iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 11 **Issue:** I **Month of publication:** January 2023

DOI: https://doi.org/10.22214/ijraset.2023.48688

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue I Jan 2023- Available at www.ijraset.com

Mathematical Modelling and Kinematic Analysis of a Tendon Driven Under-Actuated Robotic Hand

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Abstract: Providing a robotic system with dexterous skills and autonomous capabilities is a key challenge in the field of humanoid robotics, particularly in areas such as industrial manufacturing, prosthetics, and orthopaedic rehabilitation. Providing such a system would be extremely useful in these areas. In order for its functionality to be fully realised, a multi-fingered robotic hand calls on a significantly higher level of actuation and transmission systems. Under actuation techniques provide the impression of being a workable solution for achieving high degrees of dexterity in robotic hands without the need for more complex mechanical design. One of the most defining characteristics of an under-actuated robotic hand is that the needed number of actuators to control the hand is fewer in number than the degree of freedom that the hand possesses. When compared to a fully actuated version of the same hand, an identical hand with under actuation offers a considerable reduction in the complexity of the control system and a large cost savings. The current study proposes the design and kinematic analysis of an anthropomorphic five-finger robotic hand. Four of the fingers and the thumb are under-actuated, and the hand has twenty-one degrees of freedom and twelve degrees of actuation.
Keywords: Dextrous, degrees of freedom, kinematics, Prosthesis, Tendon driven, under actuation

I. INTRODUCTION

Human Hand is the most modern and complex external limit on human body. The hand is a standout amongst the most intricate and load bearing part which goes about as an information i.e. material detecting and in addition yield like physical work gadgets to human. Human hands can overwhelmingly adjust to objects with self-assertive shape and size amid getting a handle on. The growing interest in the area of robotic hand development increases due to the extensive range of applications such as pick and place tasks, upper limbs prosthesis, flexible mechanization of abundant manufacturing jobs, automatic assembly duties, and works in the unstructured environment. Current industrial advancements are limited to precise grippers and tools that are insufficient when the robot must deal with the dextrous grasping of varying geometrical shape and size substances. To accomplish the above-challenged applications, accepting the design of the human hand looks to be an acceptable solution, because the hand of the human is the utmost developed and diverse external end on the human body and a millennium advancement outcome.

The TUAT/Karlsruhe hand, which was developed in the year 2021, has five fingers and twenty degrees of freedom, and it is driven by a single actuator that may either be put within or outside the hand [1]. M. H. bin Mohamed Azri and R. L. A. Shauri have recommended an investigation into the composition of the materials used in the construction of a three-fingered robot hand's structure. This paper proposes a method for analysing the robot assembly based on the robot design and the materials utilised for the various components of the robot using a technique known as finite element analysis [2] . Gosselin et al., 2008 suggested using an anthropomorphic hand that was of the under-actuated type and had 15 degrees of freedom and one actuator. The purpose of this research is to investigate whether or not it is possible to construct a multifunctional hand using only a single actuator[3].In 2010, researchers unveiled the "smart hand," an underactuated human hand with 16 degrees of freedom and 4 degrees of actuation. All four actuators in this hand's palm are hidden away among the five fingers. Thumb flexion/extension is controlled by the first actuator, index flexion/extension by the second, mdx/ring/little flexion/extension by the third, and abduction/adduction by the fourth [4]. Six degrees of freedom and six degrees of freedom of motion make the prosthetic hand known as the Vincent hand, invented in 2011, a practical option. Including the thumb, this hand has five digits, much like a human's. This hand is operated using myoelectric sensors. It features two actuators, one for thumb flexion and one for abduction/adduction drive. To be exact, there are six actuators[5]. A novel super under actuated multifingered hand (TH-2 Hand) [6] was designed in 2006 for a humanoid robot based on a previous underactuated finger mechanism. The TH-2 Hand was attached to a humanoid robot because of its high personification, super under actuation, compactness, easy real-time control, small volume, light weight, and strong grasping function.

The TUAT/Karlsruhe hand, which was designed in 2021, consists of five fingers, has twenty degrees of freedom (DOFs), and is powered by a single actuator that may be positioned either inside or outside the hand [7]. A multi-sensory, five-fingered bio-prosthetic hand is what the HIT/DLR hand, a type of prosthetic hand, is all about. Comparable to the hand of the adult. It contains 13 joints, and the thumb, index finger, and each of the remaining three fingers are controlled by three motors individually [8]. RBO Hand-2 is an innovative design of highly biddable, underactuated, robust, and nimble anthropomorphic hand that was presented in the year 2016. In accordance with the comprehensive Feix taxonomy, the hand is capable of performing 31 of the human hand's 33 different grip deportments [9]. A Super under-actuated multi-fingered TH-3R hand that is self-adaptive and features a gear and rack mechanism together with spring limitations has been presented. This hand is made up of fingers that each have a number between one and five, and it has a total of fifteen degrees of freedom [10].Anthropomorphic underactuated hand IH2 AZZURRA series has five fingers, or four fingers and a thumb. The fingers on this hand can be stiffened manually and automatically wrap around items. This hand has an adjustable Bowden cable transmission mechanism and is tendon-actuated. [11]. The ADAM'S hand, a highly underactuated prosthetic device with just one actuator controlling all five fingers, was created in 2017. This hand resembles a human palm in that its five fingers are attached to a stationary frame through revolute joints. This hand has an adaptive transmission mechanism[12]. In 2016, Konnaris et al. proposed a tendon-driven robot hand that uses seven motors to roll an object held in the hand [13]. Gopura et al., 2020 suggested a prosthetic hand with many functionalities. This paper offers a MORA Hap-2 hand capable of self-adaptation. The user can grab numerous things with this hand by executing cylindrical grasping, hook grasping, lateral pinching, tip pinching, and palmar pinching [13] .G. Mode and C. Hand proposed the COSA-DTS hand in 2010, which is a Unique Coupled and Self-adaptive Under-actuated one. This hand's fingers grab items utilising a specific COSA grasping mode that consists of two processes: a connected grasping approach and a self-adaptive grasping process [14].Odhner and Dollar proposed employing underactuated fingers to grip and manipulate small objects from flat surfaces [15]. Hussain et al., 2018 proposed an analytical modelling of flexure joints based on screw theory[16]. Roa et al. (2012) presented power grasp planning for humanoid robot hands. In order to implement plans inspired by human grasping schedules, the author presented a methodology for estimating power grasps for hands with kinematic structure similar to the human hand[17].

A. Bicchi and V. Kumar conducted a literature analysis on robotic grasping and the work that has been done in this field over the course of the past two decades. There was a modest emphasis placed on the development of the theoretical outline and analytical results in this part of the review [18]. A study of object grabbing, the development of a theory of pushing that takes friction into account, and the application of these ideas to the automatic planning of grasping tasks are provided [19] .This article provides a concise account of the development of robot hands as well as the current state of the art in this field. The survey focuses on three different kinds of functional needs that a machine hand in an artificial system might be able to recognize.[20]. Liang et al. (2015) proposed a unique PASA Finger consisting of Parallel and Self-adaptive Fingers with fewer motors and pinching and enveloping-type grasping [21] . Sarac et al. [22] describe a unique under-actuated hand along with its design and kinematic optimization. Saliba et al., 2016 anticipated a mechatronics quasi-dynamic analysis, design optimization, and evaluation of a two-fingered under-actuated hand[23]. Groenewegen et al., 2015, specified the design of a somewhat compliant, three-Phalanx, under-actuated prosthetic finger[24]. Anthropomorphism indices of the kinematic chain for artificial hands were described in [25] in which three different anthropomorphism indices were employed to compare the kinematic chain of artificial hands to a human hand. Dunai et al., 2021 provide a detailed account of the construction of a prosthetic hand based on the concept of human hand structure[26]. Weiner et al., 2018 developed a unique 3D-printed prosthetic hand with five fingers and a mechanism that is under-actuated [27] . Maat et al. (2017) provide a description of passive prosthetic hand in which the author focuses on the type of user of the prosthetic hand, their usage, functionality, and challenges with everyday activities[28]. Kontoudis et al.,2009 proposed that the actuation mechanism driven by tendon attains both flexion/extension movement and adduction/abduction movement on the finger's metatarsophalangeal joint using two numbers of motors [29]. Li. et al.,2021 proposed a robotic hand named UCAS which is an Underactuated one and is of Powered Hand Exoskeleton used for grasp assistance [30]. Hong et al.,2019 proposed KULEX-hand, an exoskeleton for grasping and providing powerful support for patients having a partway paralyzed hand or the elderly with weakened muscle strength [31]. A fully actuated system is one where the number of actuators is equal to the degrees of freedom. This allows for more precise control and a larger sequence of joint angles. For example, a human can rotate any finger at the proximal link ("middle" joint of the finger) without rotation occurring at the carpal link. This allows for both power and precision grasps[32]. Gosselin et al., 2008 proposed an anthropomorphic hand of under actuated type having 15 dofs and one actuator. The objective of this work is to investigate the possibility of building a versatile hand with one single actuator. Author aims to thrust the concept of underactuation to its limit in order to assess its applicability in humanoid robotics. The force transmission analysis and optimization of the fingers is presented. differential mechanisms are introduced in order to produce the under actuation between the fingers [33].

The SARAH(Self Adaptive Robotic Auxiliary Hand)[34] intended for space applications which consists of three fingers 10 DoF, 2 DoA .The undractuation in this hand is accomplished by differential mechanism. Soft gripper has a singular type of gripping mechanism which has relatively simple control mechanisms and can softly and gently conform to objects of any shape and hold them with uniform pressure[35]. Meka H2 is a 12-DOF, 5-DOA compliant four finger hand (the little finger is eliminated). There is 1 actuator per each finger and another one for the thumb abduction/adduction movement (total 5 actuators) [36].

Keeping in view of this the present work deals with the modelling of a hand with five fingers approximately as the size of the human hand. The modelled robotic hand is an underactuated one in which the flexion/extension motion of the four fingers are done by individual motors and the abduction/adduction motion of the four fingers are done by individual motors. So a total of 8 actuators are used for four fingers. The thumb comprises of 5 motors for the motion. As a whole the underactuated robotic hand consists of 21 degrees of freedom with a total of 13 motors. The modelled hand is designed to grasp various shaped object.

II. MODELLING AND ANALYSIS

A Human hand has 23 DOF that is given by 17 joints [37]. The closest phalange to the hand body is called proximal phalange and the one toward the finish of the each finger is called distal phalange. The joints of the finger includes the distal inter phalangeal (DIP) and proximal interphalangeal (PIP) joints and have 1 DOF each. The metatarsophalangeal (MCP) joint has 2 DOF attributable to both abduction/adduction and flexion /extension movement. Thumb is the most complex physical structure among the hand fingers and unique in relation to the fingers in that contains just two phalanges and has 5 DOF[38].The structure of the human hand is presented in figure.1.

Fig. 1: Structure of the human hand

In the thumb the flexion/extension motion of the IP is under actuated. Flexion/Extension and abduction/adduction motion of MCP is done by 2 motors. Flexion/extension and abduction/adduction motion of CMC is also done by 2 motors. The joints of a single finger with all the phalanges are presented in figure.2.

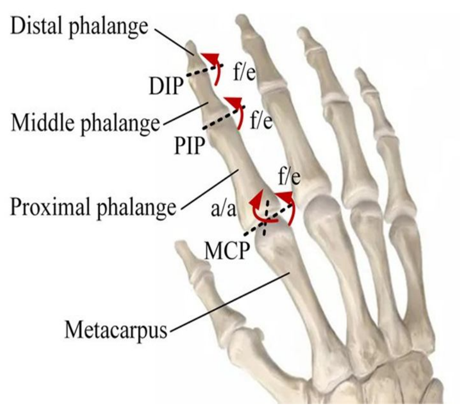

Fig. 2: Structure of the human hand

III. MODEL OF THE HAND

The proposed hand model has fifteen (15) joints, twenty one (21) DOF and twelve (12) numbers of actuators. In the present work the flexion/extension of the DIP and PIP of the four fingers i.e. index, middle, little and ring finger have been taken as under actuated. The flexion/extension and the abduction/ adduction motion of MCP joints of index, middle, ring and little fingers are operated by two separate motors. The details of the hand model with phalanx, no of joints, degrees of freedom of individual fingers are shown in figure 3.

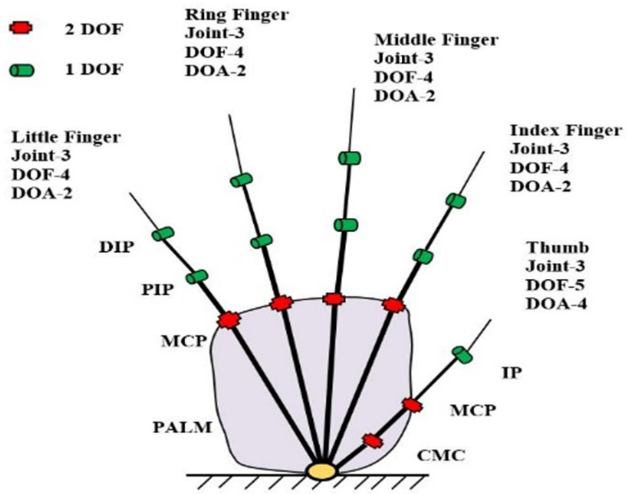

Fig.3: Model of the hand

Tendon pathways have been designed so that tendons envelope on curved surfaces with constant radius along the entire joints movement range, leading to a linear relation between tendon and joint displacements. Referring to figure-4 a single tendon is used in a single finger which can be used for the flexion /extension of the phalanges. The original position of the finger can be achieved by the springs present at the joints which are responsible for the contraction of the fingers.

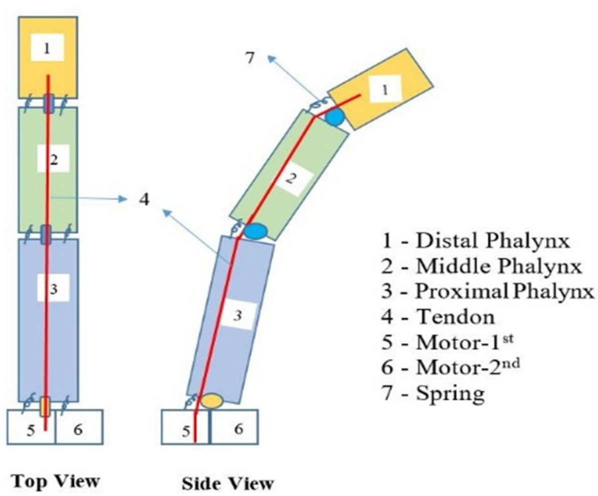

Fig. 4: model of the finger with tendon and pulley

The finger of the hand is considered as a single manipulator. Each manipulator is having 3 phalanges. The flexion and extension of the finger is accomplished by the tendon and pulley arrangement. The pulleys are mounted on the axis joining the two phalanges of the fingers. The pulleys area so arranged that it can freely rotate about the axis. Referring to the figure 5 three pulleys are mounted on the axes at points o_1, o_2 and o_3 respectively.

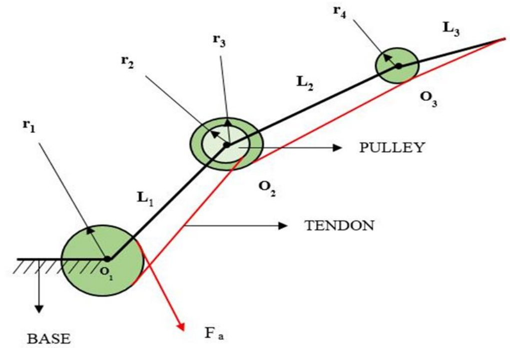

Fig. 5: Tendon and pulley arrangement

IV. KINEMATIC ANALYSIS

The Denavit-Hartenberg (DH) system for defining serial-link mechanism geometry has been considered as an essential tool for robotics design and analysis. By using the DH parameters, the kinematic solutions, planning of motion, dynamics, Jacobian and simulation can easily be find out [39]. The DH parameters comprise two link parameters and two joint parameters. The Link parameters include link length as well as link twist, whereas the joint parameters comprise the joint angles and the joint distances. After finding out the DH parameters for individual finger the transformation matrix can be utilised for transmitting the co-ordinate system between two adjacent joints. The transformation matrix can be written as follows in equation.1.

$$T_i^{i-1} = \begin{bmatrix} \cos\delta_i & -\sin\delta_i \cos\lambda_i & \sin\delta_i \sin\lambda_i & a_i \cos\delta_i \\ \sin\delta_i & \cos\delta_i \cos\lambda_i & -\cos\delta_i \sin\lambda_i & a_i \sin\delta_i \\ 0 & \sin\lambda_i & \cos\lambda_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The transformation from base frame to number of links n is

$$T_n^0 = \left[T_1^0 T_2^1 T_3^2 T_4^3 \ldots\ldots T_n^{n-1}\right] \quad (2)$$

The trajectory of the tip of the fingers in x and y coordinates are as presented in equation 3 and 4.

$$XL = L_1 Sin\beta_1 + L_2 Sin(\beta_1 + \beta_2) + L_3 Sin(\beta_1 + \beta_2 + \beta_3) \quad (3)$$

$$YL = L_1 \cos\beta_1 + L_2 \cos(\beta_1 + \beta_2) + L_3 \cos(\beta_1 + \beta_2 + \beta_3) \quad (4)$$

The finger is constituted by a 4-DOF mechanical structure, whose kinematics considering the fingertip position as end-point is described by the Denavit-Hartenberg parameters summarized. DH parameter of the Thumb is presented in table-1below.

Table 1: DH Parameter of thumb

JOINT	JOINT NAME	MOTION	θ_i	d_i	a_i	α_i
1	CMC	AB/AD	q_1	0	0	-90
2	CMC	EX/FL	q_2	0	4.6	90
3	MCP	AB/AD	q_3	0	0	-90
4	MCP	EX/FL	q_4	0	3.6	90
5	IP	EX/FL	q_5	0	3.0	-90

DH parameter of the Index finger is presented in table-2 below where all the links and joint parameters are presented.

Table 2: DH Parameter of index finger

JOINT	JOINT NAME	MOTION	θ_i	d_i	a_i	α_i
1	MCP	AB/AD	q_6	0	0	-90
2	MCP	EX/FL	q_7	0	5	0
3	PIP	EX/FL	q_8	0	2.6	0
4	DIP	EX/FL	q_9	0	1.8	0

DH parameter of the middle finger is presented in table-3 below where all the links and joint parameters are presented.

Table 3: DH Parameter of middle finger

JOINT	JOINT NAME	MOTION	θ_i	d_i	a_i	α_i
1	MCP	AB/AD	q_{10}	0	0	-90
2	MCP	EX/FL	q_{11}	0	5.2	0
3	PIP	EX/FL	q_{12}	0	3.2	0
4	DIP	EX/FL	q_{13}	0	2.0	0

DH parameter of the Ring finger is presented in table-4 below where all the links and joint parameters are presented.

Table 4: DH Parameter of Ring finger

JOINT	JOINT NAME	MOTION	θ_i	d_i	a_i	α_i
1	MCP	AB/AD	q_{14}	0	0	-90
2	MCP	EX/FL	q_{15}	0	5.0	0
3	PIP	EX/FL	q_{16}	0	3.0	0
4	DIP	EX/FL	q_{17}	0	2.0	0

DH parameter of the Little finger is presented in table-5 below where all the links and joint parameters are presented.

Table 5: DH Parameter of Little finger

JOINT	JOINT NAME	MOTION	θ_i	d_i	a_i	α_i
1	MCP	AB/AD	q_{18}	0	0	-90
2	MCP	EX/FL	q_{19}	0	3.8	0
3	PIP	EX/FL	q_{20}	0	2.2	0
4	DIP	EX/FL	q_{21}	0	1.7	0

V. TRAJECTORY AND WORK SPACE

The trajectory of the tip of all the fingers represents the path that the fingertip travels during grasping of a object. The workspace of a robot is the indication of the accessible configuration of an endeffector.it is the total volume covered by the reachable space of the end-effector. The workspace is determined by the manipulator's geometry and the joint motions' constraints. In robotics, a robot manipulator's workspace is normally defined as the set of locations that its end-effector can touch, or, in other words, the space in which the robot operates, which can be either a 3D space or a 2D surface. The range of motion of a robot is its work envelope. When a manipulator stretches forward, backward, up, and down, it creates this shape. The length of arm of a robot and the configuration of its axes dictate these distances. Each axis subsidizes a range of motion of its own.

VI. RESULT AND ANALYSIS

In the MATLAB environment, the analysis of the robotic hand was performed, and the following results were discovered. The length and the breadth of the modelled hand are 162mm and 64mm, respectively, in this model. Positions of finger tips of all the fingers are plotted as follows. The fingertip trajectory of the thumb is shown in fig.6 below. The trajectory of the tip of the index finger is presented in figure.7 below.

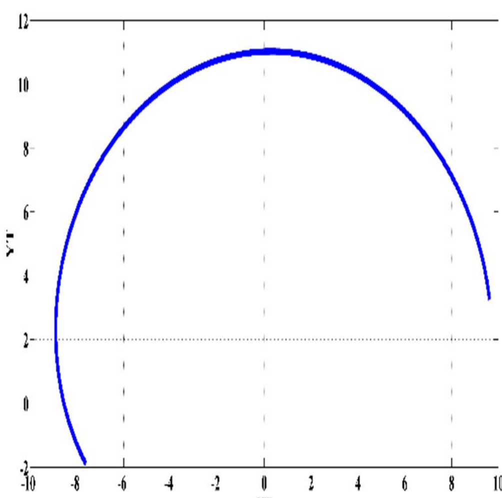

Fig. 6: trajectory of tip of thumb

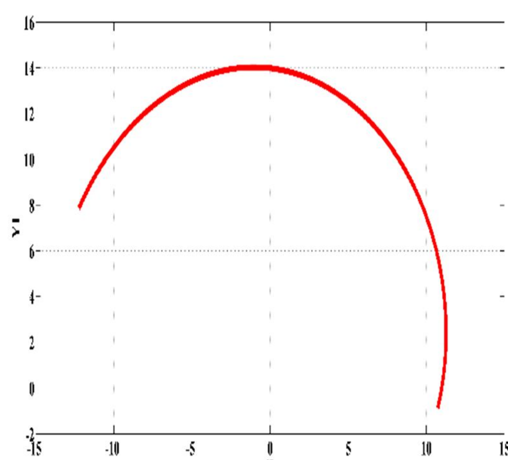

Fig. 7: trajectory of tip of index finger

The trajectory of the tip of the middle finger is presented in figure.8 below. The trajectory of the tip of the ring finger is presented in figure.9 below.

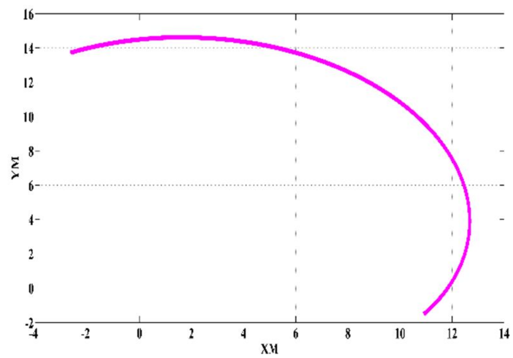

Fig. 8: trajectory of tip of middle finger

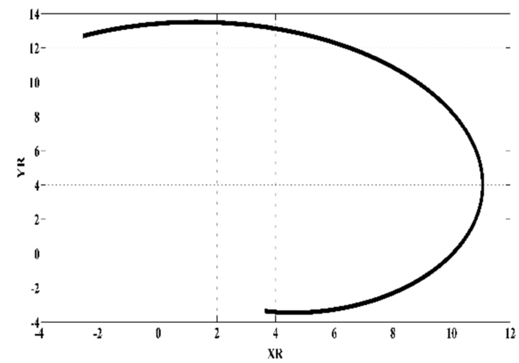

Fig. 9: trajectory of tip of ring finger

The trajectory of the tip of the little finger is presented in figure.10 below.

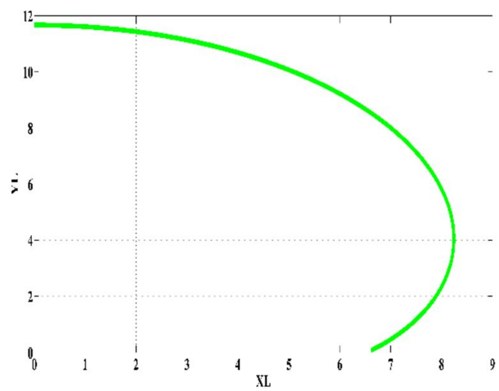

Fig. 10: trajectory of tip of little finger

Work space is obtained by referring Monte Carlo method taking sample size of 4000 in MATLAB environment. The workspace of four fingers and thumb are displayed .The isometric view of the thumb is presented in fig.11 below. The isometric view of the index finger is presented in figure 12 below.

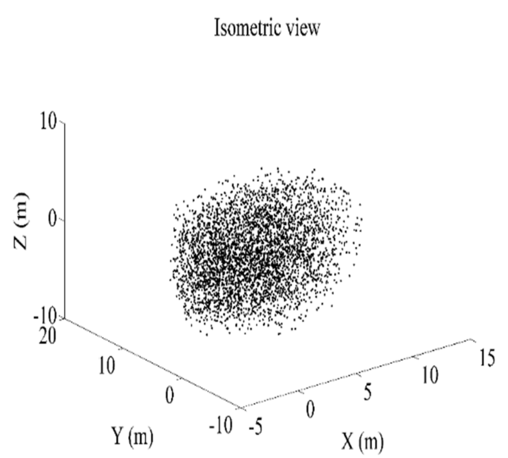

Fig. 11: Work space of thumb- isometric view

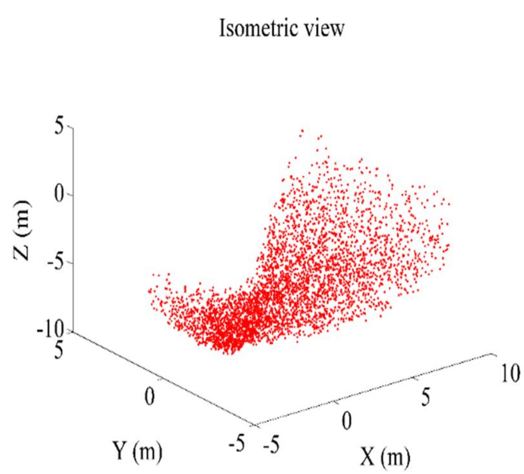

Fig. 12: Work space of Index finger- isometric view

The isometric view of the middle finger is presented in figure 13 below. The isometric view of the ring finger is presented in figure 14 below.

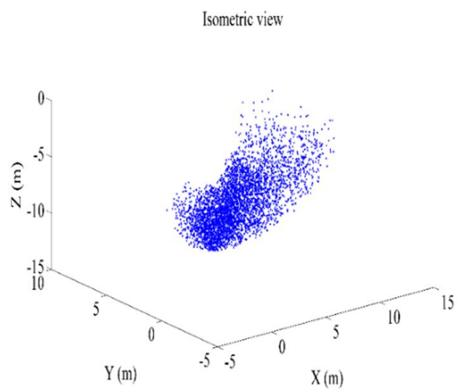

Fig. 13: Work space of middle finger- isometric view

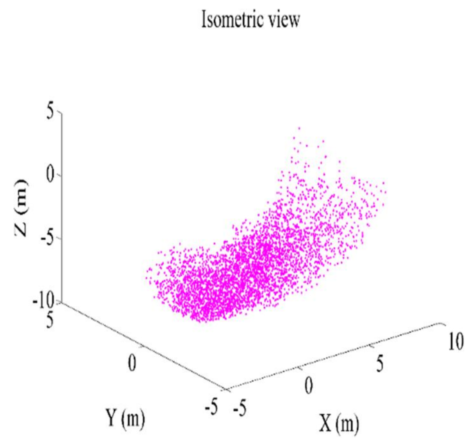

Fig. 14: Work space of ring finger- isometric view

The isometric view of the little finger is presented in figure 15 below.

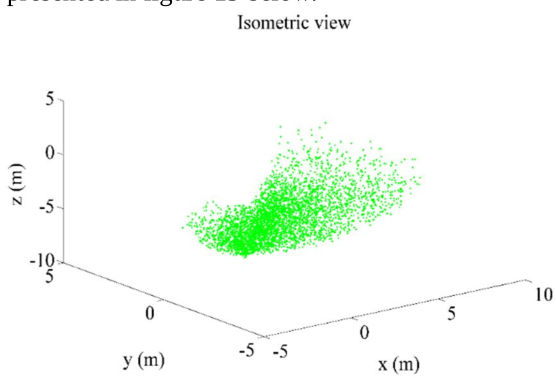

Fig. 15: Work space of Little finger- isometric view

VII. CONCLUSION

In the current work, a robotic hand with dimensions that are anthropomorphic that is, similar to those of a human hand is proposed. The thumb and the first four fingers are taken with under actuation. The arrangement of tendon and pulleys performs the under actuation procedure. The primary function of the hand's design is to enable a strong hold of varied item kinds. Shape adaptability is the motivation underlying under actuation, which is a simpler goal. The proposed hand has 12 degrees of actuation and 21 degrees of movability built into its design. The analysis is then performed using the thumb and finger Denavit Hartenberg parameters. The kinematic analysis is done on the MATLAB environment. Joint distances, phalangeal length, and workspace for all the fingers were all plotted by using various joint angles within the range. The four fingers' and the thumb's finger tip trajectories and workspace is discovered to be within the acceptable range.

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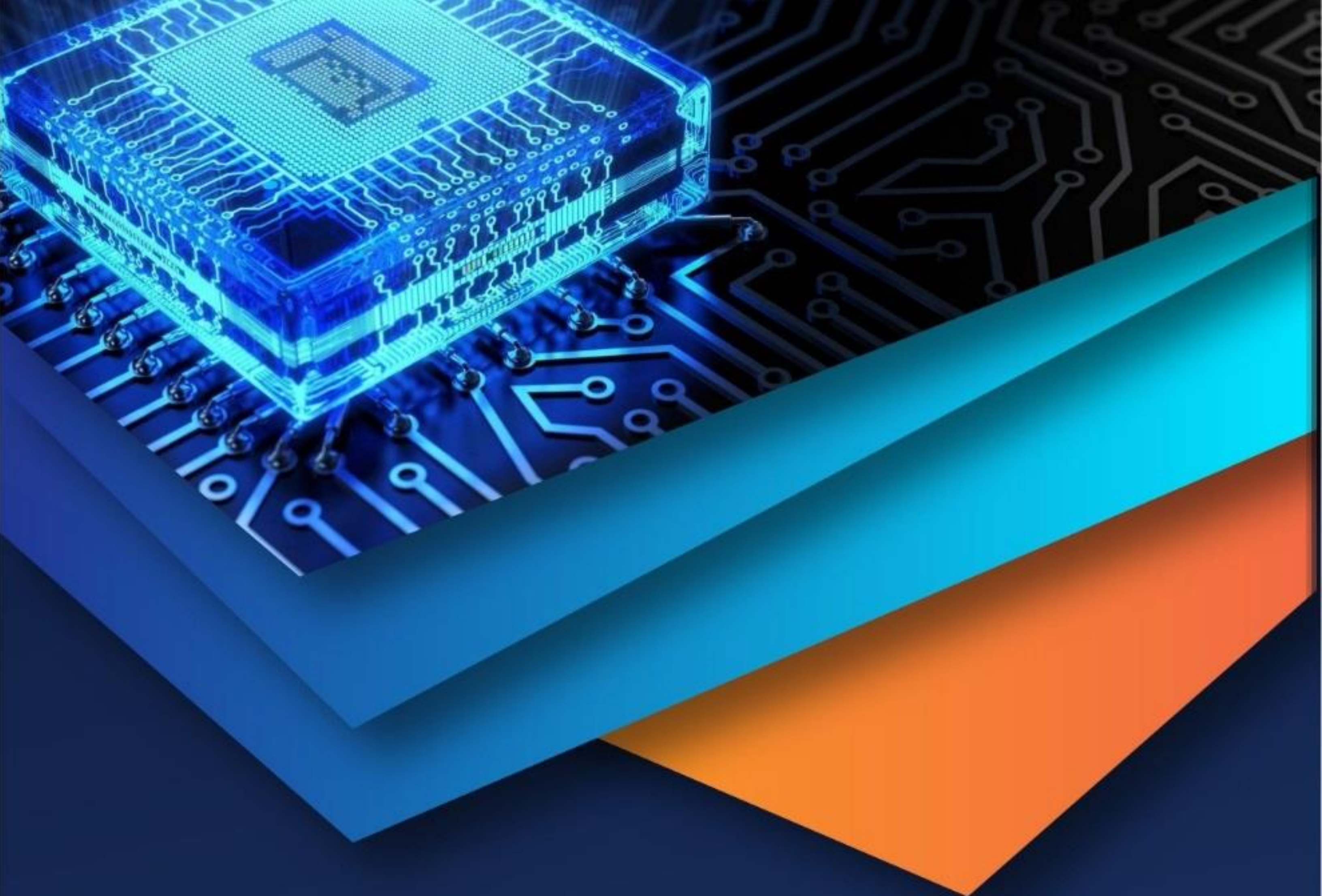

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