup at Actuation	106

LIST OF ABBREVIATIONS

PAM	-	Pneumatic Artificial Muscle
MAM	-	McKibben Artificial Muscle
3D	-	Three-Dimensional
PLA	-	Polylactic Acid
ABS	-	Acrylonitrile Butadiene Styrene

LIST OF SYMBOLS

cm	-	Centimetre
mm	-	Millimetre
kPa	-	Kilopascal
N	-	Newton (force)
%	-	Percentage symbol
C	-	Circumference of the Circle
HA	-	Desired Contraction for the McKibben Actuator during Half Actuation
LH	-	The thin McKibben actuator length for half actuation
FA	-	Desired Contraction for the McKibben Actuator during Full Actuation
FH	-	The thin McKibben actuator length for Full actuation

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Source Code for Arduino Uno	117

CHAPTER 1

INTRODUCTION

1.1 Problem Background

The human visual system is a very complex visual system, with the human eye acting as a light sensor to capture light of certain wavelength, around 400 to 700 nanometres [1] from the environment and feeding it into the central nervous system for further processing via the optic nerves [2]. The human eye or eyeball movement is controlled by six extraocular muscles, with the four extraocular muscle consisting of the superior rectus, lateral rectus, inferior rectus and medial rectus controlling the movement in the four cardinal directions (up, down, left and right) [3]. The extraocular muscles enable movement in the eye via contraction and the muscles work together as agonist-antagonist pairs to facilitate eye movement in the desired direction.

The biomimicry is the study of understanding of the design principles that govern the biological systems and extract the components of the biological design into an engineering or research design [4], [5]. As the human eyes play great importance in human daily lives, it is to no surprise that the human eye has inspired much research into robotic eye [6–10] designs.

The thin McKibben actuator was first introduced in the paper by Takaoka *et. al*, 2013 [11] is a pneumatic artificial muscle that was designed to be lightweight, thin and flexible. It has been used in numerous biomimicry designs such as human hand [12], octopus arm [13], long-legged hexapod Giacometti robot [14], and so on. While there are many works that are based on the human body, there is not much focus in research in regard to the application of thin McKibben actuators in the biomimetic field are for the human eye. Furthermore, while there are many research in regards to biomimetic human eyes, the potential of thin McKibben actuators being

applied into a similar design has not been fully explored. This presents an interesting area to research in regards to the potential of the thin McKibben actuators compared to other pneumatic artificial muscles or soft actuators.

The biomimicry of human eyes using soft actuators is a field that has potential for further exploration especially with the advent of 3D printing that enables the easy fabrication of custom plastic parts via a 3D printer, which when applied together with thin McKibben actuator has the potential to bring about a light-weight, customizable design with low manufacturing and design downtime. Furthermore, the application of thin McKibben actuators in a agonist-antagonistic muscle pairing in a ball joint is an area that has potential for further research and study, thus creating an interesting prospect of research in biomimetic robotic eye actuated by thin McKibben actuator.

Lastly, while the current soft robotic technology has not entered consumer stage application it has great potential for growth, development and application. It is hoped that the research in a biomimetic robotic eye that is actuated by thin McKibben actuators could be a small tiny step towards the application of soft robotics in the field of aerospace, deep-sea exploration, human bionic implants and more.

1.2 Problem Statement

The thin McKibben actuator has been applied in many bio-inspired and biomimetic systems, but there has been less focus on the study of its application in a biomimetic or bio-inspired robotic eye. Furthermore while there are many instances of robotic eye that is actuated by pneumatic artificial muscles and soft actuators [7–10], they were designed with larger pneumatic artificial muscles in mind, this there is an opportunity to apply the thin McKibben actuators in a bio-inspired robotic eye system that uses a ball joint structure as the main pivoting element for rotational motion.

Secondly, the robotic eye would be a good chance to showcase the implementation of the agonist-antagonist muscle relationship using thin McKibben actuators in a system using a ball joint structure as the main pivoting element. The implementation of agonist-antagonist muscle pairing using pneumatic artificial muscles and McKibben actuators is not new and has been done by many different researchers, however, there is still room for further study regarding the usage of thin McKibben actuators being used as agonist-antagonist muscle pairs in a ball joint based system. Furthermore, controlling a ball joint based system solely with agonist-antagonist pairing might be hard, and as such, there is opportunity to apply and study thin McKibben as neutralizer muscles to help reduce unnecessary movement in the robotic eye during actuation. Moreover, the behaviour of the thin McKibben actuators during the implementation of such muscles pairing is not deeply explored and warrants further investigation and testing.

Lastly, the performance of the 3D printed biomimetic robotic eye based on a ball joint system needs to be assessed. The proper methods to test the performance of the actuation of the robotic eye has to be developed and compared with other verification methods that are being used in the field.

1.3 Research Objectives

The objectives of the research are:

- (a) To develop a 3D printed robotic eye with 2 Degree of Freedom that can be actuated by thin McKibben Pneumatic Artificial Muscle.
- (b) To implement and investigate Agonist and Antagonistic muscle pairs as well as Neutralizer muscles relationships in a 3D robotic eye.
- (c) To evaluate the performance of the 3D printed robotic eye that is actuated by thin McKibben actuators.

1.4 Research Scope

The scope of the research are:

- (a) The human eye is very complex, design characteristics of the eye robot model will be limited to 2 Degrees of Freedom (up, down, left, right movement.)
- (b) The total length of the McKibben actuators in this study will be within 14 cm to 15.8 cm. This is due to the difficulty in fabrication of the McKibben actuators.
- (c) The robot will take inspiration from the human eye and will be fabricated via 3D printing using PLA material.
- (d) The implementation of Agonist and Antagonist, as well as Neutralizer muscle, will be done via manipulation of the McKibben actuators at two pressure points, 200 kPa as well as 420 kPa.
- (e) Validation of the robotic eye performance will come via two methods, which are laser pointer measurements and the Tracker application software.

1.5 Operational Definition

Some of the operational definition used is as follows:

- (a) Up thin McKibben: The thin McKibben actuator attached to the top portion of the eyeball structure of the robotic eye. Its main function is to pull the robotic eye upwards.
- (b) Down thin McKibben: The thin McKibben actuator attached to the bottom of the eyeball structure of the robotic eye. Its main function is to pull the robotic eye downwards.

- (c) Left thin McKibben: The thin McKibben actuator attached to the left side of the eyeball structure of the robotic eye. Its main function is to pull the robotic eye to the left.
- (d) Right thin McKibben: The thin McKibben actuator attached to the right side of the eyeball structure of the robotic eye. Its main function is to pull the robotic eye to the left.

REFERENCES

- [1] M. K. Mandal and M. K. Mandal, “The Human Visual System and Perception,” in *Multimedia Signals and Systems*, Boston, MA: Springer US, 2003, pp. 33–56.
- [2] A. Rizzi and C. Bonanomi, *The human visual system described through visual illusions*, Second Edi., vol. 2. Elsevier Ltd., 2017.
- [3] “Extraocular muscles,” *Kenhub*, 2019. [Online]. Available: <https://www.kenhub.com/en/library/anatomy/muscles-of-the-orbit>. [Accessed: 14-May-2019].
- [4] N. L. Volstad and C. Boks, “On the use of Biomimicry as a Useful Tool for the Industrial Designer,” *Sustain. Dev.*, vol. 20, no. 3, pp. 189–199, May 2012.
- [5] R. Raman and R. Bashir, “Biomimicry, Biofabrication, and Biohybrid Systems: The Emergence and Evolution of Biological Design,” *Adv. Healthc. Mater.*, vol. 6, no. 20, p. 1700496, Oct. 2017.
- [6] A. Lenz, S. R. Anderson, A. G. Pipe, C. Melhuish, P. Dean, and J. Porrill, “Cerebellar-inspired adaptive control of a robot eye actuated by pneumatic artificial Muscles,” *IEEE Trans. Syst. Man, Cybern. Part B Cybern.*, vol. 39, no. 6, pp. 1420–1433, 2009.
- [7] X. yin Wang, Y. Zhang, X. jie Fu, and G. shan Xiang, “Design and Kinematic Analysis of a Novel Humanoid Robot Eye Using Pneumatic Artificial Muscles,” *J. Bionic Eng.*, vol. 5, no. 3, pp. 264–270, 2008.
- [8] G. Cannata and M. Maggiali, “Models for the design of bioinspired robot eyes,” *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 27–44, 2008.
- [9] L. Li, H. Godaba, H. Ren, and J. Zhu, “Bioinspired soft actuators for eyeball motions in humanoid robots,” *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 1, pp. 100–108, 2019.
- [10] H. Li, J. Luo, C. Huang, Q. Huang, and S. Xie, “Design and Control of 3-DoF Spherical Parallel Mechanism Robot Eyes Inspired by the Binocular Vestibule-ocular Reflex,” *J. Intell. Robot. Syst. Theory Appl.*, vol. 78, no. 3–4, pp. 425–441, 2015.

- [11] M. Takaoka, K. Suzumori, S. Wakimoto, K. Iijima, and T. Tokumiya, “Fabrication of Thin McKibben Artificial Muscles with Various Design Parameters and Their Experimental Evaluations,” no. 12, p. 2013, 2013.
- [12] M. Hazwan, A. Hafidz, H. Qaid, A. Abdulrab, A. A. Faudzi, and Y. Sabzehmeidani, “PINCHING FUNCTION OF HUMAN LIKE ROBOTIC HAND USING MCKIBBEN MUSCLES,” 2019.
- [13] T. Doi, S. Wakimoto, K. Suzumori, and K. Mori, “Proposal of flexible robotic arm with thin McKibben actuators mimicking octopus arm structure,” *IEEE Int. Conf. Intell. Robot. Syst.*, vol. 2016-Novem, pp. 5503–5508, 2016.
- [14] A. A. M. Faudzi, G. Endo, S. Kurumaya, and K. Suzumori, “Long-Legged Hexapod Giacometti Robot Using Thin Soft McKibben Actuator,” *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 100–107, 2018.
- [15] P. Nigel and R. Soames, “Anatomy and Human Movement, 6th Edition,” in *Anatomy and Human Movement, 6th Edition*, 6th editio., D.-S. Rita and D. Sally, Eds. Elsevier, Churchill Livingstone, 2012, pp. 571–572.
- [16] “Vision | Anatomy and Physiology I.” [Online]. Available: <https://courses.lumenlearning.com/ap1/chapter/vision/>. [Accessed: 24-Jul-2020].
- [17] V. Dragoi, “Ocular Motor Control (Section 3, Chapter 8) Neuroscience Online: An Electronic Textbook for the Neurosciences | Department of Neurobiology and Anatomy - The University of Texas Medical School at Houston,” *Neuroscience Online*. [Online]. Available: <https://nba.uth.tmc.edu/neuroscience/m/s3/chapter08.html>. [Accessed: 14-May-2019].
- [18] “9.6C: How Skeletal Muscles Produce Movements - Medicine LibreTexts.” [Online]. Available: [https://med.libretexts.org/Bookshelves/Anatomy_and_Physiology/Book%3A_Anatomy_and_Physiology_\(Boundless\)/9%3A_Muscular_System/9.6%3A_Overview_of_the_Muscular_System/9.6C%3A_How_Skeletal_Muscles_Produce_Movements](https://med.libretexts.org/Bookshelves/Anatomy_and_Physiology/Book%3A_Anatomy_and_Physiology_(Boundless)/9%3A_Muscular_System/9.6%3A_Overview_of_the_Muscular_System/9.6C%3A_How_Skeletal_Muscles_Produce_Movements). [Accessed: 24-Jul-2020].
- [19] “Anatomical terms of muscle - Wikipedia.” [Online]. Available: https://en.wikipedia.org/wiki/Anatomical_terms_of_muscle#cite_note-5. [Accessed: 24-Jul-2020].
- [20] “Agonist and antagonist muscle pairs - Muscular system - OCR - GCSE

- Physical Education Revision - OCR - BBC Bitesize.” [Online]. Available: <https://www.bbc.co.uk/bitesize/guides/zct2hv4/revision/2>. [Accessed: 24-Jul-2020].
- [21] Joseph E Muscolino, *Kinesiology - E-Book: The Skeletal System and Muscle Function*, 3rd editio. St Louis: Elsevier Health Sciences, 2017.
- [22] K. Sangbae, L. Cecilia, and T. Barry, “Soft robotics: a bioinspired evolution in robotics,” *Trends Biotechnol.*, vol. 31, no. 5, p. 287, 2013.
- [23] A. A. Faudzi, N. I. Azmi, M. Sayahkarajy, W. L. Xuan, and K. Suzumori, “Soft manipulator using thin McKibben actuator,” *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM*, vol. 2018-July, pp. 334–339, 2018.
- [24] S. Kurumaya, H. Nabae, G. Endo, and K. Suzumori, “Exoskeleton inflatable robotic arm with thin McKibben muscle,” in *2018 IEEE International Conference on Soft Robotics, RoboSoft 2018*, 2018, pp. 120–125.
- [25] Y. Peng *et al.*, “Development of continuum manipulator actuated by thin McKibben pneumatic artificial muscle,” *Mechatronics*, vol. 60, pp. 56–65, Jun. 2019.
- [26] M. F. Mohamed, A. S. M. Hanif, and A. A. Faudzi, “Segmentation of a soft body and its bending performance using thin mckibben muscle,” *Int. J. Automot. Mech. Eng.*, vol. 17, no. 1, pp. 7533–7541, Jan. 2020.
- [27] A. Athif, M. Faudzi, J. Ooga, T. Goto, M. Takeichi, and K. Suzumori, “Index Finger of a Human-Like Robotic Hand Using Thin Soft Muscles,” vol. 3, no. 1, pp. 92–99, 2018.
- [28] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, “Soft robotics: Biological inspiration, state of the art, and future research,” *Appl. Bionics Biomech.*, vol. 5, no. 3, pp. 99–117, 2008.
- [29] R. V. Martinez *et al.*, “Robotic tentacles with three-dimensional mobility based on flexible elastomers,” *Adv. Mater.*, vol. 25, no. 2, pp. 205–212, 2013.
- [30] R. V. Martinez, A. C. Glavan, C. Keplinger, A. I. Oyetibo, and G. M. Whitesides, “Soft actuators and robots that are resistant to mechanical damage,” *Adv. Funct. Mater.*, vol. 24, no. 20, pp. 3003–3010, 2014.
- [31] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.
- [32] S. Wakimoto, K. Suzumori, and J. Takeda, “Flexible artificial muscle by bundle of McKibben fiber actuators,” *IEEE/ASME Int. Conf. Adv. Intell.*

- Mechatronics, AIM*, pp. 457–462, 2011.
- [33] S. Kurumaya, H. Nabae, G. Endo, and K. Suzumori, “Design of thin McKibben muscle and multifilament structure,” *Sensors Actuators, A Phys.*, vol. 261, pp. 66–74, Jul. 2017.
- [34] S. Koizumi *et al.*, “Soft Robotic Gloves with Thin McKibben Muscles for Hand Assist and Rehabilitation,” in *Proceedings of the 2020 IEEE/SICE International Symposium on System Integration, SII 2020*, 2020, pp. 93–98.
- [35] E. G. Hocking and N. M. Wereley, “Analysis of nonlinear elastic behavior in miniature pneumatic artificial muscles,” *Smart Mater. Struct.*, vol. 22, no. 1, 2013.
- [36] T. Abe *et al.*, “Fabrication of ‘18 weave’ muscles and their application to soft power support suit for upper limbs using Thin McKibben Muscle,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2532–2538, Jul. 2019.
- [37] S. P. Rajagopal, S. Jain, S. N. Ramasubramanian, B. V. Johnson, and S. K. Dwivedy, “Development of an Underactuated 2-DOF Wrist Joint using McKibben PAMs,” *J. Inst. Eng. Ser. C*, vol. 95, no. 4, pp. 327–334, Oct. 2014.
- [38] Y. Ariga, H. T. T. Pham, M. Uemura, H. Hirai, and F. Miyazaki, “Novel equilibrium-point control of agonist-antagonist system with pneumatic artificial muscles,” in *Proceedings - IEEE International Conference on Robotics and Automation*, 2012, pp. 1470–1475.
- [39] S. Wakimoto, K. Suzumori, and T. Kanda, “Development of intelligent McKibben actuator,” in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS*, 2005, pp. 2271–2276.
- [40] Y. Peng *et al.*, “Development of continuum manipulator actuated by thin McKibben pneumatic artificial muscle,” *Mechatronics*, vol. 60, pp. 56–65, Jun. 2019.