

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**ROBOTIC HAND DESIGN USING FLEXIBLE AND CONTINUUM
STRUCTURES**

M.Sc. THESIS

Hatice Didem ÜZGÜN

Department of Mechatronics Engineering

Mechatronics Engineering Programme

AUGUST 2015

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Thesis Advisor: Assoc. Prof. Dr. Pinar BOYRAZ

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ESNEK VE SÜREKLİ YAPILARLA ROBOTİK EL TASARIMI

YÜKSEK LİSANS TEZİ

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To all humuhumunukurukuapuas,

FOREWORD

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ABBREVIATIONS

DOF	: Degree of Freedom
ASD	: Autistic Spectrum Disorder
MEAM	: Mechatronics Education and Research Center
DIP	: Distal Intherphalangeal Joints
PIP	: Proximal Intherphalangeal Joints
MCP	: Metacarpophalangeal Joints
D-H	: Denavit- Hartenberg

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ROBOTIC HAND DESIGN USING FLEXIBLE AND CONTINUUM STRUCTURES

SUMMARY

Nowadays robots are replacing humans in many areas such as industry, military, medicine. In industry, robots are used for special tasks for example precision machinery and manufacturing. In military, it is used to do the dangerous tasks which is harmful for people. And also, in medicine it is used to help rehabilitation of neuro-muscular damages using phsyiotherapy or follow the patient's treatment process. Specially, robots that it is used for medicine look like human in order to easily human- robot interaction. This robots are called as humanoid robots. Humanoid robots, robots with an antropomorphic body plan and human- like interaction. When one robot is defined as humanoid robots, it has to have some features such as bipedal locomotion, perception, dexterous manipulation, learning and adaptive behaviour. In all features is one most important dexterous manipulation. This feature obviously necessary for behave as human.

Dextereous manipulation/dexterious hand or robotic hand is the topic has been researched for a long time. It is may be the hardest topic in humanoid robot design in order for them to work like a human hand. Human hand one of the most complex structure in human body. It has thirty degree of freedom and advanced movement capability. From the first research attempts on human hand, the researchers have been developing many types of hand designs with different working principles and structures. However, the most of these researhers use same approach for its structure which it is called rigid-link strcture. Rigid-link strucure is used to work as bones of human hand. This approach is a good one but it cannot realize the grasping capability of the human hand in full potential. Because of this, the researchers are focusing on the novel design methods using flexible back-bones and cable-based structures seen in continuum robotics.

Continuum robots can be viewed as being “invertabrate” robots, as in contrast with the “vertebrate” design of conventional rigid- link robots. Continuum robots can bend, often extend/ contract and sometimes twist at any point along their structure. This provides them with capabilities beyond the scope of their- rigid- link counterparts. And also, continuum robots gently contacts and adapts its shape to wrap around fragile objects with no prior planning or knowledge of the object and without any sensing of the contact between robot and object. This movement capability does not exist in rigid- link manipulators.

In this thesis, a robotic finger is designed using continuum robotics approach for providing a compliant interaction with the outer environment. The return spring is used to work as bones of human fingers. Three plates are used to motion as like human finger joints. And also, cables are used to transmit the motion from the motors to the finger joints. Each cable actuation is performed with one single motor in order to obtain high motion capability similar to human finger. Bezier Curve

method is used to perform kinematic analysis. Using Bezier curve method can be found both Inverse kinematic solution and Forward kinematic solution. In order to solve Forward kinematic, the amount of the exchange of cable lengths are calculated. Thus, tip point of each segment is calculated by using geometric formulas. The other control points are found by using iteration methods. And then, the shape of curve and coordinates of tip points of finger are found. To solve Inverse kinematic, the image process method can be used. The coordinates of base point and tip point are found by image processing. After that the other control points are calculated by using iteration methods. The shape of curve and the position of finger are found. Lastly, the lengths of cables are found by using image processing and the amount of the exchange of cable lengths are found. Thus, the amount of change of motor angle is found by using cable lengths informations. In this thesis, Inverse kinematic solution is used for kinematic analysis by using image process methods. Thus, the amount of the exchange of angles motor and the shape of the finger are found. In the following studies, the dynamic analysis and whole hand motion will be studied.

ESNEK VE SÜREKLİ YAPILARLA ROBOTİK EL TASARIMI

ÖZET

Günümüzde robotik uygulamaların kullanımı oldukça yaygındır. Ağırlıklı olarak endüstride hassas işlerin yapılmasında veya hem hızlı hem de hata payı az olarak yapılması gereken uygulamalarda insanların yaptığı işleri yapmak üzere kullanılmaktadırlar. Robotların endüstride kullanımı oldukça eski tarihlere dayanmaktadır. İlk programlanabilir dokuma tezgahı 1801 yılında üretilmiştir. Bilinen ilk endüstriyel robot ise 1954 yılında George Devol ve Joe Engleberger' in sahibi olduğu ABD' li Unimatom firması tarafından üretilmiştir. Dolayısıyla ilk üretilen robottan günümüze robotların gelişimi iki yüz yılı aşkın süredir devam etmektedir. Fakat son altmış-yetmiş senedir robotik, endüstrinin yanı sıra askeri uygulamalarda, uzay çalışmalarında, sağlık alanları gibi farklı alanlarda da geliştirilmekte ve kullanılmaktadır. Askeri alanlarda insan hayatı için tehlikeli olacak görevlerin gerçekleştirilmesi için kullanılırken sağlık alanında ameliyat robotları olarak kullanılabilirler. Ayrıca son yıllarda hasta insanların rehabilitasyonunda yardımcı olmak amacıyla geliştirilen robotlarda bulunmaktadır. Bu rehabilitasyon robotları bazı uygulamalarda vücudun belli bir bölgesinde zarar görmüş organın hareket etmesini sağlayarak tedaviye direkt etki ederken (bacak kaslarını çalıştırmak için üretilen bisikletler gibi) bazı uygulamalarda da rehabilitasyon için gerekli olan kuvvet ve konum gibi önemli parametreleri yüksek doğrulukla oluşturarak veya tedavi sürecini kayıt altına alarak hastanın gelişim sürecini takip etmek için kullanılmaktadırlar. Bu tür sağlık hizmetleri için geliştirilen robotlar insanlarla daha kolay iletişime geçebilsin diye genellikle insan şekline ve yeteneklerine benzer olarak tasarlanırlar. İşte bu insan yapısı temel alınarak üretilen robotlar “insansı robotlar” olarak tanımlanırlar.

İnsansı robotlar insan vücudunun yapısı ve hareket kabiliyetleri temel alınarak geliştirilirler. İki bacağı üzerine dengesini kaybetmeden yürüyebilme, gelişmiş tutma, kavrama, kavradığı nesnenin sertliğini hissederek ona uygun basıncı uygulayarak nesneye zarar vermeden taşıma özelliklerine sahip el yapısı, yedi farklı serbestlik derecesine sahip kol yapısı, tutacağı nesnenin nerede olduğunu ve boyutlarını bilmeden uzaklık algılama yetisiyle nesnelere ulaşma özelliği insansı robotlarda üzerine çalışılan başlıca konulardan bazılarıdır. İki bacağı üzerine hareket, duyma ve konuşma özelliklerine sahip geliştirilen ilk insansı robot uygulamasından bugüne kadar geliştirilen robotlar her geçen insan yapısına daha yakın olacak şekilde geliştirilmişlerdir. Burada sayılan özelliklerden bazı temel hareket yetenekleri artık neredeyse yapılan tüm çalışmalarda mevcuttur. Bu çalışmaların aralarındaki fark hareketin ne kadar gerçeğe uygun olarak gerçekleştirildiğine bakılarak belli olmaktadır. Üzerinde çalışılan ve farklı tasarım yöntemleri ile geliştirilen en önemli yapılardan bir tanesi hiç kuşkusuz ki sahip olduğu yüksek hareket kabiliyeti nedeniyle insan eli yapısıdır. İnsan eli yapısına yakın şekilde yapılmaya çalışılan robotik el uygulamaları belki de robotikte başlı başına özel bir çalışma alanıdır.

Robotik el uygulamaları uzun süredir üzerinde çalışılan ve günümüzde hala önemini yitirmemiş olan bir çalışma konusudur. Kullanım alanlarının çokluğu ve insan hayatında sağladığı kolaylıklar ile her geçen gün daha yeni yöntemler denenerek farklı alanlarda kullanımı üzerine çalışılmaya devam edilmektedir. Genel olarak bugüne kadar yapılan çalışmalar dikkate alındığında çalışmaların insan eli benzeri yapılar ve endüstride kullanılmak üzere “tutucu” olarak görev yapacak sistemler olarak ayrı alanlar için tasarlandığı söylenebilmektedir. Endüstri de kullanılan tutucular genellikle iki parmaklı bir yapı olarak tutma ve bırakma işlemlerini gerçekleştirmek adına üretilmektedirler ve tümüyle insan elinin yaptığı tüm hareketleri yapması beklenmemektedir. Mekanik , pnömatik veya hidrolik eyleyiciler ile hareket etmesi sağlanan bu yapılar endüstride çoğunlukla tutma- taşıma ve bırakma görevlerini yerine getirmek için kullanılmaktadır.

İnsan eli modeli temel alınarak yapılan çalışmalar; üç, dört veya beş parmaklı olarak tasarlanan ve insan elinin hareket yeteneğinin doğrudan modellemesi üzerine yapılan çalışmalardır. Tıp alanında ve rehabilitasyon amaçlı yapılan robotlarda en çok insan eli modeli kullanılarak üretilen eller tercih edilmektedir. İnsan eli, vücudumuzdaki en karmaşık yapıya sahip olan sistemdir. Basit bir şekilde açıklamak gerekirse elin hareketi her bir parmağın içinden geçen tendonlar sayesinde gerçekleşir. Tendonlar avuç içinden geçerek her bir parmaktaki kemiklerin etrafından dolanır ve kaslardan gelen hareketi taşıyarak parmakların istenilen hareketi gerçekleştirmesini sağlar. Robotik el uygulamalarında da tasarımın en önemli kısmı bu el hareketinin en verimli ve en gerçeğe yakın şekilde iletilmesi kısmıdır. Robotik el üzerine yapılan ilk çalışmalarda da bu tendon yapısı kullanılarak hareket yeteneği sağlanmıştır. İlerleyen yıllarda yapılan ellerde farklı tasarımlar denenerek bu hareket kabiliyeti verilmeye çalışılmıştır. Bu tasarımlar genelde eyleyicilerden alınan gücün parmaklara aktarılması için kullanılan farklı mekanizmalar (mekanik çubuklar, tendon- makara sistemleri, dişli-pinyon sistemleri vs.) gibi görülse de esasında tasarımlar arasında kullanılan en önemli fark tahrik sistemlerinin seçimiyle başlamaktadır. Temelde iki çeşit eyleyici kullanılarak tasarımlar yapılmaktadır. Bunlardan ilki ilk yapılan ellerde kullanılan tam tahrikli sistemlerdir(fully- actuated mechanism). Tam eyleyici sistemlerde elin serbestlik derecesi ile eyleyicilerin sayısı birbirine eşittir. Diğer sistem ise eksik tahrikli (underactuated) sistemlerdir. Eksik tahrikli sistemlerde sistemin serbestlik derecesi eyleyicilerin sayısından daha fazladır yani daha az eyleyici ile daha fazla yapının hareketi mümkündür. Eksik tahrikli sistemlerde eyleyicilerin azlığı sistemi daha hafif ve ucuz olmasını sağlamaktadır fakat her iki yöntem de aktif olarak el tasarımı yapılırken kullanılmaktadır. Tahrik sistemleri veya aktarma şekilleri ne kadar farklı olursa olsun aslında geleneksel el tasarımı olarak adlandırabileceğimiz bu yapılar genelde rijit yapılar kullanılarak tasarlanır. Parmak kemiklerinin yapısı tasarlanırken insan elinde olduğu gibi rijit kemik yapısı olacak şekilde mekanik sistemler kullanılır fakat bu yapıların karmaşık yapısı ve sistemin rijitliği kavrama hareketlerinin tam olarak yapılamamasına yol açmaktadır. Bu sebeple hareketin tam olarak aktarılacak kavrama işleminin gerçeğe uygun olarak yapılabilmesi için yeni yöntemler üzerinde çalışılmaktadır. Bu yöntemlerden bir tanesi de sürekli yapılar robotiği veya orijinal adıyla *continuum robotik*’tir.

Sürekli yapılar robotiği, fil hortumu veya ahtapot kolu gibi omurgasız esnek ve sürekli yapıları temel alan bir alandır. Sürekli yapılar temel alınarak tasarlanan robotlar bükülebilme hatta çoğu zaman uzama, kasılma ve bazen burulma yapısına

sahip olabilen robotlardır. Bu özellikler rijit yapılar ile tasarlanan yapılarda olmayan bir özelliktir. Sürekli yapılı robotlar nesneye hafif bir şekilde dokunup onların şeklini alabilme kabiliyetine sahiptirler. Böylelikle kavradıkları nesneye zarar verme olasılıkları azdır. Ayrıca bu işlemleri daha önce şeklini bilmedikleri nesneleri üzerlerinde sensörler olmadan daha önce planlanmamış bir şekilde gerçekleştirebilirler. Yine bu özellik geleneksel olarak tasarlanan rijit bağlantı yöntemi ile tasarlanmış robotların sahip olmadığı bir özelliktir. Sürekli yapılı robotlar üzerlerinde yeni çalışmaya başlanmış bir konudur fakat hızla gelişmeye açık bir konudur.

Gerçekleştirilen tez çalışmasında sürekli yapılar yaklaşımı kullanılarak bir el tasarımı yapılmıştır. İnsan elinde parmakları oluşturan rijit kemikler yerine sürekli bir yay kullanılmıştır. İnsan parmağında hareket yeteneğini tendonlardan alan üç adet bağlanyı noktası yerine üç ince plaka kullanılmıştır ve yine insan elindeki tendonlar yerine de plaka üzerine bağlı kablolar sayesinde parmakların hareketi sağlanmıştır. Plakalar üzerindeki kabloların her birine hareket vermesi için bir adet motor kullanılmıştır. Böylelikle tam olarak insan elinin sahip olduğu hareket fazlalığı sağlanmaya çalışılmıştır. Bu parmak yapısının kinematik analizi geleneksel kinematik analiz yapısına uygun olmadığından hareket sırasında parmağın omurgasını oluşturan yayın kinematikini analiz edebilmek için Bezier Eğrisi yöntemi kullanılmıştır. Motordan verilen açı değerine göre veya parmağın istediğimiz pozisyonda olabilmesi için yayın oluşturduğu eğri Bezier eğrisi kurallarına göre hesaplanmış ve gereken pozisyon bilgileri elde edilmiştir. İlerleyen çalışmalarda el yapısının dinamik analizi gerçekleştirilip el bütün halinde üretilerek tüm sistemin birlikte hareketi incelenecektir.

1. INTRODUCTION

Robotics is a multi-disciplinary subject combining mechanical engineering, electrical engineering and computer science and it deals with the design, construction, operation, and application of robots [1]. Robotics is used to perform a variety of tasks in a wide range of application fields such as industry, military, aerospace, medicine and biomedical. In industry, the robots perform high-precision production related tasks especially in machining. In military, the robots perform dangerous tasks instead of people. However, in medicine and biomedical applications, the robots are more involved in co-operative tasks with people instead of replacing the workforce. The robots help recover from serious physical trauma or assist people in activities of daily living. In fact, the interaction and co-operation with people are recently becoming common in industrial and military implementations of robotics as well. In order to be able to interact and work together with people, these robots are designed to assume a human-like structure. These robots, which resemble humans in terms of structure or function are called as humanoid robots.

Humanoid robots usually have anthropomorphic body structure and human-like perception and cognition abilities. From the appearance of the first humanoid robot, more and more researchers are focusing on to improve the motion and perception capability of robots to approach human-like behaviour. All these studies generally focused on bipedal locomotion, autonomous learning, dexterous manipulation, audio-visual perception, adaptive control and safe interacting with human beings and the environment. Among all these fields, design of the dexterous manipulation is one of the most difficult to achieve because of the complex structure of human hand.

The human hand has about thirty degrees of freedom. It can realize many different movements such as flexion, extension, radial deviation, ulnar deviation, pronation and supination. For these reasons, it is not easy to reproduce its strength, flexibility, and the sensitivity in a single design. In order to provide complex structure of human hand, many different methods are used in design. Among the most advanced robotic hands, the Shadow hand can be listed. This robotic hand is driven by a large number

of air muscles. The hand has 20 actuated degrees of freedom and a further 4 under-actuated movements for total of 24 joints. The Shadow hand is shown in Figure 1.1 [2].



Figure 1.1 : Shadow hand [2].

Dexterous manipulation not only requires capable hands, but also hand- arm coordination and the coordination of two hands and the vision system. Owing to the high number of joints involved, the control of grasping and manipulation is challenging. Two examples for manipulation- oriented humanoid robots are Robonaut [3], which uses the space tools designed for humans, and the robot Justin, for which DLR developed impedance- based control scheme [4]. While the performance of these robots is impressive, they cannot easily grasp and manipulate unknown objects. In order to resolve this situation, the continuum robotics is used as a new manipulation method.

Continuum robots are inspired by the biological world. These robots have the characteristics of invertebrate structure similar to such biological counterparts as elephant trunks, octopus arms and snakes. A continuum robot can use the whole length of its body to grasp objects of different shapes and sizes. Grasping the objects, it tenderly contacts and its structure is immediately adapted to the shape of objects. When continuum robots are compared to rigid-link counterparts, they can bend, twist and sometimes extend. In addition, because they have flexible structure, they grasp fragile objects without any damages. Because of all these special features, continuum robots are more successful when it is necessary to working in a specific area and grasp sensitive objects than conventional rigid-link robot manipulator.

Robot manipulators do not have to be formed from rigid- links. An alternative design possibility is to create a robot with continuous form or backbone. These robots, termed continuum robots, can be viewed as being “invertebrate” robots, as compared with the “vertebrate” design of conventional rigid-link robots. Continuum robots can bend (and often extend/ contract and sometimes twist) at any point along the structure. This provides them with capabilities beyond the scope of their rigid- link counterparts. Continuum manipulator achieves their tasks with no prior planing or knowledge of the object and without any sensing of the contact between robot and object. This would be an extremely difficult operation for a conventional rigid- link manipulator.

In comparison to rigid and conventional manipulators, continuum robot is able to use its compliant, actively controlled, continuous structure to perform the operation easily, quickly, and without a priori knowledge of the task. For this reason, continuum manipulators seem to be under more development leading to novel robotics structure in many fields.

1.1 Purpose of Thesis

Human hand is one of the most complex organs of the human body after brain. Thanks to the special structure of bones, tendons, and tissues, the human hand has high mobility and flexibility. For this reason, in the recent years, the research on human hand structure has become a remarkable topic in robotics. Robotic hands, which are designed to resemble human hands, are used like prosthetic devices, operate in man- oriented environments, and can also be tele- operated by humans through interfaces that can reproduce the operator hand behaviour [5]. Currently, there are many different robot hand designs with five or fewer fingers in agreement with criterion of its inventors. In the same way, the actuation types differ in each model, with advantage in some aspects, and disadvantages in other aspects [6]. At this point, the most important output of the research is the fidelity of the desired movement.

In this thesis work, the aim is to design and construct a new robotic hands for humanoid robot UMay. The main design principles in the thesis are drawn from continuum robotics and cable- driven systems. This robotic hand has three fingers. Each finger has an elastic backbone and the structure is moved with six cables that

work like tendons in human hands. In order to design this hand to be used in a robot with the aim of rehabilitation of children with Autistic Spectrum Disorder (ASD), the structure is chosen to be flexible and as light- weighted as possible so that is not dangerous for children.

2. LITERATURE SURVEY

2.1 Humanoid Robots

A humanoid robot is a robot having anthropomorphic or a human- like shape or function. To be more correct, not all humanoid robots has human shape. The most convenient shape of the robot can be determined by the required function for a robot. Hence, for determining the feature of humanoid robots, it must be identified what type of functions of robots are required. These features of robots can be summarized as follows;

- (i) the first type of humanoid robots can work in the environment for humans as it is,
- (ii) the second type of humanoid robots can use tools that are normally used by humans and blend in a co-operative scenario interacting with people,
- (iii) the third type of robots just have a human- like shape for having a genuine interaction with people in the social robotics field [7].

The first and second types of humanoid robots are designed with the reasoning that instead of modifying all environment and tools designed normally for humans, the robots are designed to be similar to humans to fit their environment and function like them. It is reasoned that it should be more economical to develop humanoid robots than to modify the whole human environment. However, the third type of humanoids design just focuses on visual similarity of robots to humans.

In 1495 Leonardo Da Vinci designed a mechanical device that looked like an armored knight. Leonardo Da Vinci had conducted a wide study into human anatomy. The robot knight was capable of standing, sitting, raising its visor and independently maneuvering each of its arms, neck and jaw[8]. Leonardo Da Vinci's robot and sketches are shown in Figure 2.1.

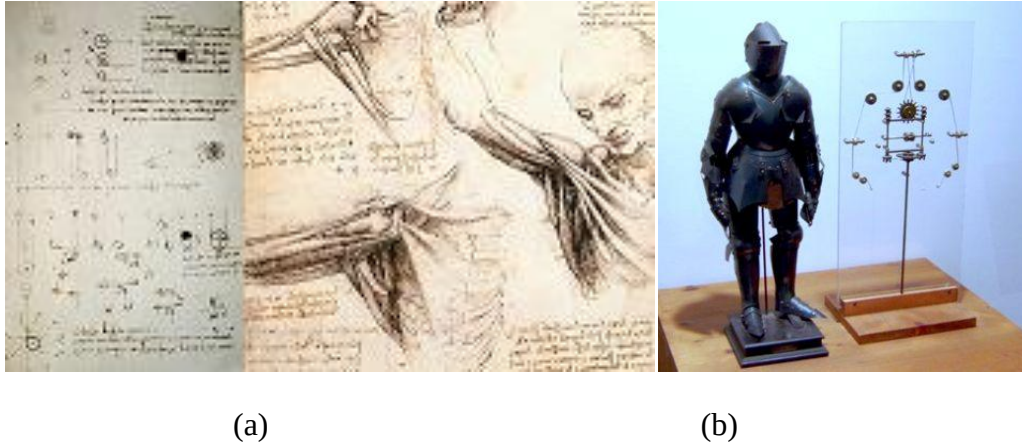


Figure 2.1 : Leonardo Da Vinci's robot: (a) Sketches, (b) Knight robot [8].

Westinghouse Electric Corporation exhibited at the 1939 and 1940 World's Fairs the tall motor man Elektro. It could be driven using the wheels on the feet, it could play recorded speech and move its head and arms. Elektro was controlled by 48 electrical relays and could respond to voice commands [9]. Elektro is shown in Figure 2.2.

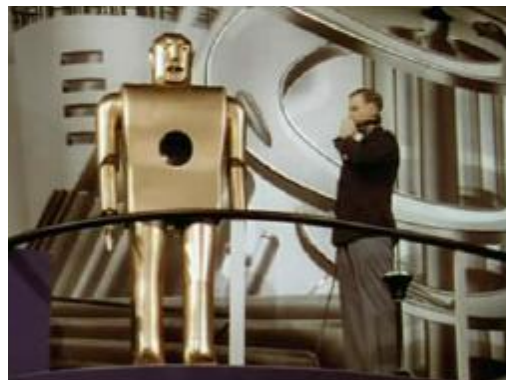


Figure 2.2 : Elektro was 1939 world's fair [10].

The construction of a human-like robot in the sense of today's humanoids was started in 1973. This robot name is WABOT-1. It was developed by Ichiro Kato et al. from Waseda University in 1973 [11]. WABOT-1 was the first full-size humanoid robot can be walk on two legs. It could recognize the objects by computer- vision, communicate with a person in Japanese, manipulate the objects by two hands. Therefore, it is reasonable to call WABOT-1 the first humanoid robot. WABOT-1 is shown in Figure 2.3.



Figure 2.3 : WABOT-1 (1973) [11].

After the first humanoid robot is designed, a great number of new humanoids is developed in the following years. The new era of humanoid was opened by the Honda humanoid P2 in 1996. The humanoid P2 is 180 cm in height and 210 kg in weight. It is the world's first self-regulating two-legged humanoid robot capable of walking. The motor drivers, battery and all necessary technology loaded on its body, therefore, it was not tethered. Next, Honda designed P3, a humanoid with 160 cm in height and 130 kg in weight, in 1997, and ASIMO is designed with 120 cm in height and 43 kg in weight, in 2000 [12]. The humanoids P2, P3 and ASIMO are shown in Figure 2.4.



P2 (1996)

P3 (1997)

ASIMO (2000)

Figure 2.4 : Humanoid robots of Honda [7].

After the year 2000, great numbers of humanoid robots are developed. In 2006, The Boston Dynamics designed a humanoid robot named PETMAN. This was an anthropomorphic robot designed for testing chemical protection clothing. PETMAN has very special properties such as balancing itself and moving freely, walk on two legs, bending and doing a variety of strenuous calisthenics in order to simulate how soldier stresses protective clothing under realistic conditions. PETMAN also simulates human physiology inside of the protective suit by controlling temperature,

humidity and sweating, all to supply realistic test conditions. PETMAN currently is still in the testing process [13]. PETMAN is shown in Figure 2.5.

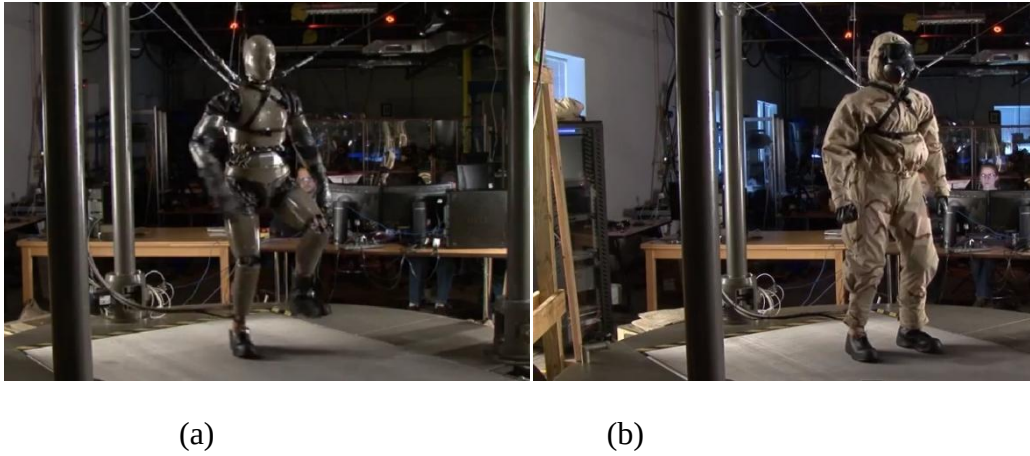


Figure 2.5 : PETMAN: (a)Without clothing, (b) With clothing [14].

Nowadays, humanoid robots are more intelligent and capable both in perception and motion. From these studies, it may seem that the most important issues for construction and control of humanoid robots have been solved; however, this is not the case. There are still open problems in humanoid design. A very small part of such problems is addressed in this thesis in design of a flexible robotic hand structure.

2.1.1 Humanoid robot UMay

Humanoid robot UMay is developed in Istanbul Technical University (ITU) Mechatronics Education and Research Center. UMay is designed to help rehabilitation of children with Autistic Spectrum Disorders (ASD). Autism is a complex disorder of brain development. These disorders are characterized, in varying degrees, by difficulties in social interaction, verbal and nonverbal communication and repetitive behaviours. Interplay with humanoid robots that provide interaction with these children has been shown to help advancing communication skills of autistic children [15]. UMay is designed to be used in clinical therapies for the children with ASD using some rehabilitation tools or toys. Also, UMay is designed to obtain a low-cost and accessible platform for the in-home rehabilitation. In many existing humanoids inand in UMay , computer- vision interface is considered as a core capability. Human- robot interaction and learning module in UMay need to use visual information to preceive its environment and interact with the object using visual-servo control [16]. Besides, In order for robots to be safer and more human

friendly when interacting with children, UMay arm is controlled by impedance control method. Impedance control does not attempt to track motion and force trajectories as separate entities but rather attempts to control motion and force by developing a relationship between interaction forces and manipulator position, that is using a mechanical impedance concept [17]. Humanoid robot UMay is shown in Figure 2.6.



Figure 2.6 : Humanoid robot UMay.

2.2 Characteristics of The Human Hand

The human hand is capable of a wide variety of functions. It can be achieved these functions owing to its special characteristic.

The hand is composed of many small bones called carpals, metacarpals and phalanges. The two bones of the lower arm, the radius and the ulna- meet at the hand to form the wrist. The carpal bones are set of eight short bones forming the wrist; they are disposed on two rows of four bones each. These bones, the size of a marble, provide the wrist's liveness and mobility. The palm hand is composed of five metacarpal bones laid out from the wrist, as a fan. The articulation of the first metacarpal bone with the carpal bones, permits the movement of touching, with the thumb, the tips of all fingers. It is from this movement that the human hand can acquire the efficiency necessary to grab and manipulate object. Every hand is

composed of 14 long bones named the phalanges. These bones compose the fingers and the thumb. Each finger has three phalanges and the thumb has only two of them [18]. All these bones are shown in Figure 2.7.



Figure 2.7 : Bones of human hand [18].

The intrinsic muscles of the hand are divided into three groups: (1) The thumb or thenar muscles, (2) the little finger or the hypothenar muscles, and (3) the lumbrical muscles. With the lumbrical muscles are the long flexor tendons, which are the extrinsic muscles of the hand [18]. The muscles structure of hand is shown in Figure 2.8.

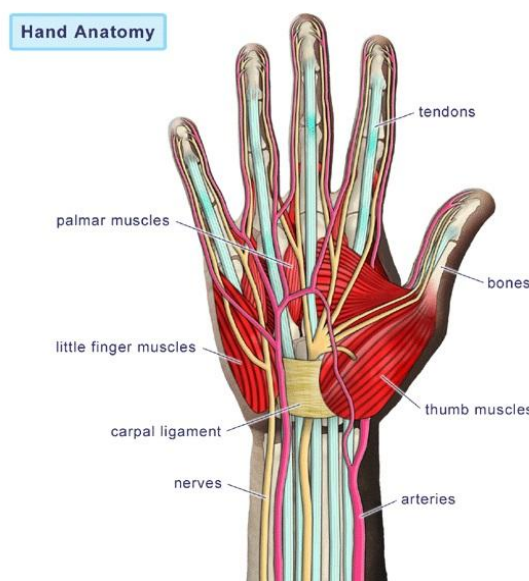


Figure 2.8 : The muscles structure of human hand [19].

The Median and Ulnar nerves are the major nerves of the hand, running the length of the arm to transmit electrical impulses to and from the brain to create movement and sensation.

In summary, each hand contains (plus or minus because everyone is different, and everyone counts these things differently) 29 major and minor bones (many people have a few more), 29 major joints, at least 123 named ligaments, 34 muscles which move the fingers and thumb: 17 in the palm of the hand, and 19 in the forearm, 48 named nerves: 3 major nerves, 24 named sensory branches, 21 named muscular branches and 30 named arteries and nearly as many smaller named branches [18].

Each of the joints of the fingers exhibits flexion and extension, but only the proximal phalanges exhibit abduction and adduction. The hand movements are shown in Figure 2.9.

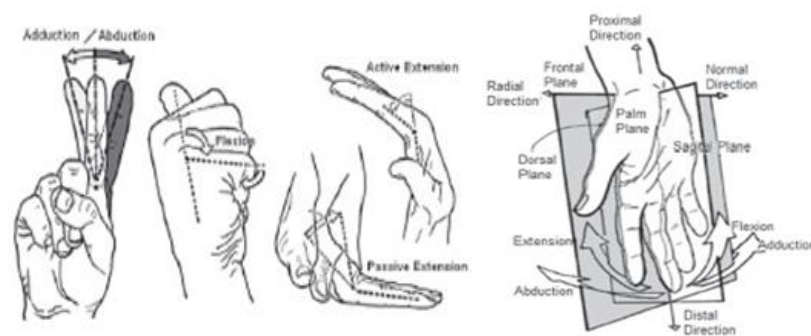


Figure 2.9 : Hand movements [20].

The thumb, which has a complex structure, exhibits flexion/ extension, abduction/ adduction, and also rotation around the axis of the metacarpal joint on the metacarpal phalange. The thumb movements is shown in Figure 2.10.

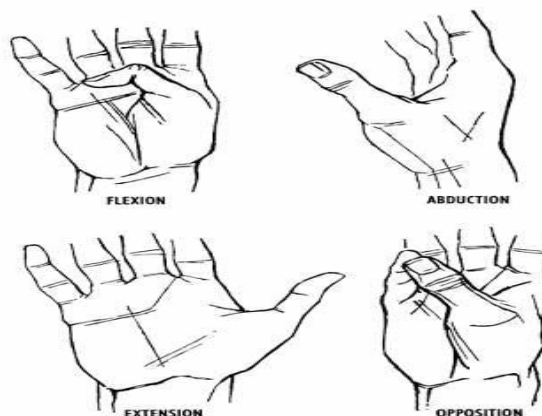


Figure 2.10 : The thumb movements of human hand [21].

2.3 Robotic Hands

Nowadays, most of the robots are used to perform certain tasks such as pick and place, camera inspection or assembly in the manufacturing lines. Especially, they can work in dangerous areas where it is forbidden for people to work due to health-hazards (i.e. Fukushima Disaster). However, their skills are more limited than that of a well-trained human being to perform highly precise operations. To achieve this precise task, great numbers of research have been undertaken to design robotic end effectors, which can work like human hand. These robotic end- effectors are also named as robotic hands. Laboratories around the world have developed robotic hands as early as in the mid '80's when the basis of these studies were laid [7].

Because of the complexity of the human hand, many different variations are possible to replicate the capabilities when designing a robotic hand depending on the application. During the design process, various properties need to be considered such as the size, shape and other dimensional aspects of the robotic hand. However, the most important design parameters are degrees of freedom (DOF), kinematics, number of actuators and sensors, and the grasping force and the method of controlling this force. These parameters should be adopted such that desired grasping an object and manipulation are possible. The mechanical design of the robotic hand can be categorized in three classes according to their DOF and actuator numbers as following: (i) fully actuated mechanism (equal number of their DOF and actuators), (ii) redundantly actuated mechanism (more actuators than DOF) and (iii) underactuated mechanism (more DOF than actuators). Indeed, a redundantly actuator mechanism is neither desired nor useful in the development. Hence, most of the times the other two mechanisms are used in design process.

Fully actuated robotic dexterous hands are able to mimic almost the full functionality of a human hand thanks to a combination of actuators, sensors and control systems. Although they could be capable, these structures may have disadvantages such as complexity, higher weight and increased cost. However, some reliable robotic hand have been realized such as DLR Hands I and II (Germany) [23], the Shadow Dexterous Hand C6M2 (England)[2] and the Utah/ MIT dexterous Hand (United States)[22].

DLR Hand II (is the successor of DLR Hand I) is a modular, belt driven, four-fingered hand aimed to be a research platform for studying robot grasping. Each finger has a differential bevel gear universal joint allowing abduction/ adduction in the first and axis flexion/ extension in the second. The PIP and DIP joints are coupled by tendons. The hand is approximately 1.5 times the size of the average human hand, as all necessary drives and electronics are integrated into the hand to enable its use on standart robots [23]. DLR Hand I and DLR Hand II are shown in Figure 2.11.

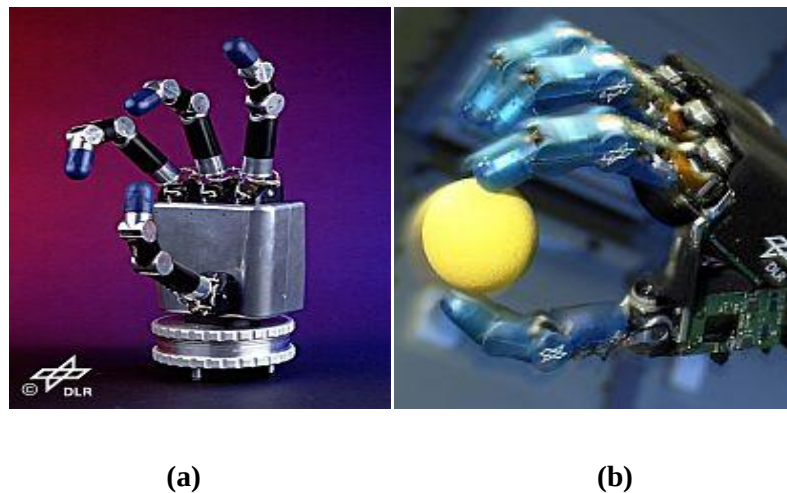


Figure 2.11 : DLR hands: a, DLR hand I; b, DLR hand II [24].

The UTAH/ MIT Dexterous Hand has 16 DOFs and three fingers each equipped with four active DOFs, plus a thumb with four DOFs. Each finger has a proximal joint allowing abduction/ adduction. The proximal joint is followed by three parallel axes to provide flexion and extension. The transmission was accomplished by belts instead of tendons. This setup did not use elastic elements to store energy, but ensured tendon tension by tension sensors and control. UTAH/MIT Hand is shown in Figure 2.12



Figure 2.12 : UTAH/MIT hand [25].

Second method used in robotic hand design involves underactuated mechanism as mentioned before. Underactuated mechanisms are such structures whose number of controlled actuators is less than their overall number of DOF [26]. Underactuated mechanisms have the advantages to have a more simplified structure, to reduce their volume, and they have light weight and lower cost. In addition to these advantages, by reducing the number of inputs (actuators), the hand's capability to adapt its shape to grasped object may be enhanced. Some examples of underactuated mechanism hand can be given such as TUAT/ Karlsruhe Humanoid Hand [27], Graspar [28] and the SDM Hand [29]. In some cases, researches have focused more specifically on the design of underactuated fingers [30].

The TUAT/ Karlsruhe Humanoid Hand is designed for anatomical consistency with the human hand. This includes the number of fingers, placement and motion of the thumb, the proportions of the link lengths and the shape of the palm. It can be also used to perform most of the human grasping motion types. The TUAT/ Karlsruhe Humanoid Hand possesses 20 DOF and is driven by one actuator which can be placed into or around the hand [23]. The TUAT/ Karlsruhe Humanoid Hand is shown in Figure 2.13.



Figure 2.13 : The TUAT/ Karlsruhe humanoid hand.

The SDM Hand is a novel adaptive and a compliant robotic hand that can grasp objects spanning a wide range of size, shape, mass and position/orientation using only a single actuator. In order to use the underactuated mechanism method, in these hands, the transmission design allows motion of other joints to continue after contact occurs on a coupled link, allowing the hand to passively adapt to the object shape. The SDM Hand is shown in Figure 2.14.

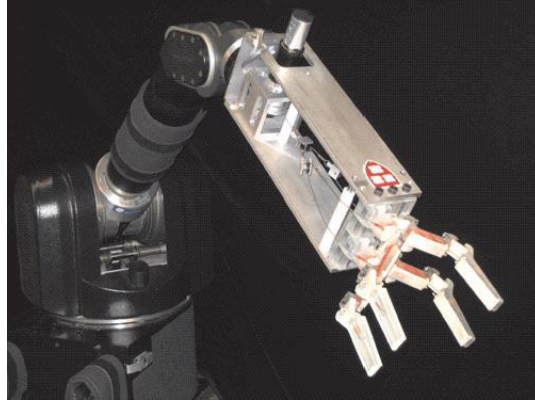


Figure 2.14 : Four-fingered, underactuated SDM hand [29].

2.4 Transmission Systems

Transmission systems are used in various mechanical systems where power must be transmitted from actuator to the links/joints over a distance. The transmission systems used in robotic hands are aimed for different purposes, therefore, the classification of transmission systems is difficult. Nevertheless, the most widely used systems are as follows;

- Chain- Belt Mechanism.
- Linkage- Driven Mechanism.
- Gear Train Systems.
- Rope-Pulley Systems.
- Rack-Pinion Drive.
- Harmonic Drive.

2.4.1 Chain- belt mechanism

In this system, each finger unit links are driven by using time belts. The rotation of the joints are provided by a chain mechanism in the finger unit. A single torque application point exist on the fist link of the finger rather than a distributed actuation on the whole finger [42]. These systems have some advantages and disadvantages:

System advantages are as follows:

- The system is robust owing to its rigidity.
- Torque transmission is strong.

- Deflections are precluded.
- The repair is easy.

System disadvantages are as follows:

- The number of chains is high.
- Assembly of the whole system is difficult.
- The problem of backlashes makes positioning inaccurate.
- The dimensions of the chain are not suitable for small size applications.

2.4.2 Linkage- driven mechanism

The system is composed of crank and rockers. In many applications, it is enough to apply four-bar mechanism analysis. The first link of the finger is actuated by a motor a slider crank mechanism transmits the motion to the remaning parts of the mechanism[42]. These systems have some advantages and disadvantages are as follows;

Advantages:

- Kinematic analyses are simple.
- It is more reliable and robust than the chain- belt mechanisms.
- Deflections are prevented.

Disadvantages:

- Manufacturing of the system is difficult.
- The system is needed a large work space area to operate.
- The system, which is made by mechanical link model, does not look like human hand.

2.4.3 Gear train system

The system comprises the gear trains mounted in each unit of the finger that forms the links. All the motion is provided by gear couplings[42]. The diameter of the gear ratio in the joints is very important to give the hand gripping motion.

Advantages:

- The position analysis for each point on the links is simpler.
- Natural hand appearance is possible.
- The rigid body assumption can be made when in use.

Disadvantages:

- The mounting of the gears is difficult.
- The system weight is increased owing to high number of the gears.
- When wear occurs owing to power reducing units which causes the system to fail, the system is not reliable.

2.4.4 Rope- pulley system

There are also called cable/ tendon driven mechanisms. Rope- Pulley transmission mechanism is the cheapest system for the hands. It transmits the rotary motion of the actuator to a joint without any change in motion type. Each link is controlled by ropes which are connected on the pulleys. The pulleys are assembled on the main shaft which have suitable diameters so that the ropes are always in tension and the motion of the links are synchronized [42]. Rope- Pulley mechanisms are mostly used for dexterous hands where the transmitted force is low, limited rotary motion and small areas are required for transmission systems.

Advantages:

- The manufacturing of this system is very simple.
- It has high precision.
- The system is light.
- Because the actuation is placed in a remote location, the maintenance is easier.
- Easy to assemble.

Disadvantages:

- Deflection may occur on the wires owing to environmental effects such as temperature changes or tension forces in the wires.
- The rope/ cable should be replaced in short time periods for maintenance.

- Rigidity of the structure is low, therefore position accuracy is difficult to attain.

2.4.5 Rack and pinion drive

Rack and Pinion mechanism changes the translational motion to rotary motion. This mechanisms are used where restricted rotary motion is needed [42]. The rotary motion angle depends on the length of the translational motion and number of teeth on the pinion.

Advantages:

- These mechanisms are very cheap.

Disadvantages:

- The system is subjected to friction.
- Backlash may occur in long term use.

2.4.6 Harmonic drive

A harmonic drive is an innovative type of transmission system that basically operates three concentric mechanical elements, namely, a rigid external ring with internal teeth called the circular spline, a non rigid flex-spline with fewer teeth that rotates within the circular spline in response to the motion of a rotating input drive element which is called “wave generator” [42]. Since harmonic drives have high torque capacities with nearly zero hysteresis, they are increasingly used in robotics applications.

2.5 Continuum Robotics

Robotics is an ever- evolving field. Researches are ongoing to discover new possibilities for novel robot structures in order to overcome the failing of the system used. This necessary development is related to system requirements. Nowadays, the well-established world of industry, conventional rigid- link manipulators have been acceptably successful, however, they still have safety issues. Their rigid-link structure despite excellent for precise positioning of their end effector, tends to be the cause of undesirable collisions when it is working in unstructured spaces. Also, in real-world environments and situations, generally it is often not possible, to deploy

rigid-link manipulators. Therefore, the robotics society is now pushing the envelope and realizing that the robot manipulators do not have to be formed from rigid-links. As a completely different approach, continuous form or backbone type of robots have become the new focus. These robots, named continuum robots, can be examined as being “invertebrate” robots, as compared with the “vertebrate” design of traditional rigid-link robots.

Continuum robots can bend (and often extend/ contract and sometimes twist) at any point along their structure [31]. These properties supply them with more special capabilities in comparison of their rigid- link counterparts. Different type of continuum robots are shown in Figure 2.15.

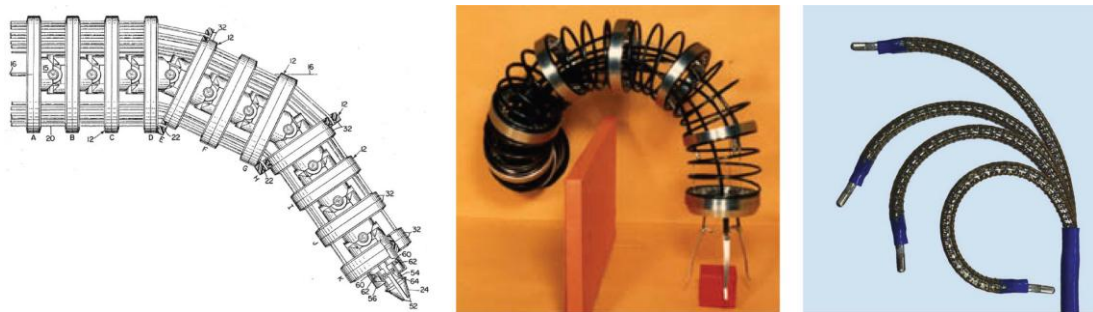


Figure 2.15 : Different types of continuum robots [43].

The continuum robots can be in contact with a fragile object in a softer manner and it adapts its shape like to this object in order to fully wrap around it. And also, it can be this motion can be achieved without any prior planning or knowledge shape of the object. With these features, they can lift the objects without any damages or breakages.

Another feature is the potential to use the backbone to avoid complex environment geometries. Thus, continuum backbone can twist and turn to pass through very narrow fields. The traditional rigid-link manipulator/ robots cannot enter this complex environment because of their structure. In summary, the continuum robots can use its compliant, actively controlled continuous structure to fulfill their task easily, quickly and without a priori knowledge.

Historically, interest in continuous backbone robots began as early as the 1960s. As for the first continuum robot, Anderson and Horn’s Tensor Arm [32] appears to have been the first prototype published in the literature. This arm was designed for underwater implementations. This arm’s prototype was not manufactured, however

developed from the laboratory stage. It was quickly realized that, while early prototypes could be made to achieve a wide range of shapes the relationship between the shapes and inputs was very complex much more than for it was for rigid link manipulators. Tensor Arm is shown in Figure 2.16.

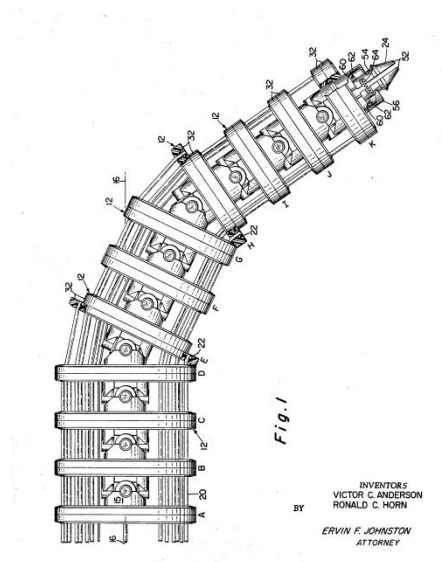


Figure 2.16 : Shape of tensor arm design [33].

Further research is related to continuum robot hardware in the 1990s focused on two directions: (1) development of the original tendon-driven design concepts of Anderson/Horn and Hirose oriented practical implementation [34,35] and applications [36-38] and (2) the new method to design continuum backbones with pneumatically actuated chambers [39-40].

Air- Octor manipulator lacks a solid continuous backbone unlike other continuum robots. Instead, it uses pneumatically- pressurized central chambers to supply the structural support essential for bending in constant curvature sections. This design allows tendon actuation of both bending and extension. Additionally, real-time kinematics and control architecture has been developed and implemented for Air- Octor [41]. Air- Octor manipulator is shown in Figure 2.17.



Figure 2.17 : Air- Octor manipulator [41].

The late 1990s and the 2000s, the amount of research has increased in continuum robot modeling, especially in kinematics. Different type of kinematic models are suggested in these studies. The new models, being matched directly to hardware constrains, enabled model based implemetation and thus real- time computer control of continuum robot shapes.

3. DESIGN OF THE ROBOTIC HANDS

Robotic hands have become one of the most important section of robotics field in recent years since it is used different areas. In order to develop its capability in direct interaction with people and objects, hand design should be planned very carefully.

For the robotic hand design to be successful it is expected to accomplish the specifically given task. In order to achieve a certain task, the design of the hand should have certain features. These features or required properties are collected and enlisted below; [42]

- Low cost.
- Light weight.
- Simple, rugged and compact design.
- High grip force to weight ratio.
- Controllable grip force.
- Controllable finger position.
- Minimal backlash and friction.
- High speed finger motion.
- Sensor ready (tactile, proximity, slip, force).
- Interface to robot or microcomputer controller.

In general, at the end of the hand design, it does not have all these features. The designer should decide what type of the system is required to achieve a certain given task. If the design can provide the necessary properties to accomplish their duty, the designer can admit this design as successful.

3.1 Design

Robotics hand can be used in a vast field to perform various tasks. For this reason, it may have to have different characteristics in each application. Therefore, the task must be defined clearly before starting the design of the robotic hand.

The robotic hand designed in this thesis work, will be used as humanoid robot UMay's hand. UMay aims to help incremental rehabilitation of children with Autistic Spectrum Disorder (ASD) utilizing its modular structure. Human-robot interaction is one of the core areas in the research effort to move towards making robots safer and more human friendly. Hence the hand design is made by considering the requirements of human-robot interaction in general.

According to the first requirement, in order to enable UMay's hand interact with children directly such as touching, serving etc., it must be safer and harmless as much as possible. For that reason, the robotic hand is designed in accordance with the structure of continuum robots. A continuum robot can be defined as a continuously bending, infinite-degree of freedom robot with an elastic structure as mentioned before. Thus, this method is used in design of a hand since it has an elastic structure. Now, when children or other people touch suddenly, the hand will demonstrate a compliant response because of the flexible nature of hand. The other reason to use this continuum structure is so that UMay can work in the unstructured environments. This means that, the hand can tenderly contact and adapt its shape around a fragile object with no prior planning or knowledge of the object and without any sensing of the contact between robot and object. This would be an extremely difficult operation for a conventional rigid-link manipulator. The last reason to use the structure of continuum robots is its high grip capability. Because of the flexible structure robot, it can hold any object with a wide variety of shapes and dimensions.

The second requirement is with respect to characteristic of finger motion and weight of the hand. When the designer is working on the robotic hand based on continuum robotics, it is known that the more motion capability, the more robust grasp can be obtained. Each finger consists of a proximal, middle and distal phalanx, and the thumb has a proximal and distal phalanx in the hands of the humans. Each of these joints exhibits flexion and extension, but only the proximal phalanges exhibit abduction and adduction. The diversity of these movements is not provided with

conventional hand design method with serial rigid-link structure. Because of these reasons, while designing the UMay's hand, the operation principle of cable-driven systems is used in addition to continuum robotic structure. While continuum robotic structure has provided a more flexible formation of hand, the cable-driven systems provide a robust control of the finger motion. When the cables are pulled, which are fixed on spring with plate, flexible structure of finger moves to the desired position and direction. In this way, these fingers exhibit flexion, extension, abduction and adduction just like with human hands. These movements are not possible with conventional design method with rigid-link models. Another advantage of cable-driven system is to decrease the weight of the design. Since the design does not need any other element helping to move, the hand becomes lighter.

The last condition is in regard to cost. UMay is designed to be used in therapies for children with ASD. For this reason, UMay is designed to obtain a low-cost and accessible platform for the in-home rehabilitation of children. Considering these circumstances, UMay's hand was designed to be low-cost without decreasing the capability of movement.

3.2 Definition of kinematic structure

In the design of robotic hand, characteristics of human hand have been taken as a model. For determination of the number of joints, the number of links and their geometrical configuration, the working principle of human hands were examined in detail. However, the structures of human hands such as rigid links, number of joints were not used in the design. Instead of these structures, characteristics of continuum robotic are used in design of this hand.

Human hand has three joints with four degrees of freedom and three rigid phalanges for each finger. Since continuum robotic characteristic are used to the design flexible structure, return spring in this thesis, is used instead of rigid phalanges.

Three plates are used to replace three joints. Thus, the structure of three joints and three phalanges is replicated in the design.

Each finger is actuated with the help of cables which are attached to the plates. Through these cables, each finger exhibits flexion, extension, abduction and adduction movements like human hand. These movements are not provided with

conventional hand design method like the one seen in serial rigid-link mechanism. Each finger has six electromechanical actuators for the six cables but only four of them have been used for actuation as described above. The other two are used as a boundary to unwanted movements of the finger. Hence, each finger has four degrees of freedom like the human finger. By this way, hand has a very high grasp capability like human hand. The robotic hand designed is drawn by using CATIA.

The robotic hand is designed in this thesis is shown Figure 2.1.

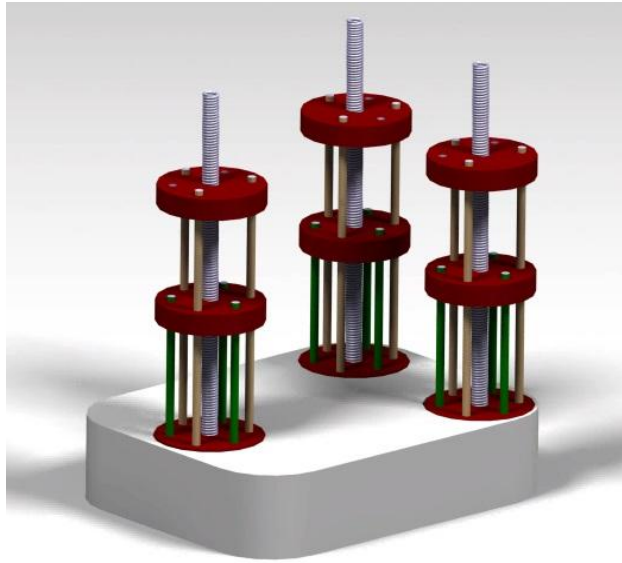


Figure 3.1 : Robotic hand design.

3.2.1 Selection of transmission system

In selection of transmission system, there are several points. Firstly, the pneumatic and hydraulic actuators are not selected because it is not suitable for concept of humanoid UMay project. For this reason, power transmission system has to be used in design. It is described that there are six methods for power transmission. These are as follows; Chain-Belt Mechanism, Mechanical Link, Gear Train System, Rope-Pulley System, Rack- Pinion Drive and Harmonic Drive. All of these power transmission methods are not suitable for continuum robotic structures since fingers consist of just spring and three plate. The conventional transmission systems are useful for series mechanisms in traditional finger designs. Therefore, other transmission systems are explored which is suitable for continuum robotic. Tendon-based design is used in many applications of continuum robotics. Perhaps the most direct approach to bend a continuous structure is the use of remotely actuated tendons. Given a backbone in the absence of external loads, the structure consistently

attains a given shape, therefore, tendons can be used to deviate it from that shape via bending. The design is quite simple and (relatively) straightforward to realize in hardware. Hence, tendon-based (i.e. cable driven) mechanism is more suitable for continuum robotic structures and it is used in the design of robotic hand. Similar to the tendons in a human hand, cables are used to transfer the actuator movement to finger joints. It has enabled us to do movement we want. In addition, since there is no other element on the hand except cables, the hand is getting lighter.

4. KINEMATIC ANALYSIS

Kinematic is an analysis method that is used to describe the movement of the robots. The robot's end point location or the joint angles should be in a certain positions to realize the movements. The relationship between the shape parameters and the end-effector coordinates are found by kinematic analysis according to the robot's geometry and the angle of the links of the robot.

4.1 Kinematic for Continuum Robots

Continuum robots, unlike the traditional rigid link robots, have a characteristic continuous backbone with no joints. Also, these robots grasp objects via whole body structure. An example of continuum robot is designed by Festo is illustrated in Figure 4.1



Figure 4.1 : Example of continuum robots [43].

Therefore, the model of robot shape and motion are more complex than those traditional robots. In contrast to kinematics for traditional manipulator which is composed of rigid link where position of any point on the robot can be fully defined by link lengths and joint angles, while analysing the natural structure of continuum robots have to be accounted because of elasticity. In order to correctly describe the position of any points on the continuum robot, one must characterize forces and moments applied to the robot by both its own actuators and external environment

[44]. From the first research in related to continuum robotic, researchers work on this kinematic analysis problem. During the development of continuum robotic, there are many different approaches to solve this problem. But, there are two main approaches are mostly used in researches.

One approach suggests that in order to solve shape of robot describe the space curve needed, then fitting the physical robot (as far as possible) to this theoretical curve [45]. In one research, clothoid curves have been recommended based on the careful analysing of biological snakes and are specially useful for mimicking biological snake locomotion [46]. In another research for improving the basic approach, define a curve as the result of a Bessel function with sines and cosines which allow a modal approach to inverse kinematics [47] .

The other approach that allows closed- form kinematics and facilities closed-form Jacobian formulation is to almost the robot as a series of mutually tangent constant-curvature arcs (“piecewise constant curvature”). Constant curvature assumption is mean that each segments which are in the same section must have the same diameter and must have same shape of curvature. According to constant curvature assumption, the continuum robot is modeled in two steps. In the first step, positions and orientations of each robot section is modeled as rigid link manipulator. These models assumption that manipulator is comprised of two revolute joints which lie at the base fo a manipulator section with intersecting axes followed by a prismatic joint and completed with two more revolute joints. The first revolute joints are used to determine local coordinate frame toward the section’s tip, the prismatic joints translate the local frame to the tip point of the manipulator and the final two revolute joints orient the local frame to point throughout the tangent of the manipulator section’s tip[48]. A continuum manipulator section is shon in Figure 4.2.

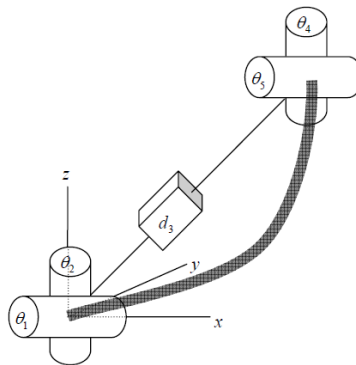


Figure 4.2 : A continuum manipulator section [48].

After these assumptions, the Denavit-Hartenberg table is created by these information for solving kinematic analysis. In the second step, curvature of each robot section is found by geometrically according to the exchange value of the cable length.

In this thesis, before start to kinematic analyze, both the first approach and the second approach were investigated in detail and the first approach is chosen to be implemented on our robotic hand.

4.2 Kinematic Analysis of Robotic Hand

The model of the robot shape and motion is the most important stage to solve kinematic analysis problem in continuum robot as mentioned before. In this thesis, the first approach, which is mentioned in previous section, is used to find the model of robot shape and position information. However, Bezier curves method is used to create suitable curve for each section of finger instead of the other approaches in [46-48].

Bezier curves method is based on Bernstein polynomials. It needs $n+1$ control points in order to create n th degree curve. When first and last point of curve are known, curve is plotted easily by this method. But, the other control points must be found properly in order to find the truest solution. These control points must be on the tangent lines which pass through first and last points. Place of control points on the tangent lines is found by using iteration method.

In this thesis, Bezier curves are used to find shape of finger, when it is grasped objects. In order to we know position of first point and last point of each finger section with the help of Umay's computer vision ability, the shape of finger is found without complex mathematical formulas by this method. Bezier curves and its kinematic implementation in this thesis work will be explained following parts.

4.2.1 Bezier curve

Bezier curves are named after their inventor, Dr. Pierre Bezier. Bezier was an engineer in the Renault car company. In the early 1960's, he develop this curve formulation in order to lend itself to shape design of vehicle body.

Many different Bezier curves can be created by depending on number of control points as mentioned before. For plotting nth degree curve, it is used n+1 control points. Three different Bezier curves and their related control polygons are shown in Figure 4.3.

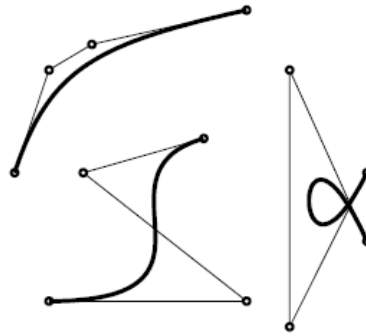


Figure 4.3 : Examples of cubic Bezier curves [47].

Each control polygon is composed of four control points that are connected with line segments. A Bezier curve passes through its first and last control points, and is tangent to the control polygon at those end points. These features are the basis of the Bezier curves. Bezier curve equation will be explained in following section.

4.2.2 The equation of a bezier curve

The equation of a Bezier curve is similar to the equation for the center of masses. Consider the four masses m_0 , m_1 , m_2 and m_3 are located at points P_0 , P_1 , P_2 , P_3 . Are shown in Figure 4.4 (a)

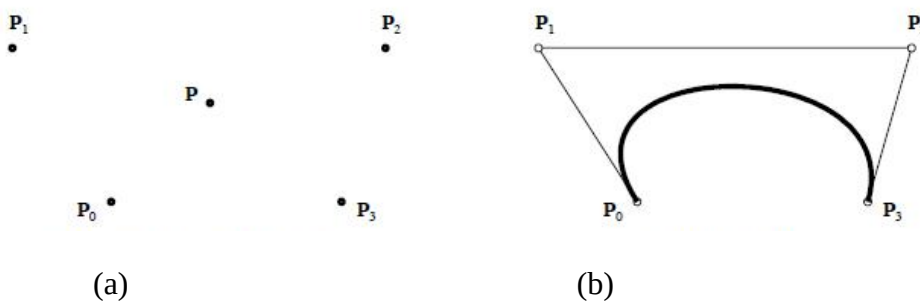


Figure 4.4 : Bezier curves in terms of center of mass: (a) Position of points, (b) Bezier curve [47].

The equation for the center of mass is given in Eq 4.1.

$$P = \frac{m_0 P_0 + m_1 P_1 + m_2 P_2 + m_3 P_3}{m_0 + m_1 + m_2 + m_3} \quad (4.1)$$

Instead of being fixed these masses with constant values, each mass varies as a function of a parameter t . Specially, let

$$m_0(t) = (1 - t)^3, m_1(t) = 3t(1 - t)^2, m_2(t) = 3t^2(1 - t), m_3(t) = t^3 \quad (4.2)$$

For each value of t , the masses assume different weights and their center of mass changes continuously. As t varies between 0 and 1, a curve is swept out by the moving center of mass. In Figure 4.3: (b) shows the Bezier curve that is obtained results when the point masses in Figure 4.3: (a), are taken as control points. This curve is a cubic Bezier curve. Curve is named like this because of the mass equations are degree three polynomials in t .

The variable masses $m_i(t)$ are usually called “blending functions” and the locations P_i are known as “control points”. The blending functions, in the case of Bezier curves, are known as Bernstein polynomials.

Bezier curves of any degree can be defined. Figure 4.5 shows sample curves of any degree one through four [47].

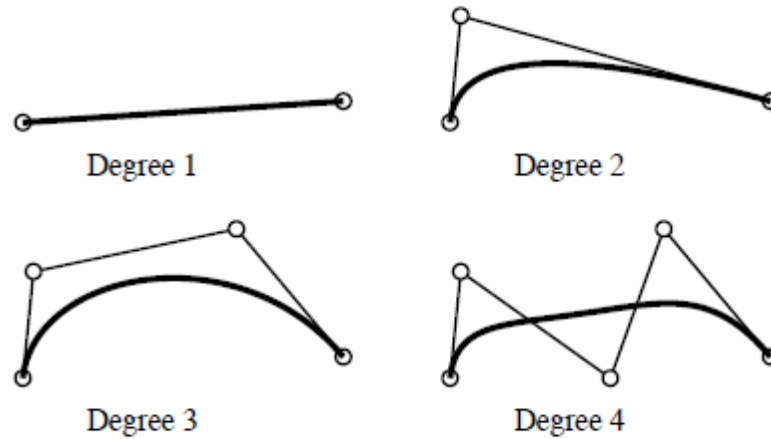


Figure 4.5 : Bezier curves of various degree [47].

A degree n Bezier curve has $n+1$ control points whose blending functions are denoted $B_i^n(t)$, where,

$$B_i^n(t) = \binom{n}{i} (1 - t)^{n-i} t^i, i=0, 1, \dots, n \quad (4.3)$$

Remember that

$$\binom{n}{i} = \frac{n!}{i!(n-i)!} \quad (4.4)$$

$\binom{n}{i}$ is mean that “n – choose- i” and is called a binomial coefficient because it arises in the binomial expansion

$$(a + b)^n = \sum_{i=0}^n \binom{n}{i} a^i b^{n-i} \quad (4.5)$$

In the degree three case, n=3 and

$$B_0^3 = (1-t)^3, B_1^3 = 3t(1-t)^2, B_2^3 = 3t^2(1-t), B_3^3 = t^3. B_i^n(t)$$

is also referred to as the ith Bernstein polynomial of degree n. The equation of a Bezier curve is given in Eq.4.6.

$$P(t) = \sum_{i=0}^n \binom{n}{i} (1-t)^{n-i} t^i P_i \quad (4.6)$$

4.2.3 Bezier curve for kinematic analysis

Kinematic analysis of continuum robots is more difficult than traditional rigid-link manipulators. In contrast to traditional manipulator, we have to find the shape of continuum manipulator in addition to the position and angle information. In order to solve our kinematic analysis problem and find shape of fingers, we use Bezier curves method. In order to each finger section has four points, we use cubic Bezier curve model.

When cubic bezier curve is created for analysis, four control points (P_0, P_1, P_2, P_3) are used. From these four control point, P_0 and P_3 are known. P_1 and P_2 points are located on the tangent line which passes through first and last control points. True position of these two control points are found by iteration method.

In this thesis, P_0 and P_3 points are selected as first and last connect point between two plates as shown Figure 4. 6.

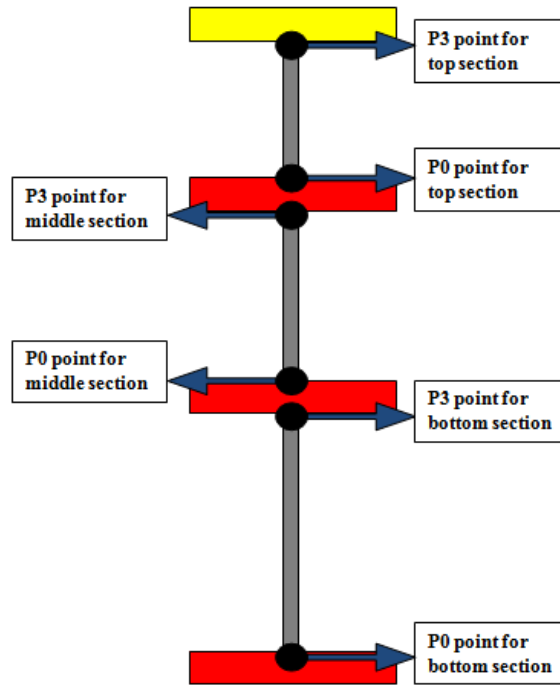


Figure 4.6 : Control points of finger section.

Kinematic analysis is performed by some steps as given below

1. The position coordinates of object are detected by the camera on the humanoid robot.
2. When finger touch this object, base point P_0 and tip point P_3 coordinates are found for each segment of finger.
3. The coordinates of each edge of plate are found. These coordinates are used to find tangent lines which is necessary to find P_1 and P_2 .
4. P_1 and P_2 coordinates are calculated by iteration code. While iteration, for first iteration we give two random distance on the tangent line. After that because we have four control points, the first Bezier curve is drawn. If the shape of curve does not fit the shape of spring, we give two new control points. Until the shape of curve and shape of spring match, this iteration go on.
5. After iteration has been done, we find the shape of each segment.
6. The cables length are calculated geometrically by using coordinates of plates or it can be find image processing method.

7. The motor angle is calculated by difference from amount of cables length changes.

After all these steps, the relationship between tip point of finger and motor angle is found. Also, this method can be used to find position of tip points depending amount of motor angle change.

In order to explain these steps, an example implementation is given below. The necessary points to calculation are shown on the Figure 4.7.

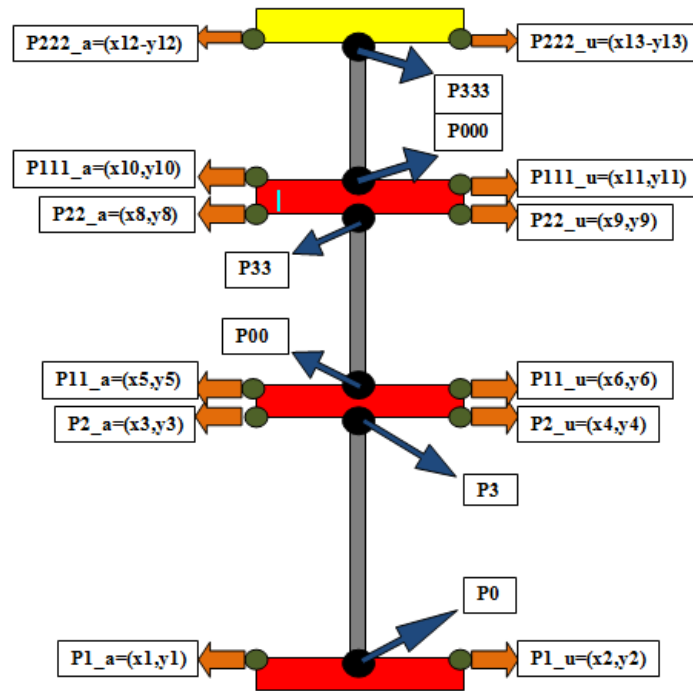


Figure 4.7 : The schema of finger structure.

P_0 , P_3 , P_{00} , P_{33} , P_{000} and P_{333} points base point and tip point of each segment of finger. P_{1-a} and P_{1-u} are used to find location of control point P_1 , P_{2-a} and P_{2-u} are used to find location of control point P_2 for the first segment. P_{11-a} and P_{11-u} are used to find location of control point P_{11} , P_{22-a} and P_{22-u} are used to find location of control point P_2 for the second segment. Likewise other segments, P_{111-a} and P_{111-u} are used to find location of control point P_{111} , P_{222-a} and P_{222-u} are used to find location of control point P_{222} for the last segment.

While we calculating Bezier curve, firstly we choose necessary points on the photo. After take coordinate informations of these points, we find the distance between of P_{1-a} and P_{1-u} and P_{2-a} and P_{2-u} .

The formulas of this function are given below

$$d_{x1} = P_{1-u}(1) - P_{1-a}(1) \quad (4.7)$$

$$d_{y1} = P_{1-u}(2) - P_{1-a}(2) \quad (4.8)$$

$$dst = \sqrt{d_{x1}^2 + d_{y1}^2} \quad (4.9)$$

$$d_{x1} = \frac{dx1}{dst} \text{ and } d_{y1} = \frac{dy1}{dst} \quad (4.10)$$

$$r_1 = (d_{y1}, -d_{x1}) \quad (4.11)$$

Thus, we find a point r_1 on the tangent line for control point P_1 . In the same way,

$$d_{x2} = P_{2-u}(1) - P_{2-a}(1) \quad (4.12)$$

$$d_{y2} = P_{2-u}(2) - P_{2-a}(2) \quad (4.13)$$

$$dst = \sqrt{d_{x2}^2 + d_{y2}^2} \quad (4.14)$$

$$d_{x2} = \frac{dx2}{dst} \text{ and } d_{y2} = \frac{dy2}{dst} \quad (4.15)$$

$$r_2 = (d_{y2}, -d_{x2}) \quad (4.16)$$

The point r_2 is found on the tangent line for control point P_2 . This formulas are used to find all other points for the P_{11} , P_{22} and P_{111} , P_{222} in the same way.

After these points are found, we give random distance and try to find exact control points. The formula is used to iteration is given Eqs. 4.17. and 4.18.

$$P_1 = P_0 + [d_1 * r_1(1) \quad d_1 * r_1(2)] \quad (4.17)$$

And

$$P_2 = P_3 + [d_2 * r_2(1) \quad d_2 * r_2(2)] \quad (4.18)$$

Where d_1 and d_2 are random distance values in order to use find exact position of control points. And also in order to plot bezier curve, the bezier curve equations are used. These equations are given in Eq. 4.19 and Eq. 4.20.

$$x = (1-u)^3 P_0(1) + 3(1-u)^2 u P_1(1) + 3(1-u)(u)^2 P_2(1) + (u)^3 P_3(1) \quad (4.19)$$

$$y = (1-u)^3 P_0(2) + 3(1-u)^2 u P_1(2) + 3(1-u)(u)^2 P_2(2) + (u)^3 P_3(2) \quad (4.20)$$

where $u \in [0,1]$

After these equations are used, Bezier curve of robotic finger is found. These implementation is calculated just first implementation. The other iteration is calculated same equations.

Implementation of Inverse Kinematic Analysis

In order to implementation, the below picture is choosen. The finger image is shown in Figure 4.8.

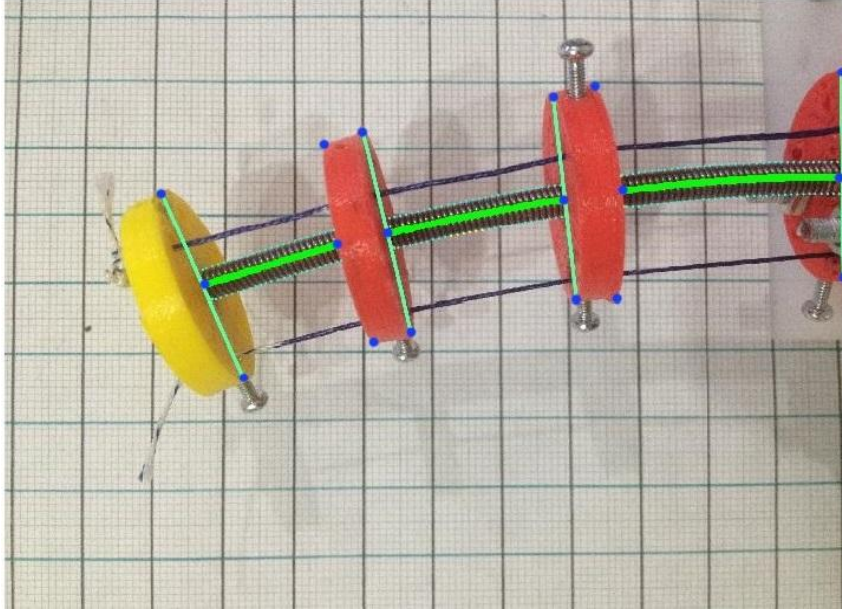


Figure 4.8 : Finger image for using iteration.

In order to find Bezier curve;

Firstly choose points on the image and we obtain these values;

For the first section;

$$P_0 = [1035 \ 195.2610]$$

$$P_3 = [849.9963 \ 206.0478]$$

$$P_{1-a} = [1038 \ 281.5551]$$

$$P_{1-u} = [1036 \ 104.1728]$$

$$P_{2-a} = [827.2243 \ 116.1581]$$

$$P_{2-u} = [846.4007 \ 259.5331]$$

For finding P_1 , firstly we find r_1 with Eqs. (4.7- 4.11)

$$d_{x1}=1036-1038$$

$$d_{x1}= - 2$$

$$d_{y1}=104.1728-281.5551$$

$$d_{y1}= -177.3823$$

$$dst=177.3935$$

$$d_{x1}= -0.0113 \text{ and } d_{y1}=-0.9999$$

$$r_1= (-0.9999, 0.0113)$$

After r_1 is found, the control points of P_1 is found by using Eq. 4.17

$$P_1=P_0+[d_1 * r_1(1) \quad d_1 * r_1(2)]$$

For the iteration we choose $d_1= 118$

$$P_1= [1035 \ 195.2610] + [(-0.9999)*118 \ (0.0113) *118]$$

$$P_1= [917.0118 \ 196.5944]$$

Thus the control point of P_1 is found for the first iteration.

The same calculations are implemented to find control points of P_2 by using Eqs. (4.12 - 4.17)

$$d_{x2}=669.0184 - 629.4669$$

$$d_{x2}= 39.5515$$

$$d_{y2}=327.0993 - 154.5110$$

$$d_{y2}= 172.5883$$

$$dst=176.8724$$

$$d_{x2}= 0.2236 \text{ and } d_{y2}= 0.9758$$

$$r_2= (0.9758, - 0.2236)$$

After r_2 is found, the control points of P_2 is found by using Eq. 4.18

$$P_2=P_3+[d_2 * r_2(1) \quad d_2 * r_2(2)]$$

For the iteration we choose $d_2 = 93$

$$P_2 = [849.9963 \ 206.0478] + [(0.9758)*93 \ (-0.2236)*93]$$

$$P_2 = [940.7457 \ 185.253]$$

After P_1 and P_2 are found, the Bezier curve is found by using Eqs. 4.19 and 4.20

$$x = (1 - u)^3 P_0(1) + 3(1 - u)^2 u P_1(1) + 3(1 - u)(u)^2 P_2(1) + (u)^3 P_3(1) \quad (4.19)$$

$$y = (1 - u)^3 P_0(2) + 3(1 - u)^2 u P_1(2) + 3(1 - u)(u)^2 P_2(2) + (u)^3 P_3(2) \quad (4.20)$$

The result of these equations are given us the Bezier curve coordinates of tip point of the first section where $u=0.99$. Because when u is choosen as one, the coordinares is equal to zero, the value of u is taken as 0.99.

$$x = (1-0.99)^3 (1035) + 3(1-0.99)^2 (0.99)(917.0118) + 3(1 - (0.99)) (0.99)^2 (940.7457) + (0.99)^3 (849.9963)$$

$$x = 861.015$$

$$y = (1 - 0.99)^3 (195.2610) + 3(1 - 0.99)^2 (0.99)(196.5944) + 3(1 - (0.99)) (0.99)^2 (185.253) + (0.99)^3 (206.0478)$$

$$y = 205.433$$

when $u=0.99$ the bezier curve coordinates are found as $(x,y)=(861.015, 205.433)$

where $u=0.01$

$$x = (1-0.01)^3 (1035) + 3(1-0.01)^2 (0.01)(917.0118) +$$

$$3(1-(0.01)) (0.01)^2 (940.7457) + (0.01)^3 (849.9963)$$

$$x = 1031.5020$$

$$y = (1 - 0.01)^3 (195.2610) + 3(1 - 0.01)^2 (0.01)(196.5944) +$$

$$3(1 - (0.01)) (0.01)^2 (185.253) + (0.01)^3 (206.0478)$$

$$y = 195.2966$$

when $u=0.01$ the Bezier curve coordinates are found as $(x,y)=(1031.5020, 195.2966)$

After these coordinates are found, it is shown that openly, when $u=0.01$, the coordinates of bezier curve are very close to the value of coordinates of P_0 .

In the same way, when when $u=0.99$, the coordinates of bezier curve are very close to the value of coordinates of P_3 .

The length of Bezier curve is found by using the difference of the length of between these two coordinates.

According to the values which are found above, the length of Bezier curve for the first section is found in the end of first iteration.

The length of bezier curve $L= 184.8668$ in terms of pixel. The curve length $L=26.166$ mm in terms of millimeter.

At the end of Inverse Kinematic analysis we find motor angle which is necessary to go to the desired end point. In order to find motor angle, we need to the amount of exchange of cable length. The cable length is found by measuring the length of cable over image.

The length of cable $d1$ is equal to 182. 7019 in terms of pixel. We convert to millimeter and find as $d1=25.86$ mm. We know the original length of cable $d0$ is equal to 26.7mm.

And now we find the change of cable lengths;

$$dx=d0-d1;$$

$$dx=0.84 \text{ mm.}$$

By using this information we find motor angle as geometric. In order to find angle, arc length formula is used.

The arc length formula is given in Eq. 4.21.

$$\alpha = \frac{dx * 360}{2 * \pi * r} \quad (4.21)$$

where; dx is the the amount of cable length, r is the radius of the pulley which is attached to the motor. ($r=12.33$ mm)

Using this formula

$$\alpha = \frac{(0.84) * 360}{2 * \pi * (12.33)}$$

$$\alpha = 3.903362^\circ$$

Actually, we find the angle of rotation angle for pulley. For finding real motor angle we use the ratio between the pulley and the motor shaft.

At the end of this calculation, we find motor shaft angle as $\Theta=16.0428^\circ$.

With this calculation, we solve Inverse kinematic analysis for the robotic finger and we find that if we want to go to the tip point P_3 , the motor shaft should rotate 16.0428° .

In fact the most important point related to solution, we do not use Bezier curve length, while we were founding motor angle. The difference between of continuum robotic manipulator and traditional rigid-link manipulator, exactly appear at this point. While kinematic analysis is finding for traditional manipulator, we use link length in order to find motor angle. However, while we were solving kinematic analysis of continuum robots, we use its shape. To explain more clearly, we need to look again our solution steps. While we making solution, firstly we found shape of curve for a finger section and its tip point coordinates. After that we calculate the length of cable when finger is on the pre-existing coordinates. And then we found motor angle as approximately sixteen degrees are in related to cable length. But in fact, the finger is shown in Figure 4.8 rotated thirty degree. In order to we use flexible structure instead of rigid link, the finger is affected from motion as permitted by this flexible structure. In this reason, while the kinematic analysis is solving for continuum robots, we have to find the shape of finger structures and its tip points coordinates unlike other traditional systems.

Going back to the application, we found curve of first section. For the second and third section, calculations is implemented on the MATLAB and found these information;

For the second section, length of Bezier curve is found as $L_2=21.64$ mm when $d_1=43$ and $d_2=20$

For the third section $L_3=16.6178$ mm and $d_1=22$ and $d_2=5$. And we find shape of curve for each segment in the first iteration. These curves are shown in Figure 4.9.

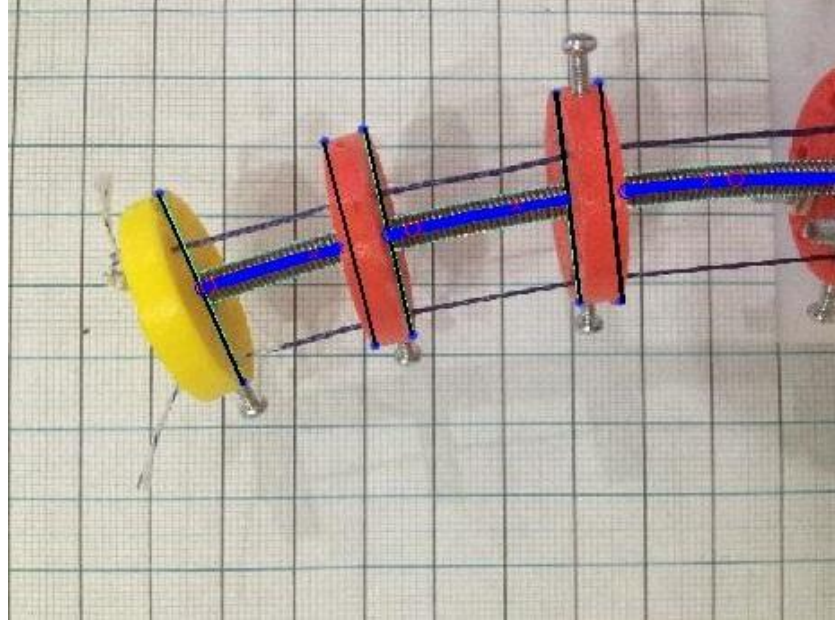


Figure 4.9 : Bezier curve for all finger

After fifth iteration, the shape of bezier curve which is found by above equations is overlap with shape of finger segments. Thus, we obtain both length of curve for each segment and shape of the finger.

In order to ensure whether these curves fit on the real curve of spring or not, we find ground truth table of the natural shape of curve.

For generating truth table, we find coordinates of each coil on the both sides of spring. In order to find these points' coordinates, we mark each coil with blue dots. One example of ground truth table is shown in Figure 4.14.

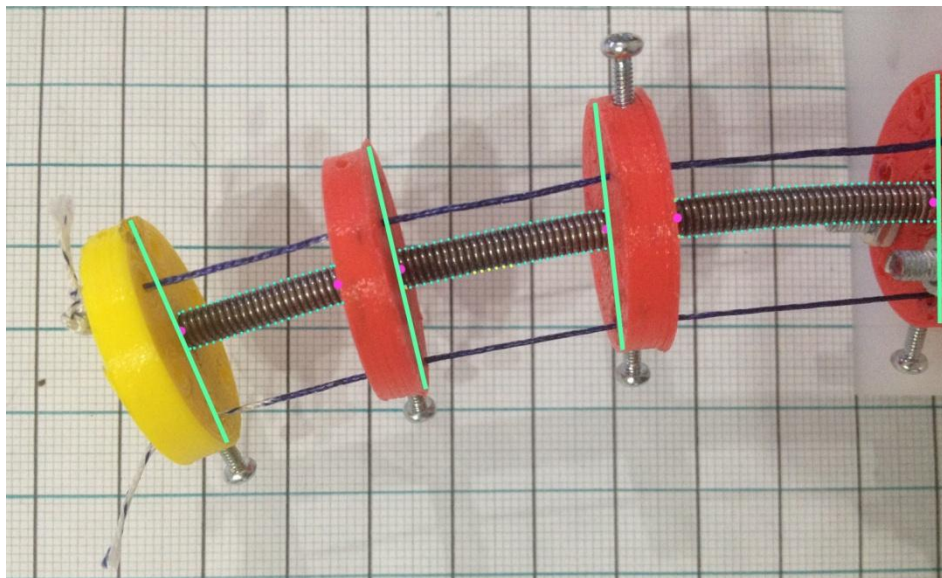


Figure 4.10 : Marked image for truth table.

After coupling these dots, we obtained natural shape of spring. The ground truth curve is shown in Figure 4.15.

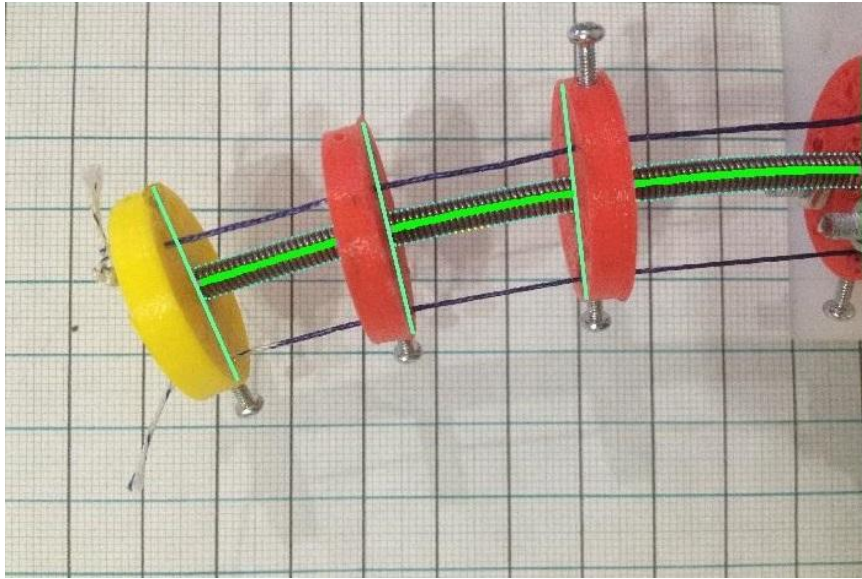


Figure 4.11 : Curve of truth table.

In order to compare curve of truth table and curve of bezier curve for different angles, some applications are given following section.

4.2.4 Application of Kinematic Analysis

In this section, some implementation is shown for different motor angles. These angles are selected randomly. Image processing method is used to find the real curves and compare the with Bezier solutions. In this method, firstly the robotic finger images were acquired. Later, each sides of the spring is marked to create the ground truth table. The ground truth table is necessary to see the natural shape of the curve and assess how accurate the calculations are. After that, the control points are marked on the image and plot Bezier curve was calculated and plotted.

The ground truth table and the Bezier curve which is plotted on the ground truth table curve are plotted for different angles of motor.

These curves are shown in the between the Figure 4.12 and Figure 4.21

Truth table when motor rotate 30 degrees

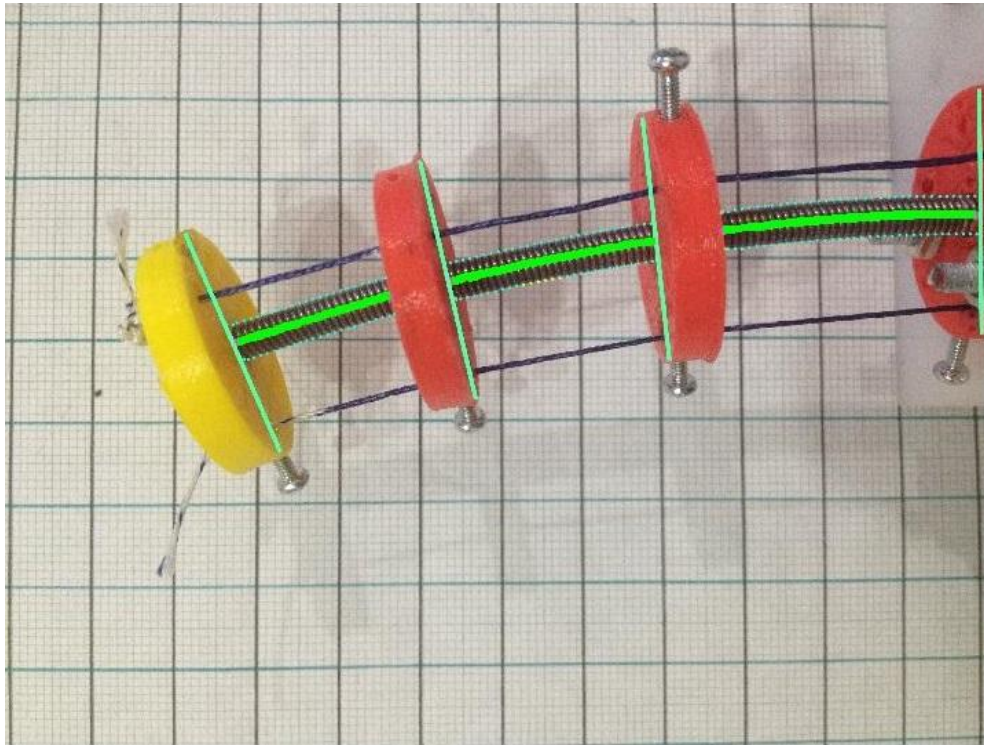


Figure 4.12 : Truth table for thirty degrees.

Bezier curve when motor rotate 30 degrees

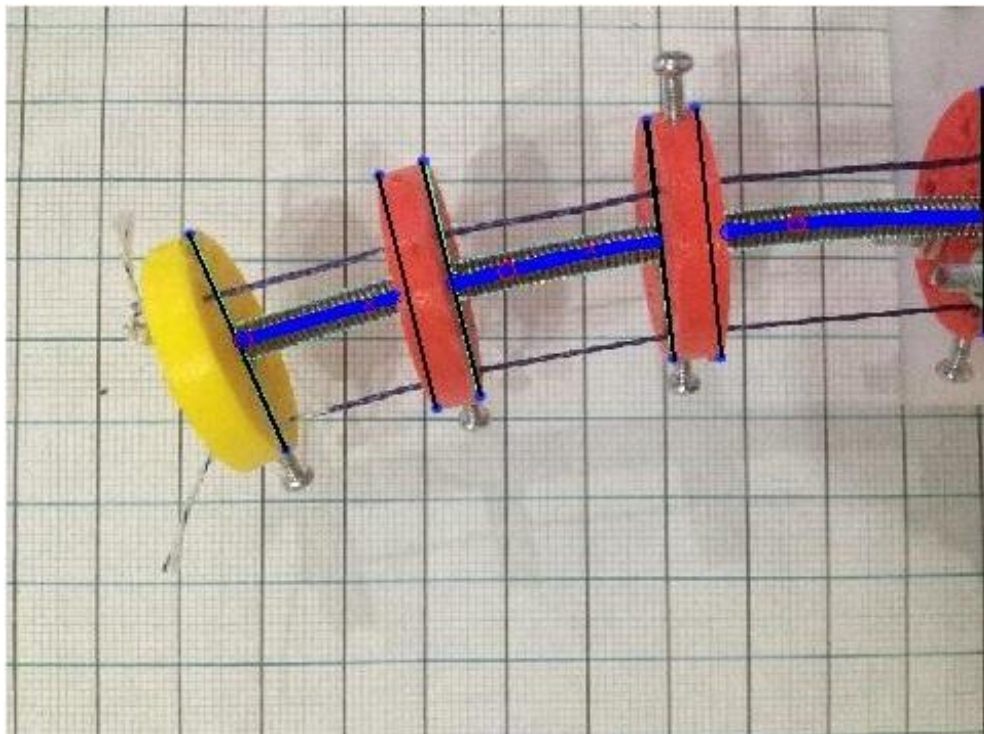


Figure 4.13 : Bezier curve for 30 degrees.

Truth table when motor rotate 45 degrees

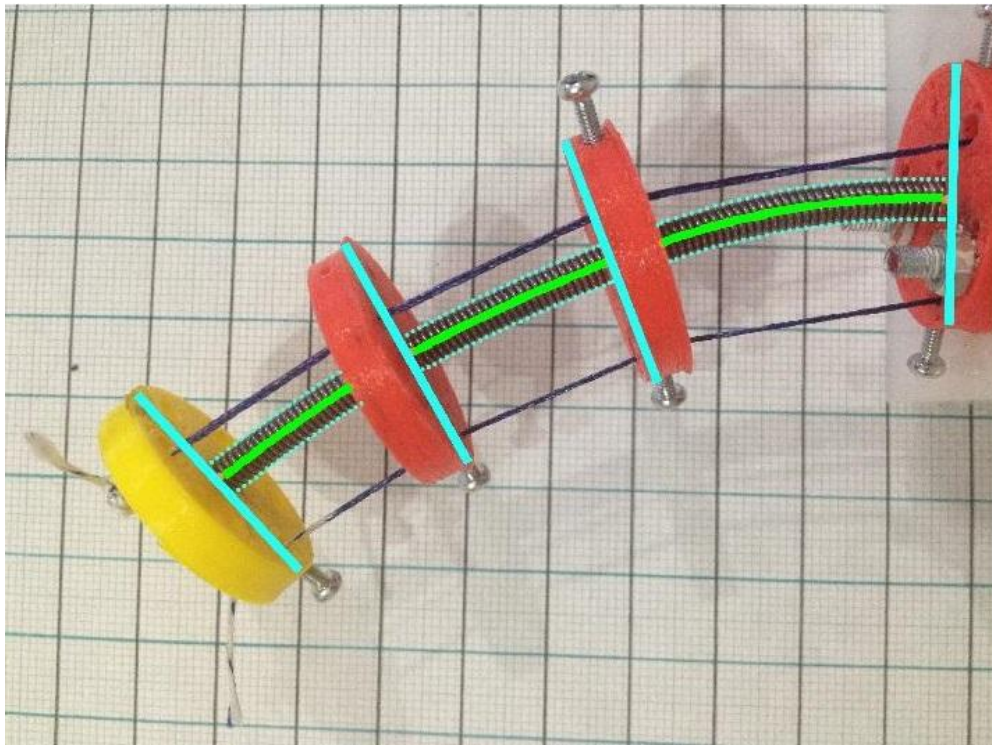


Figure 4.14 : Truth table for fourty-five degrees.

Bezier Curve when motor rotate 45 degrees

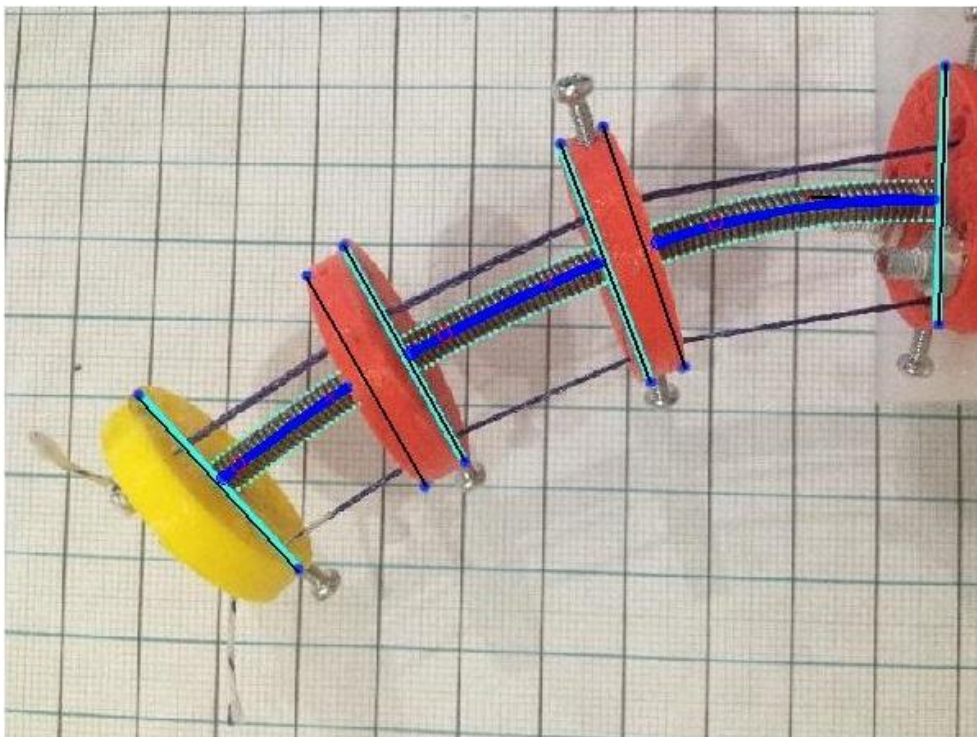


Figure 4.15 : Bezier curve for fourty-five degrees.

Truth Table when motor rotate 60 degrees

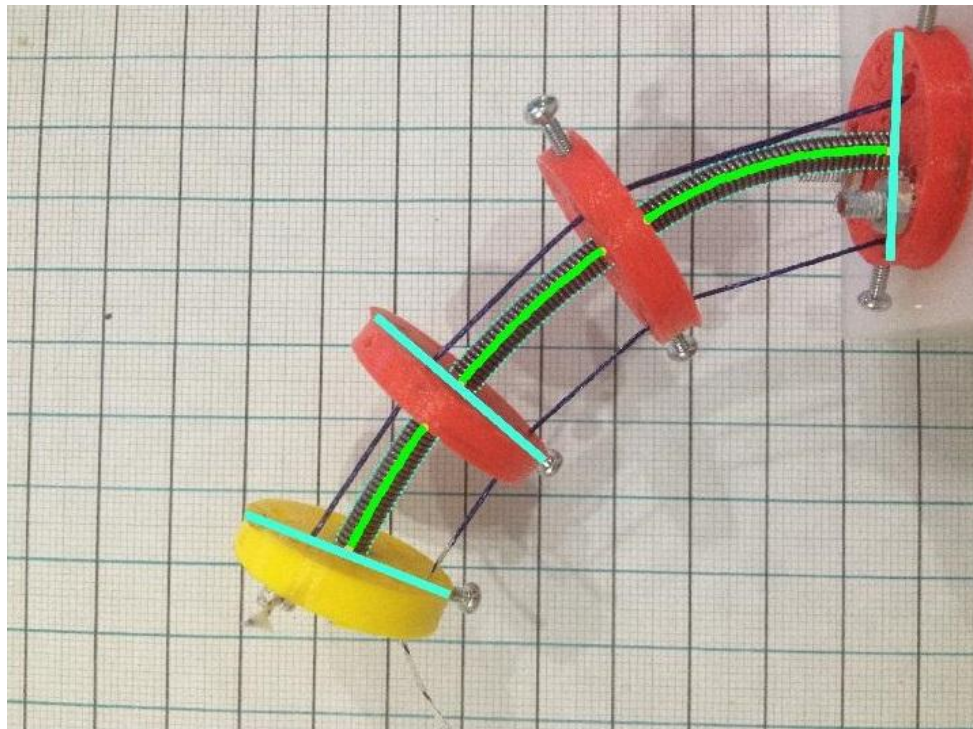


Figure 4.16 : Truth table for sixty degrees.

Bezier curve when motor rotate 60 degrees

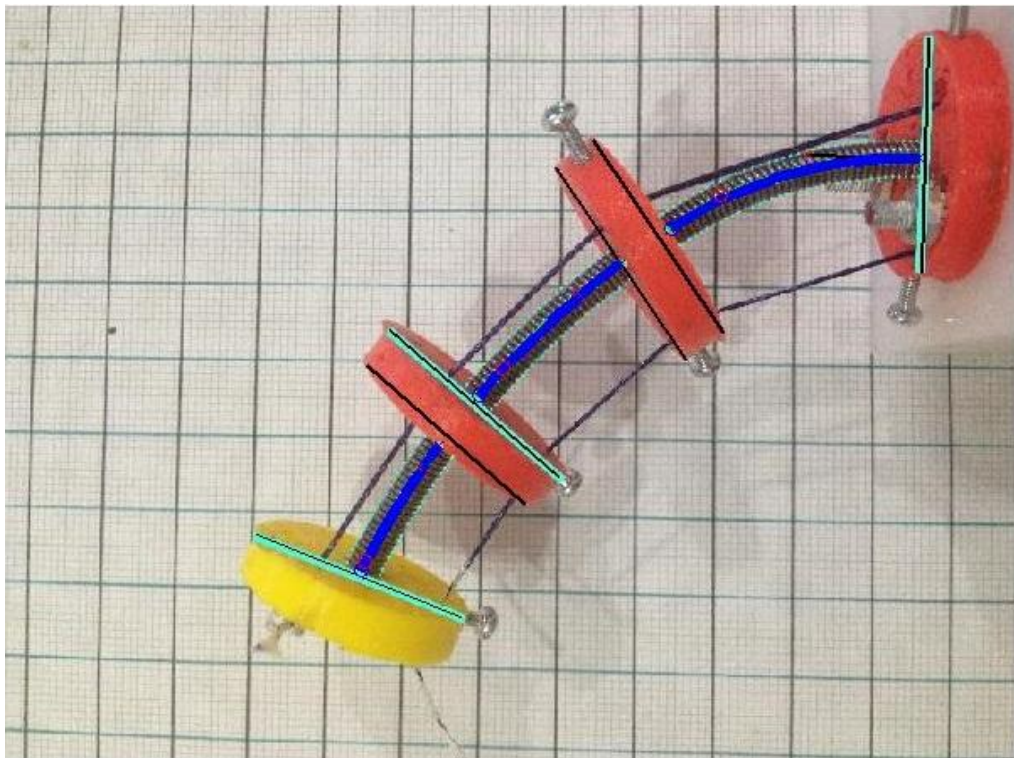


Figure 4.17 : Bezier curve for sixty degrees

Truth Table when motor rotate 90 degrees

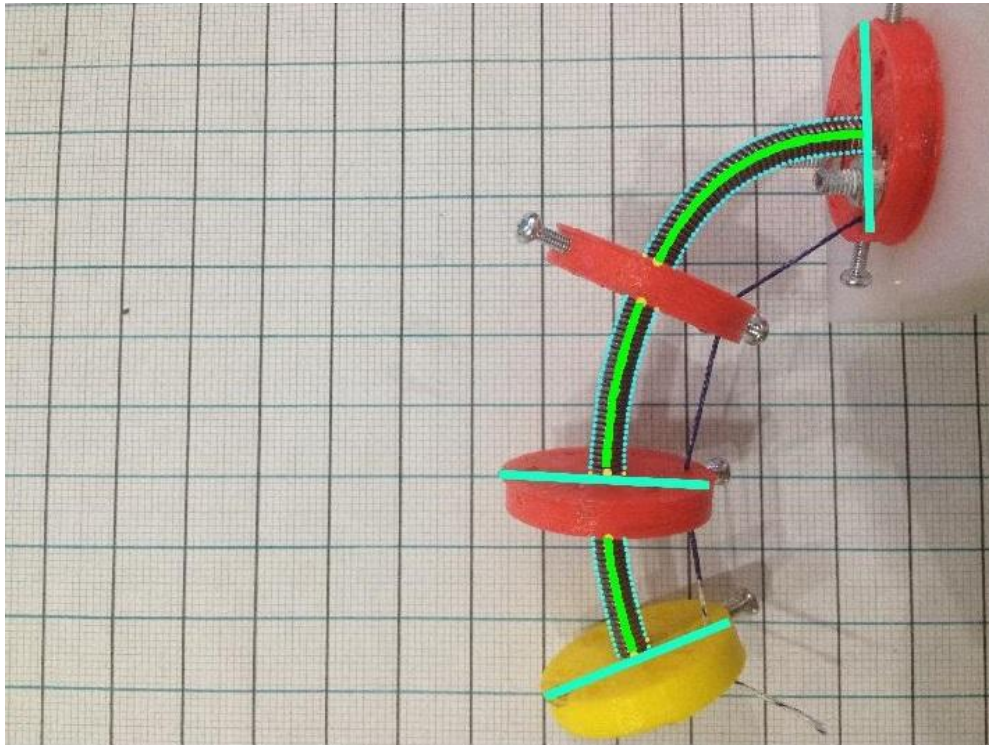


Figure 4.18 : Truth table for ninety degrees.

Bezier curve when motor rotate 90 degrees

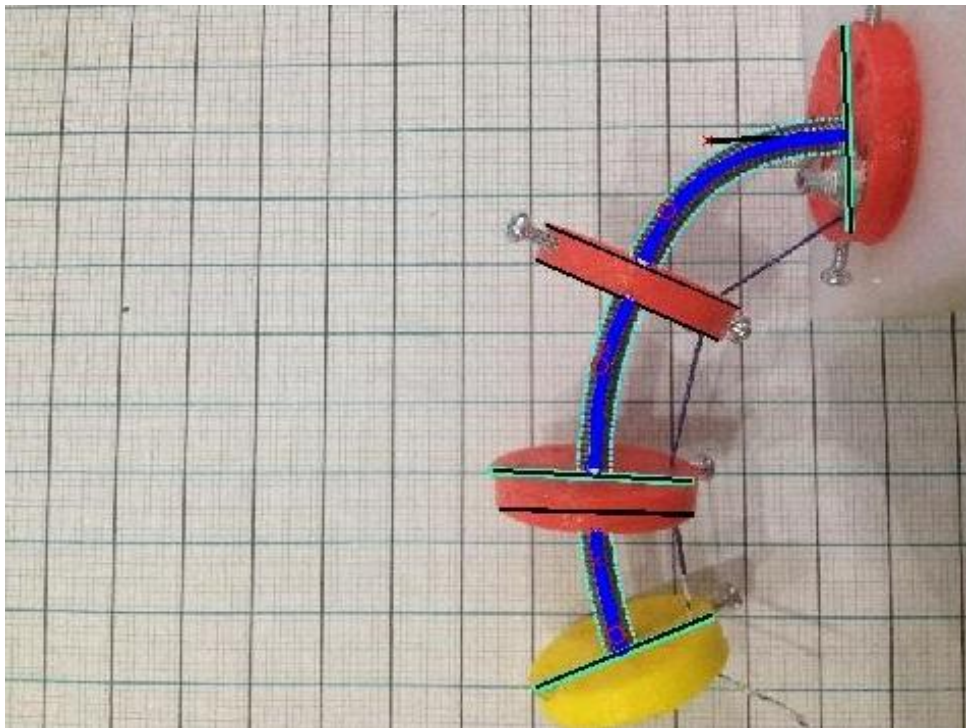


Figure 4.19 : Bezier curve for ninety degrees.

Truth table when motor rotate 120 degrees

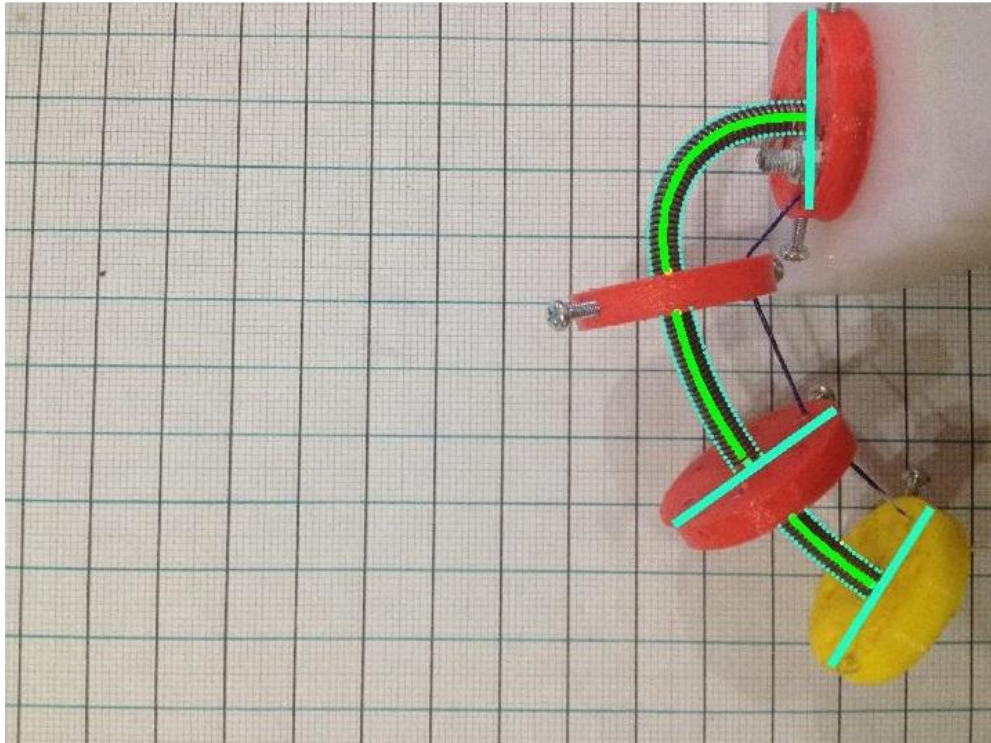


Figure 4.20 : Truth table for one hundred and twenty degrees.

Bezier curve when motor rotate 120 degrees

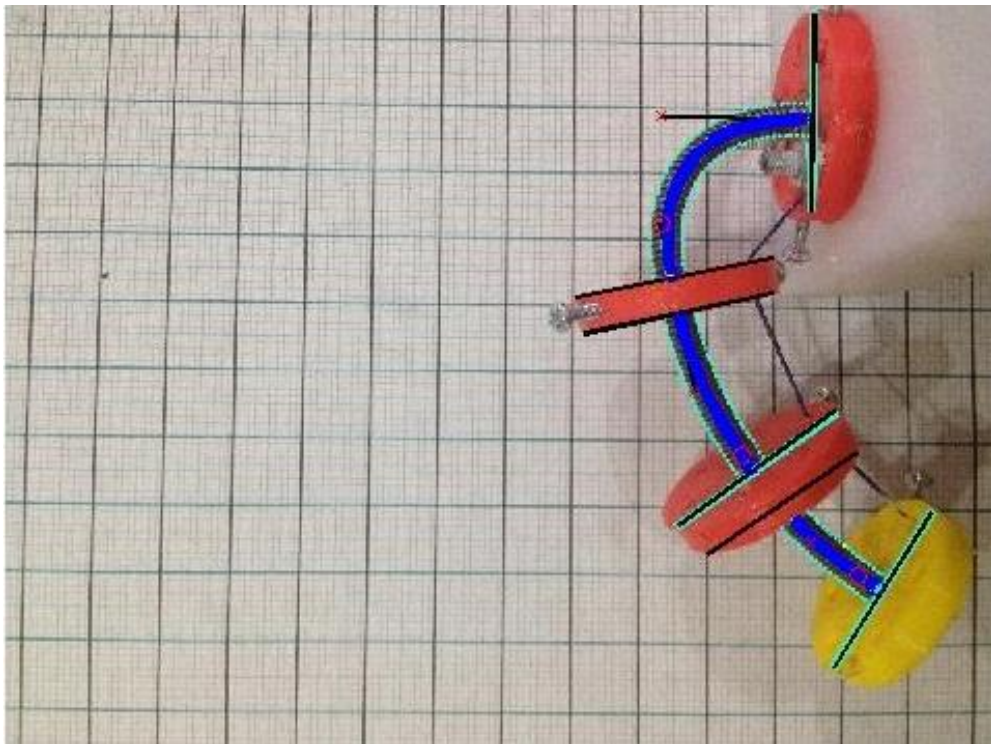


Figure 4.21 : Bezier curve for one hundred and twenty degrees.

As shown in the above figures, curve of the ground truth table and bezier curves are almost matched. Thus, the shape of spring is found correctly for different degree of motor shaft turns by using Bezier curve method. When the shape of spring is found, the position of the plates is found and the position of tip point can be found based on kinematic analysis.

5. CONCLUSIONS AND FUTURE WORK

In this thesis work, robotic hand is designed using a flexible and continuum robotic. In order to realize its design, we used the methods in continuum robotics. The return spring is used instead to imitate the bones of finger. This flexible structure provides us a completely different approach compared to rigid- link structure of human hand. Three plates are used to provide motion of joints. Three cables are attached on the first plate and six cables are attached on the second plate. These cables are used for transmission of motion from motor to finger and it operates just like the tendons of human hand. Each cable is driven by one motor. This design provide us high capability of movement just like human finger. In order to try new method for kinematic analysis of continuum robots, Beizer curve method is used to for this analysis. When the cables are actuated to move the finger to the intended position, the shape of return springs can be detected by Bezier curves. This approach is different from other kinematic analysis methods used in continuum robotics as well. Thanks to Bezier curve method, the position of tip point or motor angle can be calculated easily. This method is used for both Forward kinematic analysis and Inverse kinematic analysis. In addition, mathematically Bezier curve method is easier to model compared to other kinematic analysis methods. Through some simple implementation, it is shown that Bezier curve method has given information of the robot shape parameters used for kinematic analysis. In the future studies, the full dynamic analysis will also be developed to complete the full analysis for better control.

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APPENDICES

APPENDIX 1

THE CODES FOR FIND BEZIER CURVE

```
clear
clc
close all
original = imread('30_ty.JPG');

imshow(original);
hold on
impixelinfo

%alt kısım için

%P0 için
[x0, y0]=ginput(1)
p0=[x0, y0]

%P3 için
[x, y]=ginput(1)
p3=[x, y]

%alt plaka için sağ alt
[x1, y1]=ginput(1)
p1_alt=[x1, y1]

%alt plaka için sağ üst
[x2, y2]=ginput(1)
p1_ust=[x2, y2]

%üst plaka için sol alt
[x3, y3]=ginput(1)
p2_alt=[x3, y3]

%üst plaka için sol üst
[x4, y4]=ginput(1)
p2_ust=[x4, y4]

%orta plaka için

%p0 için
```

```

[xp, yp]=ginput(1)
p00=[xp, yp];

%p3 için
[xx, yy]=ginput(1)
p33=[xx, yy]

%alt plaka için sağ alt
[x11, y11]=ginput(1)
p11_alt=[x11, y11]

%alt plaka için sağ üst
[x22, y22]=ginput(1)
p11_ust=[x22, y22]

%üst plaka için sol alt
[x33, y33]=ginput(1)
p22_alt=[x33, y33]

%üst plaka için sol üst
[x44, y44]=ginput(1)
p22_ust=[x44, y44]

%üst kısım için

%p0 için
[xs, ys]=ginput(1)
p000=[xs, ys];

%p3 için
[xxx, yyy]=ginput(1)
p333=[xxx, yyy]

%alt plaka için sağ alt
[x111, y111]=ginput(1)
p111_alt=[x111, y111]

%alt plaka için sağ üst
[x222, y222]=ginput(1)
p111_ust=[x222, y222]

%üst plaka için sol alt
[x333, y333]=ginput(1)
p222_alt=[x333, y333]

%üst plaka için sol üst
[x444, y444]=ginput(1)
p222_ust=[x444, y444]

```

```

t=input('tamam mi')

while t<1
    close all

    imshow(orijinal);
hold on
%kontrol noktaları iterasyonu için normal bulma ilk kısım
r1 = findNormal(p1_alt,p1_ust);
r2 = findNormal(p2_alt,p2_ust);
d1 = input('d1');
d2 = input('d2');

%kontrol noktaları iterasyonu için normal bulma orta
kısım
r11 = findNormal(p11_alt,p11_ust);
r22 = findNormal(p22_alt,p22_ust);
d11 = input('d11');
d22 = input('d22');

%kontrol noktaları iterasyonu için normal bulma son kısım
r111 = findNormal(p111_alt,p111_ust);
r222 = findNormal(p222_alt,p222_ust);
d111 = input('d111');
d222 = input('d222');

%alt plakanın orta noktası ilk kısım
p1_orta=(p1_alt+p1_ust)./2;

%alt plakanın orta noktası orta kısım
p11_orta=(p11_alt+p11_ust)./2;

%alt plakanın orta noktası son kısım
p111_orta=(p111_alt+p111_ust)./2;

%kontrol noktası_1 ilk kısım
p1=p0 + [ r1(1)*d1 r1(2)*d1];

%kontrol noktası_1 orta kısım
p11=p00 + [ r11(1)*d11 r11(2)*d11];

%kontrol noktası_1 son kısım
p111=p000 + [ r111(1)*d111 r111(2)*d111];

%ust plakanın orta noktası ilk kısım
p2_orta=(p2_alt + p2_ust)./2;

%ust plakanın orta noktası orta kısım
p22_orta=(p22_alt + p22_ust)./2;

```

```

%ust plakanın orta noktası son kısım
p222_orta=(p222_alt + p222_ust)./2;

err = 6;
iteration = 1

p2=p3 + [ r2(1)*d2 r2(2)*d2];%ilk kısım
p22=p33 + [ r22(1)*d22 r22(2)*d22];%orta kısım
p222=p333 + [ r222(1)*d222 r222(2)*d222];%son kısım

L=findBezierLength(p0,p1,p2,p3)%ilk kısım
err = L - 1389;
iteration=iteration+1;

L1=findBezierLength(p00,p11,p22,p33)%orta kısım
err = L1 - 1389;
iteration=iteration+1;

L11=findBezierLength(p000,p111,p222,p333)%son kısım
err = L11 - 1389;
iteration=iteration+1;

hold on;

%ilk kısım
plot([p1_alt(1) p1_ust(1)], [p1_alt(2)
p1_ust(2)], 'Color','k', 'LineWidth', 2)
plot([p2_alt(1) p2_ust(1)], [p2_alt(2)
p2_ust(2)], 'Color','k', 'LineWidth', 2)
plot([p0(1) p1(1)], [p0(2)
p1(2)], 'Color','k', 'LineWidth', 2)
plot([p2(1) p3(1)], [p2(2)
p3(2)], 'Color','k', 'LineWidth', 2)

hold on

%orta kısım
plot([p11_alt(1) p11_ust(1)], [p11_alt(2)
p11_ust(2)], 'Color','k', 'LineWidth', 2)
plot([p22_alt(1) p22_ust(1)], [p22_alt(2)
p22_ust(2)], 'Color','k', 'LineWidth', 2)
plot([p00(1) p11(1)], [p00(2)
p11(2)], 'Color','k', 'LineWidth', 2)
plot([p22(1) p33(1)], [p22(2)
p33(2)], 'Color','k', 'LineWidth', 2)

hold on

%son kısım
plot([p111_alt(1) p111_ust(1)], [p111_alt(2)
p111_ust(2)], 'Color','k', 'LineWidth', 2)

```

```

plot([p222_alt(1) p222_ust(1)], [p222_alt(2)
p222_ust(2)], 'Color', 'k', 'LineWidth', 2)
plot([p000(1) p111(1)], [p000(2)
p111(2)], 'Color', 'k', 'LineWidth', 2)
plot([p222(1) p333(1)], [p222(2)
p333(2)], 'Color', 'k', 'LineWidth', 2)

plotBezierLength(p0,p1,p2,p3, 'b'); %ilk kısım
plotBezierLength(p00,p11,p22,p33, 'b'); %orta kısım
plotBezierLength(p000,p111,p222,p333, 'b'); %son kısım

t=input('tamam mi')
end

```

APPENDIX 2

THE CODES FOR FIND NORMAL

```
function res = findNormal(p1,p2)

dx = p2(1) - p1(1);
dy = p2(2) - p1(2);
dst = sqrt(dx^2+dy^2);
dx = dx / dst;
dy = dy / dst;
res(1) = dy;
res(2) = -dx;
```

APPENDIX 3

THE CODES FOR FIND BEZIER LENGTH

```
function res = findBezierLength(p1,p2,p3,p4)

u = 0:1e-3:1;

for i=1:length(u)
    x(i) = (1-u(i))^3*p1(1)+3*(1-u(i))^2*u(i)*p2(1)+3*(1-
u(i))*u(i)^2*p3(1)+u(i)^3*p4(1);
    y(i) = (1-u(i))^3*p1(2)+3*(1-u(i))^2*u(i)*p2(2)+3*(1-
u(i))*u(i)^2*p3(2)+u(i)^3*p4(2);
end

d = 0;
for i=1:length(x)-1
    d = d + distance(x(i),y(i),x(i+1),y(i+1));
end

res = d;
```

APPENDIX 4

THE CODES FOR PLOT BEZIER LENGTH

```
function res = plotBezierLength(p1,p2,p3,p4,color)

u = 0:0.1:1;

for i=1:length(u)
    x(i) = (1-u(i))^3*p1(1)+3*(1-u(i))^2*u(i)*p2(1)+3*(1-
u(i))*u(i)^2*p3(1)+u(i)^3*p4(1);
    y(i) = (1-u(i))^3*p1(2)+3*(1-u(i))^2*u(i)*p2(2)+3*(1-
u(i))*u(i)^2*p3(2)+u(i)^3*p4(2);
end

plot(x,y,color,'LineWidth',5)
axis equal
hold on
plot(p1(1),p1(2),'bx')
plot(p2(1),p2(2),'rx')
plot(p3(1),p3(2),'ro')
plot(p4(1),p4(2),'bo')

line([p1(1) p1(2)], [p2(1) p2(2)])

line([p3(1) p4(1)], [p3(2) p4(2)])

hold on
```

APPENDIX 5

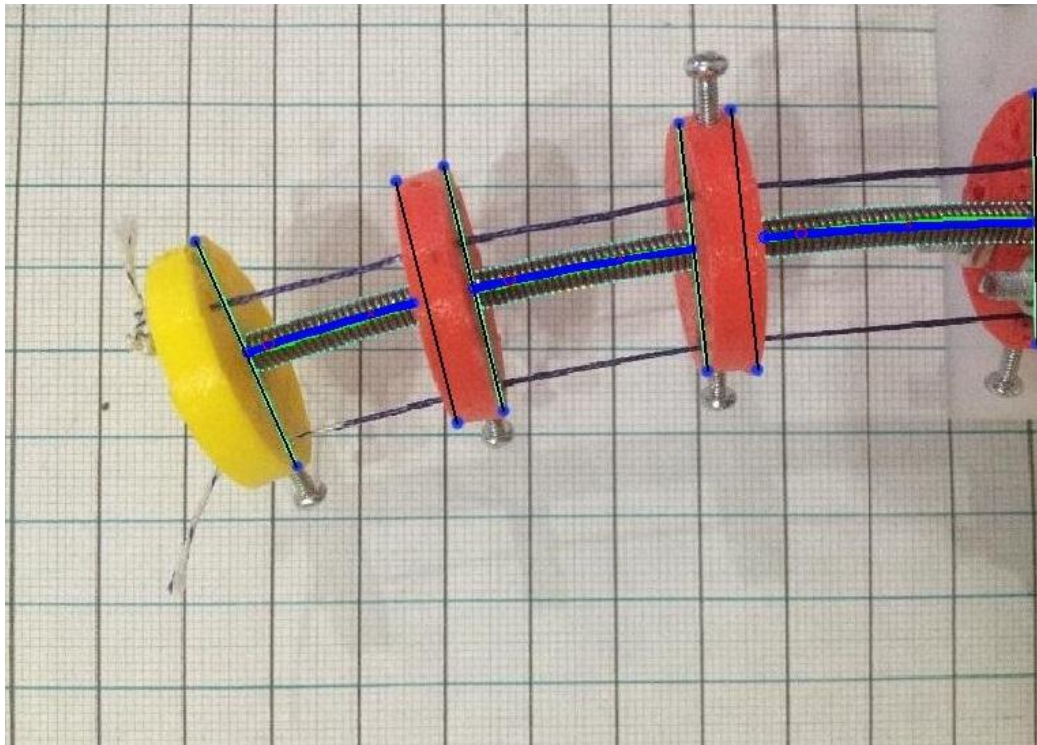
THE RESULT OF ITERATION

The First Iteration

For the first section; $d_1=85$, $d_2=25$

For the second section; $d_1=50$, $d_2=20$

For the last section; $d_1=20$, $d_2=20$



The curve length of each section is given below;

$$L_1=183.1188$$

$$L_2=151.2479$$

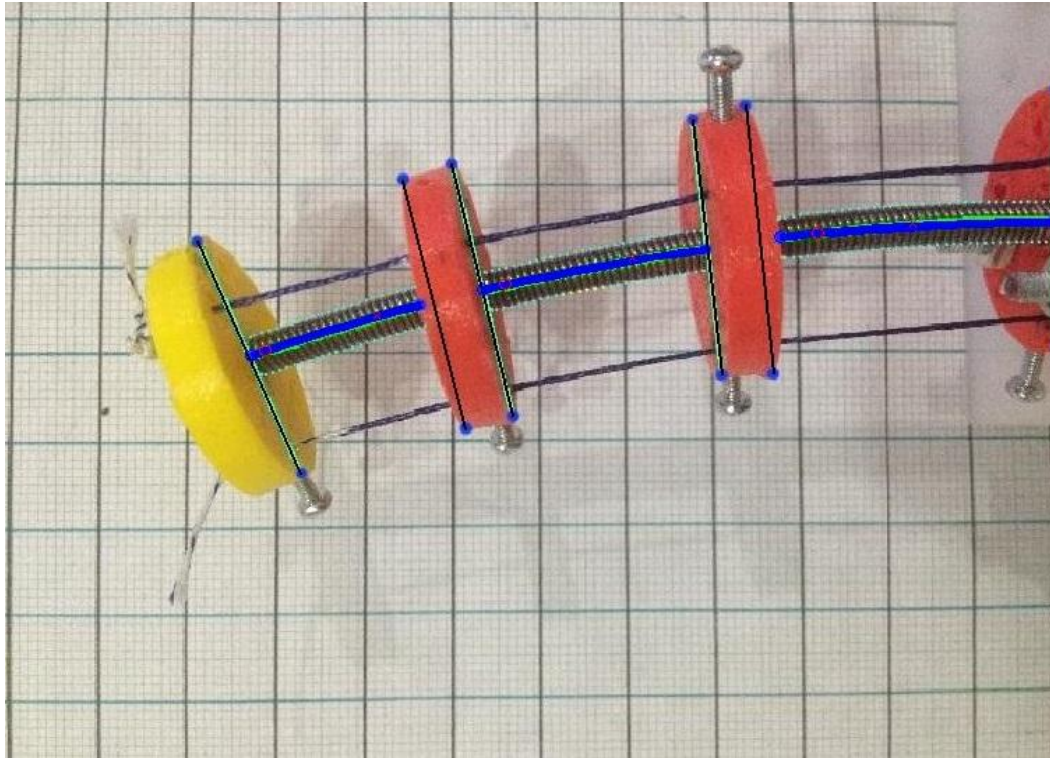
$$L_3=116.0016$$

The Second Iteration

For the first section; $d_1=95$, $d_2=25$

For the second section; $d_1=50$, $d_2=15$

For the last section; $d_1=30$, $d_2=10$



The curve length of each section is given below;

$$L_1=183.1188$$

$$L_2=151.2479$$

$$L_3=116.0016$$

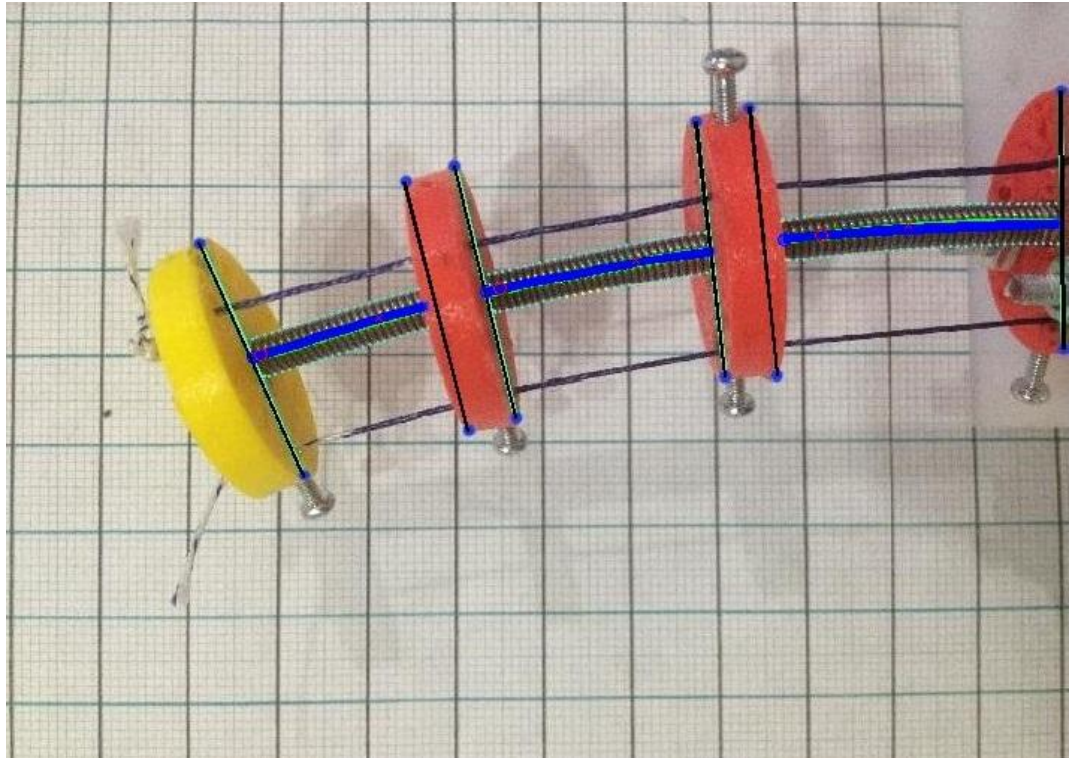
In order to curve does not match with shape of spring, we continue to do the iteration

The Third Iteration

For the first section; $d_1=100$, $d_2=25$

For the second section; $d_1=50$, $d_2=15$

For the last section; $d_1=30$, $d_2=10$



The curve length of each section is given below;

$$L_1=183.6423$$

$$L_2=156.2040$$

$$L_3=115.8698$$

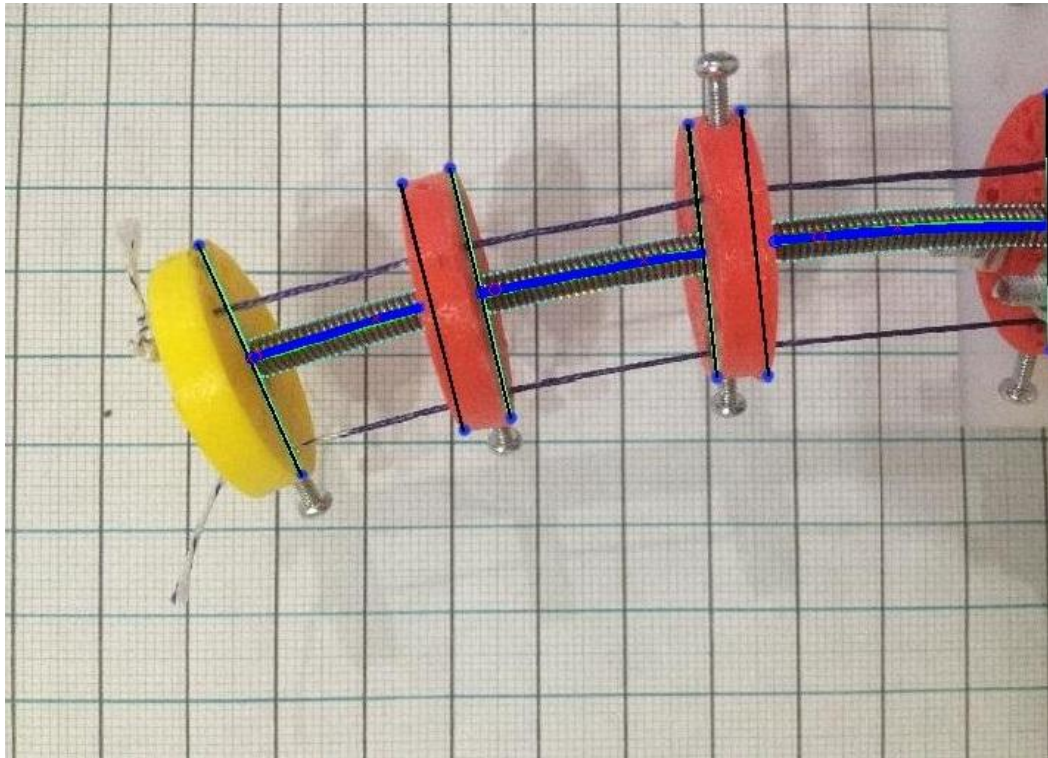
In order to curve does not match with shape of spring, we continue to do the iteration

The Fourth Iteration

For the first section; $d_1=100$, $d_2=30$

For the second section; $d_1=40$, $d_2=10$

For the last section; $d_1=30$, $d_2=2$



The curve length of each section is given below;

$$L_1=183.6463$$

$$L_2=151.1526$$

$$L_3=115.83314$$

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