

UTHM Hand: Modelling and Simulation of Dexterous Anthropomorphic Hand

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Abstract—Human hands are a critical part of human body. This paper describes a multi fingered dexterous anthropomorphic hand, developed by the authors. The focus of the hand is the replacement of human operators in hazardous environments and also in environments where zero tolerance is observed for the human errors. The robotic hand will comprise of five fingers (four fingers and one thumb) each having four degrees of freedom (DOF) which can perform flexion, extension, abduction, adduction and also circumduction. For the actuation purpose pneumatic muscles and springs will be used. The robotic hand will be controlled by a specially designed glove, which the human operator will wear. The glove is embedded with multiple BendSensors to track the movement of all the joint of the operator's hand. The paper exemplifies the mathematical modelling and simulation for the robotic hand.

Keywords—Robotic hand, Multi-fingered hand, dextrous hand, anthropomorphic hand, pneumatic muscles.

I. INTRODUCTION

Robots have become an integral part of modern human life. With every passing year the population of robots are being increased. The industry has replaced a large number of human workers with lesser number of robots on the grounds of economy and efficiency. A robot is a modern version of slave, which perform any task in its capacity satisfying the old human instinct to rule. A robot follows the command as ordered by the human master. Therefore the humans can still enjoy mastering a thoughtless, speechless but efficient slave under their authority.

Hands have been thought of being the key to the intelligence of humans. Aristotle and Anaxagoras had been discussing this matter hundreds of years ago [1]. Among all the creatures inhabiting this earth, humans are the only living being that have been gifted with this kind of hands. These hands are capable of doing many tasks in our daily routine like dexterously handling different things and even sensing. Human hand has been an area of interest and research since the advent of intellect and has been considered to be one of the reasons that human intelligence is superior to all living creature on Earth. It has been confirmed by the several findings of paleoanthropologists, showing that the mechanical dexterity of the human hand has been a major factor in allowing Homo sapiens to develop a superior brain.

Our hands are the most complicated and delicate part of our bodies, which consist of fifty four bones in a variety of size and hold the capacity to perform a great range of tasks [1]. The research on humanoid robotic hand has been developed for the past few decades which range from the simplest design of parallel jaw grippers to complex configurations of dexterous multi-fingered hands.

The need for the robotic hand is increasing day by day as more and more automation is being introduced in industry. The industrial losses involving human errors are being tried to get rid off by using robotic hands in manipulation of delicate things and repetitive assembling tasks both for accuracy and speed of work. The risk of human operator working in hazardous environments is also being removed by introducing use of robotic hands in space, high radiation environments, metal melting industry, chemical industry, cutting industry, automobile industry and the list goes on with different types of environments.

In order to match the needs of industry and knowledge exploration, the research in the field of robotics was started long ago and has been going on for many decades now. Researchers and developers have been trying harder getting closer to the characteristics of human hand. The artificial hands made can be stronger and faster than the human hand but only in some specific tasks; the performance of human hand is by far greater than these artificial hands if a broad scope of manipulation tasks is considered [3]. The robotic hands have evolved from the very basic two fingered design for gripping to fully anthropomorphic robot hands that can perform a very good grasp. Grasping is one of the major topic in the field of robotic hands. Researchers have been using different techniques in order to strive for better grasping.

The authors has developed a robotic hand that can be used anywhere as a human replacement. The robotic hand is dexterous as well as anthropomorphic as it can perform dexterous movements like human and is similar in size and shape to human hand. The complete system should be able to fix the reprogramming issue and reduce the human injuries in extreme environments.

II. LITERATURE REVIEW

There has been much research conducted on robotic hands. The history of robotic hands can be dated back to 1961 when

Heinrich Ernst develops the MH-1 a computer operated mechanical hand at MIT [4]. This hand was also a gripper that used two fingers to pick and could hold some blocks using electric motors as actuators and touch sensors for the object identification.

Grippers are very application specific so they don't try to mimic the actual human hand. Mostly the finger count is two or three summing to a low DOF which causes the robot hand unable to act dextrously. Theoretically the least number of degrees of freedom to achieve dexterity in a robotic hand with rigid, hard-finger, non-rolling and non-sliding contacts, is nine [5]. The proof for this theory was the development of Stanford/JPL hand.

Many research works had been done on grippers [6], [7], [8], [9] and many companies started production for grippers. Universities, automotive companies, other industries and even space programs for some countries are involved in buying these grippers. The concentrated research work for grippers was done in 1980s and early in the decade of 1990 the idea for gripper robotic hands was well established.

The development of MIT/UTAH hand [10] was the beginning of more complex robotic hand structures. This hand was capable of dextrously manipulating objects. It had four fingers and over twenty five DOF including the wrist joint. Much research work has been done in dextrous manipulation done by robotic hands and highly manoeuvrable and anthropomorphic hands have been reported. By anthropomorphic we mean to be same as human in all aspects like number of fingers, size, shape and the ability for flexible movement to perform humanly tasks like grasping. Compared to the grippers, the anthropomorphic hands are much more complex as they require increased number of actuators and more limitations on size and shape. With the passage of time, the complexity has been increasing as researchers are unfolding more and more dextrous capabilities of human hand. But still no robotic hand has been able to stand the actual human hand in a wide spectrum of tasks because of the difference of toolbox of nature and researchers. A much detailed study on the robotic hands performing dextrous manipulation can be seen in [3].

Electric motors are most commonly used choice for the artificialists in order to move the joints [11], [12], [13], [14]. Electric motors have been proved to be very accurate in position and velocity control and also provide much force for the grasping function achieved by the robotic hand. The use of electric motor also simplifies the mechanical design of the hand. Also when using electric motors different approaches has been seen where some attaching the motors directly to the joints avoiding the extra mechanics involved, some using tendon cables with motors, some using tendons and pneumatic actuators, some using gearing with motors and some others are the hybrid of these approaches.

By using the tendon cables with electric motors the overall structure of the robotic hand is simplified. They are very low in mass and can provide stiff transmission of energy. But with using tendon cable there are some problems as well like the elasticity issues that causes inaccurate angle control for the joint. Another big problem with using tendon cables is pulleys

as pulleys occupy much space and cause difficulty in routing the tendon cables.

The MIT/UTAH hand had three fingers and one thumb [10]. They removed the little finger to avoid complexity in their dextrous robotic hand. Each finger had four DOF and four joints, three for the flexion and extension and the fourth one for abduction and adduction. Each joint is separately controlled by a pair of tendon cables so total eight cables are routed for each finger. Pneumatic actuators were used for the finger movements.

NASA's Robonaut Hand had twelve DOF and five fingers like human hand [15]. But the DOF varies through the fingers as the fingers are grouped in two sections namely dextrous and grasping fingers. The dextrous fingers (index and middle) and thumb had three DOF each while the ring and pinkie with one DOF and one palm DOF were used for grasping. Brushless DC motors and gear head were used for the finger actuation. The motors were placed outside the hand for keeping the size of hand small. The mechanical design for these fingers was very complex but very well planned to match the size of an astronaut glove. The geometry of the components was extremely complex so putting them altogether inside was much difficult task.

The anthropomorphic NTU hand had seventeen DOF with five fingers and was comparable to the size of human hand [16]. The thumb and index finger had four joints each and can perform all the actions as the dextrous human fingers while the other three fingers had three joint each and are not able to perform abduction and adduction. This hand had very complex gearing involved in its fingers as it had a special set of arranged gear trains present in for every joint along with a smart motor that was performing the joint actuation.

The DIST-Hand was developed with sixteen DOF and high level of dexterity [17]. It had four fingers actuated by tendon drive and DC motors. The tendon cable needed pulleys which caused friction so in order to reduce the friction a combination of pulley and ball bearings was used. The DLR-Hand also used dc motors with transmission tooth belt and harmonic drive gears [18]. This hand had thirteen DOF with three fingers and a thumb.

Compact fluidic hand had been developed and reported with fourteen DOF [19]. The hand is powered by fluidic actuators and a miniaturized hydraulic system was developed to be embedded inside the robot hand. The hand is reported to be anthropomorphic and dextrous with purely mechanical actuation system. But the strength of the grasp achieved is small.

The Keio hand had been developed having twenty DOF almost the same as human hand [20]. It is reported to be dextrous and anthropomorphic as the size of hand is same as that of a grown up human. This hand has been actuated uniquely using ultra-sonic motors along with elastic elements. Another unique design using spring as actuating element has been reported [21]. The said robot had three fingers and was reported achieve very high acceleration. This robot was reported for capturing purposes.

III. MATHEMATICAL MODEL

A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modelling. The goal from the mathematical modelling is to model the robotic hand when it is given an input angle. Therefore the model of complete hand will have 20 joints and all of these 20 joints have similar model. This model involves angular motion as all the movements are performed by pin joint links. The mathematical modelling for a system to reach the response of the system is as follows;

- Create free body diagram
- Generate differential equation to model the system
- Transform the equation into transfer function
- Get the step response of the system

Free body diagram

Each of the finger's joint is a pin joint which allows the finger segments to move around the joint. The finger joints are kept at the default position with the help of springs which oppose the flexion movement of the finger. The flexion movement is performed by the finger segment when a force is applied by the pneumatic muscle. The force is caused due to the contraction of pneumatic muscle. The free body diagram which shows the model of the joint system (which is the plant in this case) is shown in Figure 1. The output of the system is the movement performed by the finger which is measured as an angle. The input to the plant is the force from the muscle while the output is the angle θ_o .

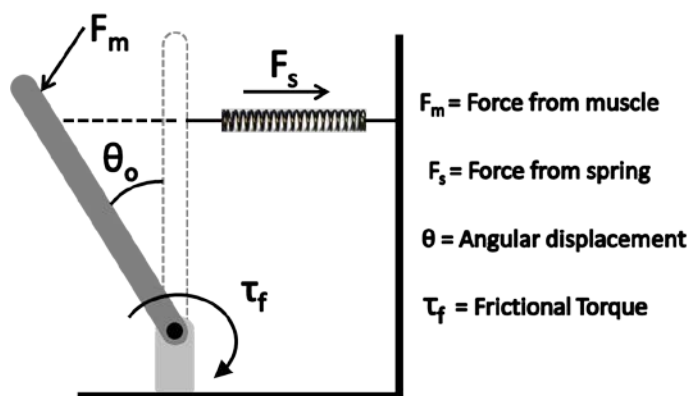


Figure 1 Free Body Diagram of the Plant

Differential Equation

The force of muscle is linear to the angle required to move. The input angle is translated into the pressure inside the pneumatic muscle, which in terms is related to length shrinkage of the muscle. The length shrinkage will pull the tendon string that will result in robotic joint movement, which is calculated by measured angle. Therefore

$$F_m = k_m \theta_i$$

Here k_m is the conversion constant from input angle and force from muscle. The force of spring is calculated according to Hooke's law which states

$$F_s = k_s x$$

k_s is the spring constant and x is the displacement of spring from rest position. In this case the displacement is angular displacement θ which is given by

$$x = l\theta_o$$

Here l is the length of force of spring from the joint. Therefore the force of springs becomes

$$F_s = k_s l \theta_o$$

As the forces acting on the plant create turning effects of force therefore the calculation for torques due to these forces is required. Let r be the length of force of muscle from the joint.

$$\tau_m = F_m \cdot r$$

$$\tau_s = F_s \cdot l$$

$$\tau_s = k_s l \theta_o \cdot l$$

$$\tau_s = k_s l^2 \theta_o$$

The pin joint also has some frictional value which should be taken into account as well, therefore

$$\tau_f = B\omega$$

$$\tau_f = B\dot{\theta}_o$$

Here B is the frictional constant. The D'Alembert's law says that the sum of all the torques is equal to the inertial torque.

$$\sum \tau = J\dot{\omega}$$

Here J is the moment of inertia and $\dot{\omega}$ is the angular acceleration. The moment of inertia for a rod of length L and mass m (Axis of rotation at the end of the rod) is given as [45]

$$J = \frac{mL^2}{3}$$

Therefore the inertial torque becomes

$$\text{Inertial torque} = \frac{mL^2}{3} * \ddot{\theta}_o$$

The torque produced due to the muscle is counter clock wise and taken as positive while the torque produced due to the spring is clock wise and taken as negative.

$$\sum \tau = J\dot{\omega}$$

$$\tau_m - \tau_s - \tau_f = J\dot{\omega}$$

$$F_m \cdot r - k_s l^2 \theta_o - B\dot{\theta}_o = \frac{mL^2}{3} * \ddot{\theta}_o$$

$\ddot{\theta}_o$ is the angular acceleration and is the second derivative of angular displacement. This equation gives the relationship between the input F_m and output θ_o .

Transfer Function

The transfer function of the plant can be derived from the differential equations relating the input and output of the plant. Usually the Laplace Transform of the differential equation is

taken to acquire the transfer function. The Laplace transform for the equation computed earlier will be

$$F_m(s).r - k_s l^2 \theta_o(s) - Bs \theta_o(s) = \frac{mL^2}{3} * \theta_o(s) * s^2$$

Simplifying the equation becomes

$$\frac{\theta_o(s)}{F_m(s)} = \frac{3r}{mL^2 s^2 + Bs + 3k_s l^2}$$

Constant Parameters

In the equations mentioned above there are certain constants that should be taken care of before the modelling can be proceeded to simulation.

The first constant to be considered is the contact of conversion for force from muscle. The input angle that will be received from the master to slave is the input angle and depending on the value of this angle the force from the muscle will be generated. The input angle will cause air to flow into the pneumatic muscle due to which the muscle will be inflated and hence the length of the muscle will be shortened. This shrinkage in length of the muscle will pull the tendon string that will be tied between muscle and corresponding finger segment. This pull will cause the finger segment to bend to the required angle. This complete actuation system is completely linear. Hence the higher the input angle the greater will be the force. The range of the angle of the finger joints will be from 0° to 120° . Considering this range of input angle, the value of conversion constant k_m is set as 3.

The spring that will be used in the system will be moderate. The spring will be used to bring back the finger segment to the default position. The finger parts will be made from a lighter material therefore it will not require a big pull to return them to original position. If the spring that is used is very hard then it will require the muscle to exert extra force such that the muscle will need to overcome the force from spring before it start moving the finger segment. Therefore we choose a spring constant for a medium range spring which not too hard such that it will waste the force neither it is too light such that it cannot even pull the finger segment. Therefore the value is taken to be as 10.

The frictional torque in the system can be neglected as it will be very small value but still in order to maintain the effect of the friction, the value can be taken as a small value. This frictional torque will always be opposite to the direction of motion. The value taken in this case is 0.3.

The physical attributes of the system are $l = 18.5mm$, $L = 26.4mm$, $r = 16.3mm$ and $m = 100gm$.

Sensor Gain/Model

The sensor that will be used in the system is sensitive to the bend angle. It will be a resistor that will change its value linearly over the value of bend angle. This sensor will be used in the master and slave both modules. The angle that can be measured in degrees is converted to analog voltage by using the sensor in voltage divider configuration. This analog voltage has to be digitized in order to be processed by the controller. This process is done by using analog to digital convertor (ADC).

The ADC's result is a digital value that can be called digital angle as shown in Figure 2.

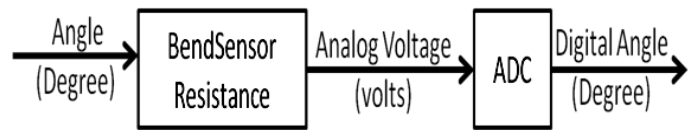


Figure 2 Sensor Model

Consider using a 12-bit ADC the maximum digital angle can be 4096, while the maximum joint angle can be 120° . Assuming the circuit is biased in a condition that the input angle of 120° gives the output digital value of 3600. By using this assumption and electronic circuit biasing the sensor gain equal 30, the model becomes as in Figure 3.

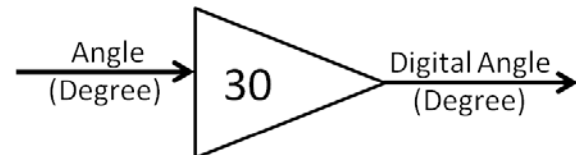


Figure 3 Sensor Model Simplified

The equivalent model shows that the sensor can be modelled as a gain in the system when converting the angle to digital angle.

Step Response

To get the step response of the system the MATLAB Simulink toolbox was used. The values have been added in the design of MATLAB model as shown in Figure 4.

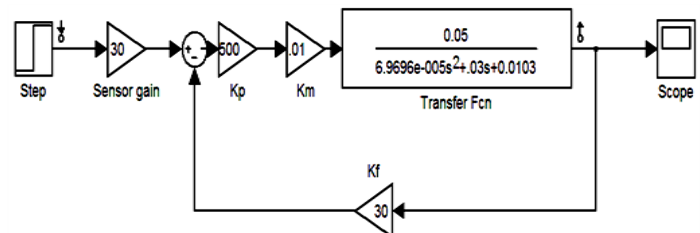


Figure 4 System Model using Transfer Function in MATLAB

The step response of the system with $k_p = 500$ is shown in Figure 5. The step response of the plant has an overshoot of 6.35%. The settling time has been computed by taking $\pm 1\%$ as the error band. The magnitude of the input step was 90° .

Ramp Response

By using the same system as shown in Figure 4, the ramp response of the system is shown in Figure 6. The yellow is output while pink in input ramp. The slope of the input ramp signal is 99° , which means it can reach the value of 99° in 1 second.

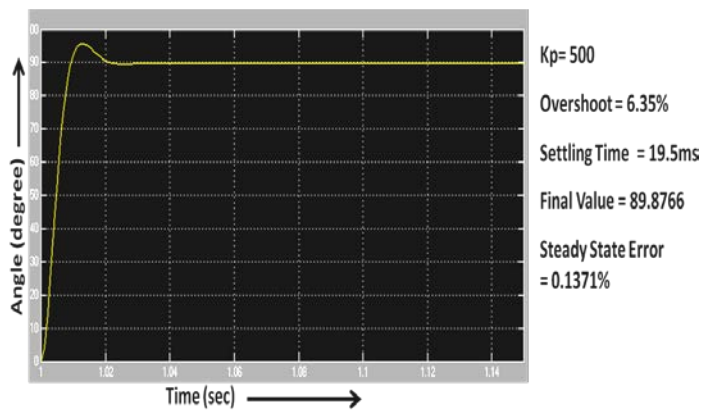


Figure 5 Step Response of system with $K_p = 500$

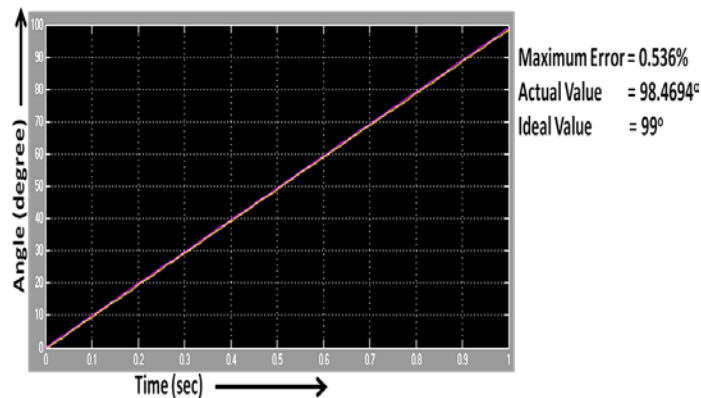


Figure 6 Ramp Response of system

The maximum error that was observed in the system is when the ramp value reaches 99° . The actual system value lags behind the ideal ramp value by a difference of 0.5306° with a percentage of 0.536%.

Using the measurements from the mechanical design [22] in SolidWorks software, the torque's components are shown in Figure 7. Only the perpendicular component of the force is responsible for magnitude of the torque produced. A greater value of torque can be produced by a greater value of angle θ . The details of the torque modelling can be found in [23].

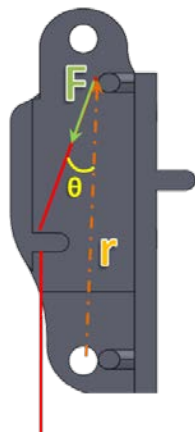


Figure 7 Ramp Response of system

In this project the tendon strings pull the finger segments of the robotic hand at an angle θ . The line in the red show the tendon string placed in the finger segment that is pulled by the pneumatic muscle. The direction of force on finger segment, when the tendon is pulled, is shown in Figure 7.

The maximum force that can be achieved from the pneumatic muscle is calculated by the weight of load lifted at 3.5 bars. The pneumatic muscle is capable of lifting 3kg at a pressure of 3.5 bars. Force is given as

$$f = ma$$

When lifting the load the acceleration is equal to gravitational pull g . Therefore

$$f = mg$$

$$f = 3 \times 9.8 = 29.4N$$

This is the force exerted by the pneumatic muscle. The force actually applied at the finger segment is subjected to tendon tension and the frictional forces faced by the tendon. By ignoring these factors the force applied at the finger segment is taken as calculated above.

$$f_{muscle} \cong f_{finger_segment} = 29.4N$$

The torque can be calculated by the cross product of $f_{finger_segment}$ and the distance of hook from the joint r . This force is taken as constant among all the joints, as pneumatic muscles being used in this project are identical for all the finger segments. The joint torque varies among the joints depending on the distance r and the angle of force θ . The calculated maximum torque produced for all joints, using the measurements of r and θ from the designed robotic hand, and the kinematic details are presented in Table 1.

Table 1. Torque produced at all joints

Joint	Connects	r (mm)	θ (degrees)	$\tau = F r \sin\theta$ (Nmm)
J1	Lower Proximal-Palm	5.08	37.43	90.77491
J2	Upper Proximal- Lower Proximal	29.5	16.42	245.1652
J3	Middle-Proximal	29.5	17.77	264.6971
J4	Distal-Middle	16.32	33.64	265.8006
J5	Lower Proximal-Palm	5.08	37.43	90.77491
J6	Upper Proximal- Lower Proximal	22.9	25.08	285.3837
J7	Middle-Proximal	22.9	26.23	297.5645
J8	Distal-Middle	16.32	33.64	265.8006
J9	Lower Proximal-Palm	5.08	37.43	90.77491
J10	Upper Proximal- Lower Proximal	22.9	25.08	285.3837
J11	Middle-Proximal	29.5	17.77	264.6971
J12	Distal-Middle	16.32	33.64	265.8006
J13	Lower Proximal-Palm	5.08	37.43	90.77491
J14	Upper Proximal- Lower Proximal	22.9	25.08	285.3837
J15	Middle-Proximal	22.9	26.23	297.5645
J16	Distal-Middle	16.32	33.64	265.8006
J17	Lower Proximal-Palm	5.08	37.43	90.77491
J18	Upper Proximal- Lower Proximal	19.6	33.54	318.3836
J19	Middle-Proximal	16.3	39.7	306.1103
J20	Distal-Middle	16.32	33.64	265.8006

More details of the torque calculation can be seen in [24]. Translational and rotational mathematical modelling using Denavit–Hartenberg model can be seen in [25]. The details of BendSensor and its usage can be seen in [23] and for EMG based joint angle sensor [26].

IV. SYSTEM RESULT

For the system results, the step and ramp response of the system was acquired. The test was done on the distal joint of all the fingers by providing step function as an input. In this test a certain value of the pneumatic force was applied to the joints and the resultant data from the joint angle's ADC was shown at the terminal software. The data was then copied from the terminal software to Microsoft Excel where it was plotted to see the step response of the joints.

The value of K_p that was used in the controller is different for different joints. As each joint has its specific dimension like segment length, mass, the length of moment arms for spring and muscle forces etc., the value of K_p changes and hence the joint response also changes. The value of K_p has been tried in the system such that the response is comparable to the simulated response with low overshoot and faster settling time. The response graph of the thumb is shown in Figure 8. The data for the joints was acquired by using the terminal program connected to microcontroller. The settling time is greater than the settling time that was observed in the simulation, but the value is still very good and fast in terms of practical system.

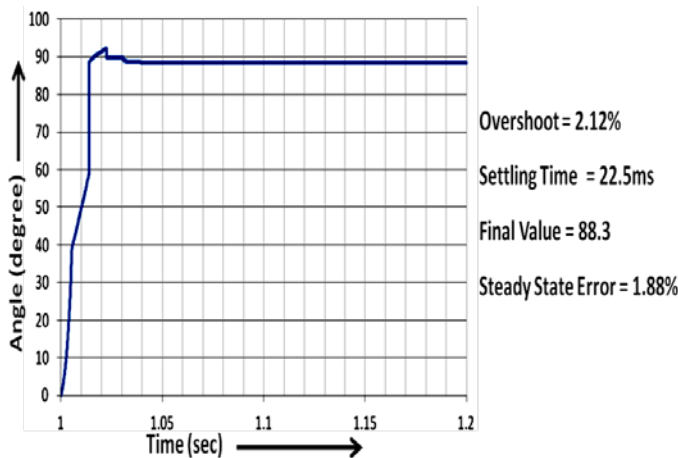


Figure 8 Step response of distal segment of thumb

The steady state error is recorded to be present in the distal segment of the thumb and it has the value of 1.88%. The error range for the steady stated was set as $\pm 2\%$.

The ramp response of the distal segment of thumb is shown in Figure 9. The real-time values are processed by average filter which reduces the spikes in the system. Still the maximum value of error recorded in this data is 8.156%. This value is big but when seen in combination with step response it can be said that the system has a good tracking ability. It reduces the big deviations but still have a maximum error of 8.156%.

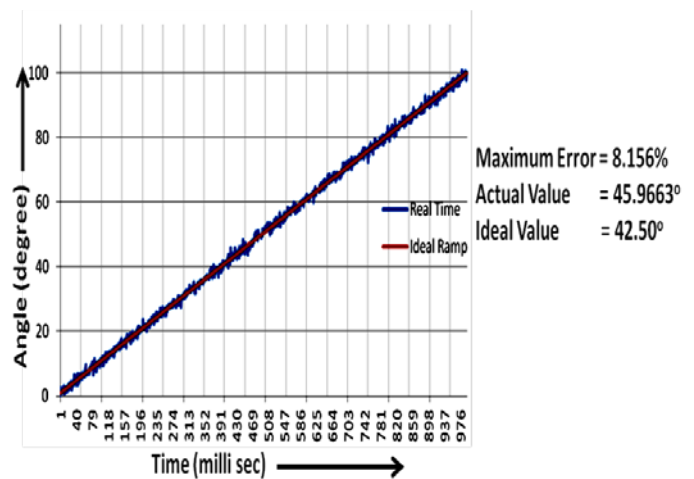


Figure 9 Ramp response of distal segment of thumb

V. CONCLUSION

The mathematical modelling of the robotic hand has been explained in this paper. The mathematical model was derived from the free body diagram of the robotic finger's joint. The complete model of the robotic hand will be difficult to accommodate in this paper. The complete model comprises of all the finger joints, which are twenty five in the complete hand. Step and ramp response was simulated for the robotic hand in MATLAB and the end result was also computed by acquiring data from the robotic finger's joints. The system result and simulation result shows the similar pattern.

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