Grasp Analysis Of A Four-Fingered Robotic Hand Based On Matlab SimMechanics

E. Neha∗, M. Suhaib, S. Asthana and S. Mukherjee

∗Jamia Millia Islamia, New Delhi, Delhi, 110025, India
 IGDTUW, New Delhi, Delhi, 110006, India
 Indian Institute Of Technology, Delhi, India

Abstract
The structure of human hand is a complex design comprising of various bones, joints, tendons, and muscles functioning together in order to produce the desired motion. It becomes a challenging task to develop a robotic hand replicating the capabilities of the human hand. In this paper, the analysis of the four-fingered robotic hand is carried out where the tendon wires and a spring return mechanism is used for the flexion and extension motion of the fingers respectively. Stable grasping and fine manipulation of different objects is desired from any multi-finger robotic hand. In this regard it becomes necessary to check the performance of the four-fingered robotic hand. Simulations are performed for the hand to grasp objects of different size and shapes and the hand model is controlled in MATLAB environment using the SimMechanics toolbox. Here the Kinematics and Dynamics study of the hand system is carried out by importing the Solidworks model into the SimMechanics. Simulation results demonstrate that the developed hand model is able to grasp objects of varying size and shapes securely.

Keywords:
SimMechanics, Multi-finger hand, Robotic gripper, Tendon-driven mechanism.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>error vector</td>
</tr>
<tr>
<td>r</td>
<td>Cartesian Position</td>
</tr>
<tr>
<td>ṙ</td>
<td>Cartesian Space Velocity</td>
</tr>
<tr>
<td>r̈</td>
<td>Cartesian Space Acceleration</td>
</tr>
<tr>
<td>J_i (θ)</td>
<td>Jacobian Matrix for the i-th Manipulation variable</td>
</tr>
<tr>
<td>J^#</td>
<td>Pseudoinverse of the jacobian matrix</td>
</tr>
<tr>
<td>f_i (θ)</td>
<td>function of (θ)</td>
</tr>
<tr>
<td>M (θ)</td>
<td>inertia matrix</td>
</tr>
<tr>
<td>V (θ, θ̇)</td>
<td>Centripetal and Coriolis forces terms</td>
</tr>
<tr>
<td>G(θ)</td>
<td>gravity vector</td>
</tr>
</tbody>
</table>

Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ</td>
<td>Joint Angle</td>
</tr>
<tr>
<td>˙θ</td>
<td>Joint Velocity</td>
</tr>
<tr>
<td>¨θ</td>
<td>Joint Acceleration</td>
</tr>
</tbody>
</table>

Superscript

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>manipulation variable</td>
</tr>
<tr>
<td>n</td>
<td>degree of joint space</td>
</tr>
<tr>
<td>m</td>
<td>degree of Cartesian space</td>
</tr>
</tbody>
</table>

∗Corresponding author
Email address: eramneha@gmail.com
1. Introduction

Stable grasping and fine manipulation of different objects by a multi-finger robotic hand require a number of contact locations on the surface of the objects where the fingertips collide. A number of techniques have been proposed to control the robotic hands for grasping tasks [1].

The grasp capability analysis has been carried out by researchers by applying different load at the fingertips [2] and the balancing capability of any object by the hand is analyzed. The analysis of multiple robot arms is also carried out in similar manner where the coordination of robot arms is examined along with the determination of maximum applicable force/torque [3] and formulated the problem as an optimization problem under the constraints of the dynamic equation of the robots and their joint driving torque limits. However, the multi-fingered grasp is different from that one of multiple robot arms, in that forces can be applied in one direction only. The fingers can only push, not pull, on the object because there is no adhesive between the object and the fingers. Therefore the grasp capability of multi-fingered hands is not same as the grasp capability of multiple robot arms [4].

The eigan-grasp approach is adopted in order to plan for stable robot grasps [5]. A data-driven grasp technique is also derived on similar lines [6]. A neural network is adopted to analyse the grasps of 3D shapes objects [7].

Synthesized image data is utilized to train a classifier to predict grasping points based on features extracted from 2D images [8], [9]. A collision-free stable grasps are planned for dexterous hands in cluttered environments [10]. The task wrench space is also used by various researchers to investigate task oriented grasping [11], [12]. This employs the analysis of the contacts and the potential wrench space of a grasp [13]. A number of methods are presented to solve the configuration problem of a robotic hand for grasping a given object with a specific contact region [14]. A Bayesian network to model task constraints is designed in goal-oriented grasping [15]. A method to analyze grasp affordance on objects based on object edge reconstructions is also developed [16]. Also, a part-based planning algorithm is proposed to generate stable grasps from human demonstration [17].

The structure of control is based on the decomposition of grasping and manipulating forces in accordance to the coulomb friction between the specified object and the robot fingers [18] and [19]. The control schemes involved in independent grasping and manipulating motions or forces is mostly a beneficial area of robotics research [20]. A number of theoretical methods have been proposed by various researchers along with their control strategies for the analysis of different hands. Thereafter these manipulation problems were recognized faster and various control schemes are applied in solving their issues. The control of position with respect to the applied force is analyzed in order to compensate the uncertainties regarding stiffness of the constraint environment. Later, the force control sensors were employed for solving the problem [21]. Various methods for automatic grasp generation were demonstrated based on object shape primitives [22]. Simulations are performed in MATLAB/ Simulink environment for the 3D visualization of the robotic system using the block diagram and programming tools [23]. Also, researches are now being carried out to perform a simulation of the multi-finger robotic gripper to attain stable grasping [24].

Computer simulations are performed to verify and check the performance of the robotic hands prior to experimentations [25]. Various software packages are available to solve equations, control, data manipulation, 3D visualization along with the programming facility [26]. Different software available for graphical programming and realizing the robotic hands in the virtual environment are LabVIEW [27], VRML, MATLAB Simulink and SimMechanics [28].

Due to the rising demands, several types of research are being conducted on simulations of different robots in the virtual environment. Numerous MATLAB based tools are available.
to carry out simulations of the robot manipulator [29]. Different types of industrial robots and parallel manipulators have also been examined using the MATLAB SimMechanics [30]. The integration of the design software with the MATLAB SimMechanics proves to be an efficient tool in the area of research and development [31]. The improvement of effective computational platforms for simulating the behavior of robotics structures constitutes a fundamental device for designers, customers, and researchers of this subject. These simulation platforms are very crucial for robot manipulation because they permit the computation of the robot’s trajectories which might be required for grasping objects in the environment [1].

The representation of a CAD model in SimMechanics environment comprises of blocks having a definite physical and mechanical meaning. A list of blocks is present in the library for different components such as bodies, joints, sensors and actuators, constraints and drivers, and force elements. Along with these standard blocks, the modeling of the complex system also requires advanced functioning blocks. All blocks are configurable by the user via graphical user interfaces as known from Simulink [32]. MATLAB programming functions can also be incorporated with custom blocks in order to obtain the output according to the desired need.

The integration of the CAD model of the four finger robotic hand with simulation software is carried out in order to examine its behavior and check its performances while grasping different objects [33]. The paper uses SolidWorks for the development of CAD Model of a robot and SimMechanics is used to simulate the robot in a virtual environment. The four-fingered robotic hand’s assembly is first exported as an XML and STL files using SimMechanics CAD translator module [34]. They are then imported into MATLAB SimMechanics as a model file. The imported model is attached to sensors and actuator controls to analyze the simulations [35]. This paper describes to design and simulate a Four-Fingered gripper to provide motions for the fingertips while grasping different objects. The fingers are to be controlled in a manner to grasp any object at the contact points.

In this paper, a four-fingered tendon actuated robotic hand structure is proposed for grasp analysis, which is designed to mimic a human hand in order to perform grasping and manipulation tasks. The paper is organized as follows: in Section 2, the modeling of the Four-Fingered Robotic Hand mechanism is presented using CAD software. The model is then imported into Matlab using SimMechanics. In Section 3, the developed control system is presented to study the control strategies of the hand mechanism and obtain the desired outputs. Simulations results are presented in section 4 where the robotic hand is examined to grasp objects of different shapes and sizes. Graphs are plotted to obtain the joint positions in terms of angles, joint velocity, joint acceleration and torques at the time of grasp. Finally, the results are analyzed to draw conclusions as presented in Section 5.

## 2. Modeling of Hand

A number of robotic hands are developed in the past with the aim to mimic a human hand [36]. Different hand adopts different mechanism and drive technologies according to their respective designs. The UTAH/MIT hand was developed to carry out research with three fingers. This hand is actuated by means of tendon transmission along with pneumatic actuators [37]. The Stanford/ JPL hand also employs a tendon driven mechanism for both flexion and extension of the fingers [38]. Similarly, the Ultralight hand also comprises of the pneumatic actuation placed inside the fingers for the flexion/retraction of fingers [39]. Various prosthetic hands are also designed to replace human hands [40]. The Robonaut Hand came with the aim to replicate an astronaut hand in terms of size, strength and kinematics to meet the requirements of NASA
for extra vehicular activities [41]. The actuation of this hand is remote, with brushless motors and flexes shaft transmission system. The Barret hand is also actuated by means of brushless motors where only four joints are controlled out of the eight joints of the three fingers. Electrical motors are generally employed in order to produce a larger grip force as compared to pneumatic drives. The DLR hand II has a modular design in which the actuation is placed inside the fingers provided by electric motors [42].

In this section, solid model of the Four-Fingered Robotic Hand mechanism is developed using the SolidWorks software and further, simulation is carried out in Simulink. To transfer the model from SolidWorks to Matlab and Simulink, the designed model is embedded in SimMechanics. In order to make a realistic model, the dimensions and design are set keeping in view of the human hand. The proposed hand has three fingers connected in series and one opposing thumb. There are three phalanges (links), i.e., proximal, middle and the distal phalanges, in every finger. Each finger has three DOFs while the thumb has two DOF’s. The proximal link of the thumb has fixed joint and is connected to the base. All the other links of the fingers have rotational joints with one DOF. Thus, the hand has a total of 11 DOFs. In addition, the palm is also introduced for power grasping. The assembled part of the whole mechanism along with a cylindrical object to be grasped is shown in Fig. 1.

A Tendon (string) flows through each finger to transfer the movement of the actuator from one link to the other simultaneously. The tendon is fixed to the tip of each finger from one end, while the other end of the string is left free, which could be either connected to weights or actuators. The phalanges of the finger contract on the application of force (tension) in the tendon from the free end side. Each phalange is connected to the adjacent phalange by the pin joint. A moment is created at the pin joint which forces the phalange to move. A constant force spiral spring is used to retract the gripper to its rest position [43].

This newly designed four finger robotic hand is different from the other hands as all the previously designed hands used either tendon actuation for both extension/flexion of the fingers, or used the electric and pneumatic motors for the actuation process. But in this hand tendon actuation system is used for the flexion of the fingers where as a spring return mechanism is incorporated for extension of the fingers. The spring return mechanism enables the rapid accomplishment of the extension of fingers when they are released after grasping an object, in order to minimise various frictional and time losses. There is a considerable amount of frictional and time losses in other previously designed hands having either tendon actuation for both extension/flexion of fingers or using electric and pneumatic motors. This auto retraction of the fingers due to the spring mechanism is an important feature of this hand.

![Fig. 1. Final assembled model of four-fingered robotic hand grasping an object.](image1)

![Fig. 2. Major assembly with no redundant parts and mapping of revolute joints.](image2)
For simplicity, all redundant parts have been removed in order to perform the desired simulations as shown in Fig. 2. Mechanical systems are modeled and simulated using different tools to specify different bodies and their mass properties, Kinematic constraints, motion limits to execute and measure body motion limits etc. [28].

The CAD model file is converted to an XML file and imported to SimMechanics by the sim import inbuilt MATLAB function. The block diagram model converted from CAD model is shown in Fig. 3. The physical model represents all the body parts in the form of blocks with different DOF’s, positions, orientations and masses. Further simulations are performed using this model in order to produce the Flexion motion of the fingers for grasping tasks. All the joints are modeled using revolute block providing one DOF. The base, palm along with the phalanges are modeled using body blocks.

The four-fingered robotic hand mechanism has four sub-systems namely, first finger subsystem, second finger subsystem, third finger subsystem and Thumb subsystem (see Fig. 3). All the subsystems of the fingers have an equal number of blocks with symmetric Patterns while the thumb subsystem has fewer blocks with similar patterns. A rigid Base plate is attached to the other transformation plates in order to control the motions using a control system.

### 3. Controller Design

The control system is developed based on the kinematics of the model where the joint parameters are calculated when the hand moves to grasp an object. The joint angles are calculated for each joint using a predefined sinusoidal trajectory with a period of 2π for both flexion and extension of fingers. The robot finger must move along a prescribed trajectory through the robot finger workspace. This task is specified using the kinematic relationships between the joint variable \( \theta \in \mathbb{R}^n \) and the manipulation variable are expressed by:

\[
r_i = f_i(\theta),
\]

On differentiating the above Eq.(1),

---

*Corresponding author

Email address: eramneha@gmail.com*
\[ \dot{r}_i = J_i(\theta)\dot{\theta}, \quad (2) \]

Where \( J_i(\theta) \) is the jacobian matrix of the \( i \)-th manipulation variable. The pseudoinverse of the jacobian matrix is used to determine the general solution to Eq. (2) as given below:

\[ \dot{\theta} = J_i^\#(\theta)\dot{r}_1 \quad (3) \]

Where \( J_i^\#(\theta) \in R^{nxm} \) is the pseudoinverse of the jacobian matrix \( J_i \) [43].

The control system of robot fingers is a collection of joint controllers attached at every single joint to drive it individually. The model that is used to compute the torque is based on the rigid body dynamic equation [44] which is as follows:

\[ \tau = M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) \quad (4) \]

Where \( M(\theta) \) is the \( n \times n \) inertia matrix of the manipulator, \( V(\theta, \dot{\theta}) \) is an \( n \times 1 \) vector produced by Centripetal and Coriolis forces terms, and \( G(\theta) \) is an \( n \times 1 \) vector of gravity terms. The elements of \( M(\theta) \) and \( G(\theta) \) is a function that depends on \( \theta \), that is the joint angle of all the joints of the hand. Differentiate Eq. (2) to obtain

\[ \ddot{r}_i = J_i\ddot{\theta} + J_1\dot{\theta} \quad (5) \]

Now, a feedback control scheme is designed so that the following equation illustrates the closed loop characteristics.

\[ \ddot{e} + s_1 \dot{e} + s_2 e = 0 \quad (6) \]

\[ e = r^d(t) - r \quad (7) \]

Where \( r^d(t) \) and \( r \) are the desired and actual trajectory respectively. \( e \) is the error vector and \( s_1 \) and \( s_2 \) are the positive feedback coefficients. The above feedback scheme is to be incorporated in Eq. (5) to get,

\[ J_i\ddot{\theta} = \ddot{r}^d(t) - J_i\dot{\theta} + s_1 \dot{e} + s_2 e = k_i(\theta, \dot{\theta}, t) \quad (8) \]

For \( i=1 \),

\[ \ddot{\theta} = J_1^\#k_1 \quad (9) \]

A number of controller options are available in SimMechanics Simulink library. The four-finger robotic hand has asymmetric design; therefore the same controller can be applied to the other subsystems. MATLAB programming functions are incorporated with custom blocks to control the subsystems according to the desired needs.

Fig. 4 shows the block diagram of the control system added to the mechanism. Graphs are plotted to compare the peak values at the time of proper grasp. In the thumb mechanism, two of the links or phalanges are active with the revolute joint between them to control the subsystem.

Fig. 5 shows the thumb control system where an input signal is provided for every joint using the control system shown in Fig. 4 in order to perform the grasping task and obtain the desired four outputs. Similarly, Fig. 6 shows the finger mechanism, where three revolute joints are controlled to calculate the position, velocity, acceleration and torque for each of the joint motion while grasping an object. The control objective is to move the hand in 10 seconds time in order to grasp an object and come back to its rest position.
Fig. 5. Thumb control system.

Fig. 6. Finger control system.

*Corresponding author
Email address: eramneha@gmail.com
4. Simulations And Results

The 3D virtual environment is created for the four finger tendon actuated robotic hand in order to grasp different objects. For the grasping process and analysis, simulations are performed where the hand is examined for grasping two different types of objects. The grasping stability has to be examined for holding objects of both uniform as well as varying cross sections along the z-axis. A Cylindrical object is chosen for an object of the uniform cross-section and a Spherical object for varying geometry about the z-axis.

4.1 Cylindrical Objects

Three cylindrical objects were chosen and placed at a fixed position in the 3D space. The grasping process involves the movement of the hand from its rest position to hold an object and thereafter returning back to its home position. Simulations are conducted where the initial position of the hand is shown in Fig. 7 at the beginning of the grasp. Then the hand moves to reach the object as shown in Fig.8 to grasping a cylindrical object.

![Fig. 7. Initial position of hand before grasping.](image)

The simulation time is set as 10 seconds for the complete grasp process where the Position in radians as the motion is angular, the Velocity in radians per sec, the Acceleration in radians per sq. sec and the Torque in N-mm can are computed for the thumb and fingers separately. In case of the cylinder, as the cross-section is uniform, all the three fingers perform the same motion. Fine motion simulation results are presented for the thumb and finger for grasping the three cylinders of varying diameters as shown in Fig. 9 to Fig. 11. Thereafter plots are analyzed and the peak values of hand parameters are recorded while grasping cylinders of varying diameters listed in Table 1.
Fig. 9. Motion plots while grasping a cylinder c1.
After analyzing the plots obtained from the simulation for grasping cylindrical objects of varying diameters, it has been observed that as the diameter of the cylinder decreases, the joint angles for the thumb as well as the fingers increases. This further leads to an increase in the joint velocity and acceleration, and as a result the torque required for the movement of the fingers also increases.
4.2 Spherical Objects
A spherical ball is placed at a fixed position within the workspace of the hand in the 3D space to perform the grasping task. The process involves the movement of the hand from its rest position to hold an object and thereafter returning back to its home position. Simulations are conducted where the initial position of the hand is shown in Fig. 12 at the beginning of the grasp. Then the hand moves to reach the object as shown in Fig. 13 to grasping a spherical object.

The simulation time is set as 10 seconds for the complete grasp process where the Position in radians, Velocity in radians per sec, Acceleration in radians per sq. sec and the Torque in N-mm are computed for the thumb and fingers separately. In case of the sphere, all the fingers exhibit different motions and thus simulation results are presented for the thumb and the three fingers for grasping a sphere as shown in Fig. 14.
Thereafter plots are analyzed and the peak values of hand parameters are recorded while grasping a sphere of as listed in Table 2.
Table 2. Peak values of hand parameters while grasping spherical object.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameters</th>
<th>Sphere of diameter 3.5 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Position (radians)</td>
<td>Thumb</td>
</tr>
<tr>
<td>2.</td>
<td>Velocity (rad/sec)</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Acceleration (rad/sec²)</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Torque (N-mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14. Motion plots while grasping a sphere.
The angular motions of all the fingers are distinct while grasping a sphere. Therefore, after analyzing the plots obtained from the simulation for grasping a spherical object, it has been observed that the third finger shows the maximum value of the joint angle, velocity, acceleration and torque. This proves that, with an increase in the joint angles, the velocity as well as acceleration increases and as a result, the torque required for the movement of the fingers also increases.

5. Conclusions

The present works demonstrate a control process for simulating the grasp performance of the designed Four-fingered tendon actuated robotic hand in the virtual 3D environment. Simulations are performed for the hand to grasp different objects where the hand model is controlled in MATLAB environment using the SimMechanics toolbox. MATLAB programming functions have been incorporated with custom blocks to control the subsystems according to the desired needs. The fingers are controlled in order to mimic the kinematics and dynamics of the human hand. For this purpose, three cylindrical objects of distinct diameters and a sphere were used to analyze the grasp capabilities of the robotic hand. Results are obtained for the different angular motions, joint velocities, accelerations and torques required to perform the grasping tasks. The peak values of these parameters were examined and the hand performance is evaluated. These studies indicate that the designed hand can perform smooth and stable grasping of objects with different size and shapes. Future work involves the determination of different contact points by the fingertips of the hand while grasping any objects and validation of the obtained results experimentally as well as through Kinematics using MATLAB Programming.

References


