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Robotic Grasping and Fine Manipulation Using Soft Fingertip

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1. Introduction

The ability to create stable, encompassing grasps with subsets of fingers is greatly increased by using soft fingertips that deform during contact and apply a larger space of frictional forces and moments than their rigid counterparts. This is true not only for human grasping, but also for robotic hands using fingertips made of soft materials.

The superiority of deformable human fingertips as compared to hard robot gripper fingers for grasping and manipulation has led to a number of investigations with robot hands employing elastomers or materials such as fluids or powders beneath a membrane at the fingertips.

When the fingers are soft, during holding and for manipulation of the object through precise dimensions, their property of softness maintains the area contact between, the fingertips and the manipulating object, which restraints the object and provides stability. In human finger there is a natural softness which is a combination of elasticity and damping. This combination of elasticity and damping is produced by nature due to flesh and blood beneath the skin. This keeps the contact firm and helps in holding the object firmly and stably.

2. Background

Over the past several decades, object manipulation and grasping by robot hands has been widely studied [1–7]. Multifingered-hand research has focused on grasping control [8] and visual and tactile control [9]. Grasp-less manipulation [10], i.e., manipulation without hand grasping and power grasping [11] using the palm of the robot hand have also been proposed. These studies assume that fingertips and manipulated objects are rigid, making point contact, and have analyzed manipulation as quasi-static. Such assumptions are useful for kinematic and static analysis of robot finger grasping and manipulation, but rarely apply in actual dynamic grasping and manipulation. Manipulation and grasping by soft fingertips contribute to grasping stability due to the area of contact and high friction involved.

One approach to investigate in this area is by first analyzing the stability of dynamic control of an object grasped between two soft fingertips through a soft interface using the

viscoelastic material between the manipulating fingers and a manipulated object and then modeling it through bond graph method (BGM). The fingers are made viscoelastic by using springs and dampers. Detailed bond graph modeling of the contact phenomenon with two soft-finger contacts considered to be placed against each other on the opposite sides of the grasped object as is generally the case in a manufacturing environment is made. The viscoelastic behavior of the springs and dampers is exploited in order to achieve the stability in the soft-grasping which includes friction between the soft finger contact surfaces and the object. This work also analyses stability of dynamic control through a soft interface between a manipulating finger and a manipulated object. It is shown in this work that the system stability depends on the viscoelastic material properties of the soft interface. Method of root locus is used to analyze this phenomenon.

Ultimate objective of this work is to design and develop a robotic gripper which has soft fingers like human fingers. Soft fingers have ability to provide area contact which helps in dexterous grasping, stability and fine manipulation of the gripping object.

Robotics is gaining new and extensive application fields, becoming pervasive in the daily life. Manipulation skills at macro and micro scale are very important requirements for the emergent robot applications, both in industry (e.g. handling food, fabrics, leather) and in less structured domains (e.g. surgery, space, undersea). The manipulation and grasping devices and systems are a vital part of industrial, service and personal robotics for various applications and environments to advance manufacturing automation, to make safe hazardous operations and to enhance in different ways to the living standards.

The human hand which has the three most important functions: to explore, to restrain objects, and to manipulate objects with arbitrary shapes (relative to the wrist and to the palm) is used in a variety of ways [12]. The first function falls within the realm of haptics, an active research area in its own merits [13]. My work does not attempt an exhaustive coverage of this area. This work in robotic grasping is to understand and to emulate the other two functions. The task of manipulating objects with fingers (in contrast to manipulation with the robot arm) sometimes is called dexterous manipulation. This work will be fascinated with constructing mechanical analogues of human hands and will lead us to place all sorts of hopes and expectations in robot capabilities.

Probably the first occurrence of mechanical hands was in prosthetic devices to replace lost limbs. Almost without exception prosthetic hands have been designed to simply grip objects [14]. In order to investigate the mechanism and fundamentals of restraining and manipulating objects with human hands, later a variety of multifingered robot hands are developed, such as the Stanford/JPL hand [14], the Utah/MIT hand [15], and other hands. Compared to conventional parallel jaw grippers, multifingered robot hands have three potential advantages: (1) they have higher grip stability due to multi-contact points with the grasped object; (2) they can grasp objects with arbitrary shapes; (3) it is possible to impart various movements onto the grasped object. However, multifingered robot hands are still in their infancy. In order for the multifingered robot hands to possess the properties so that robots implement autonomously the tasks of grasping in industry, it is necessary to study the planning methods and fundamentals of robotic grasping as well.

The vast majority of robots in operation today consist of six-jointed "arms" with simple hands or "end effectors" for grasping objects. The applications of robotic manipulations range from pick and place operations, to moving cameras and other inspection equipment, to performing delicate assembly tasks. They are certainly a far cry from the wonderful fancy about the stuff of early science fiction, but are useful in such diverse arenas as welding,

painting, transportation of materials, assembly of printed circuit boards, and repair and inspection in hazardous environments [14, 16].

The hand or end effector is the bridge between the manipulator (arm) and the environment. The traditional mechanical hands are simple, out of anthropomorphic intent. They include grippers (either two- or three-jaw), pincers, tongs, as well as some compliance devices. Most of these end effectors are designed on an ad hoc basis to perform specific tasks with specific tools. For example, they may have suction cups for lifting glass which are not suitable for machined parts, or jaws operated by compressed air for holding metallic parts but not suitable for handling fragile plastic parts. Further, a difficulty that is commonly encountered in applications of robotic manipulations is the clumsiness of a robot equipped only with these simple hands, which is embodied in lacking of dexterity because simple grippers enable the robot to hold parts securely but they cannot manipulate the grasped object, limited number of possible grasps resulting in the need to change end effectors frequently for different tasks, and lacking of fine force control which limits assembly tasks to the most rudimentary ones [16].

3. Gripper

Any mechanism which can grasp different objects is called as gripper. It is actually a subsystem of handling mechanism which provides a temporary contact with the object to be grasped. The Gripper ensures that the position and the orientation of the object that is grasped are constrained enough so that the process of carrying, joining etc is done efficiently. This term "gripper" is also used where no actual grasping, rather holding of the object for example in vacuum suction takes place. [17]

4. Classification

Grippers can be classified on the basis of various aspects ranging from type of grasping to number of fingers as discussed below:

4.1 Classification on basis of type of contact
There are three basic types of grippers on the basis of type of contact, shown in figure 1:
- Point Contact
- Line Contact
- Area Contact

4.1.1 Point contact
As the name indicates, point contact gripping takes place when the gripping fingers and the object to be grasped come in contact at some particular points. In this type of gripping there are at least three to four points of contact between the gripping fingers and the object to be grasped.

4.1.2 Line contact
In line contact the contact between the gripper jaw / finger takes place in the form of a line which is dependent on the shape of the object. In Line Contact one has to make sure that the hypothetical lines which are formed during contact are parallel or as close to parallel as possible otherwise proper grasping becomes far too difficult.

4.1.3 Area contact

Instead of points or lines, there is a whole surface area of the fingers that is coming in contact with the object. Generally in area contact, contact of two surface areas from opposite sides is enough to completely constrain the object.
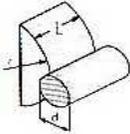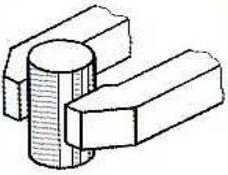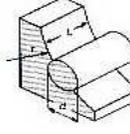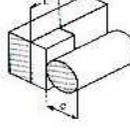
	contact	surface pressure *p*	gripper jaw shape
line contact		$p = 0{,}418 \sqrt{\dfrac{F_K \cdot E_r}{L}\left(\dfrac{2}{d} + \dfrac{1}{r}\right)}$	
		$p = 0{,}418 \sqrt{\dfrac{F_K \cdot E_r}{L}\left(\dfrac{2}{d} - \dfrac{1}{r}\right)}$	
		$p = 0{,}418 \sqrt{\dfrac{2 \cdot F_K \cdot E_r}{L \cdot d}}$	
point contact		$p = m \cdot \sqrt[3]{\dfrac{F_K \cdot E_r^2}{r^2}}$	
		$\dfrac{d}{2} < r$	
surface contact		$p = \dfrac{F_K}{a \cdot b}$	
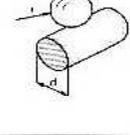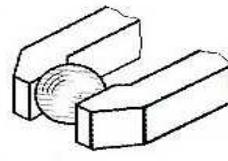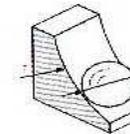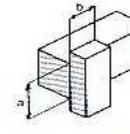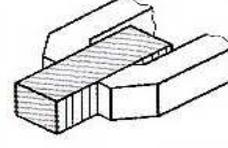
Fig. 1. Types of contacts, their pressure force and the general gripper jaw shape. [18]

Where:

F_k	=	Contact Force
E_r	=	$(2 * E_t * E_s)/(E_t + E_s)$
E_t	=	Young's Modulus of object
E_s	=	Young's Modulus of gripper finger/Jaw.

4.2 Classification on basis of number of fingers

On the basis of number of fingers, grippers can be classified into two, three, four, and more number of fingers:

4.2.1 Two finger grippers

Two finger grippers only have two fingers by which they grasp the object. These types of grippers have generally area contact because they generally due to the shape of the fingers cannot give more than two points of contact and as discussed before, this is not enough to grasp the object firmly and to constrain its degrees of freedom.

4.2.2 Three finger grippers

Due to the fact that the gripper has three fingers, it can have both area and surface contact. But the usage of three fingers in grasping also increases the design complexity and the complexity of the control that must be developed for it.

4.2.3 Four finger grippers

Four Finger Grippers are sometimes a combination of two finger grippers and at other times a combination of independent fingers working together. These grippers are used in relatively high cost and precision demanding applications.

4.2.4 Five finger grippers

These grippers are developed purely on research basis to make the grasping dexterous (closer to human hand gripping approach). There are grippers with more than five fingers as well.

4.3 Classification on the basis of gripping method

There are basically four types of grippers on the basis of their gripping method. Table 1 shows the types of gripping methods along with the non-penetrating and the penetrating examples.

Gripping Method	Non Penetrating	Penetrating
Impactive	Clamping Jaws, Chucks, Collets	Pincers, Pinch Mechanisms
Ingressive	Brush elements, hooks, hook and loop	Needles ,pins , hackles
Contigutive	Chemical adhesion(glues) ,Surface Tension Forces	Thermal adhesion
Astrictive	Electrostatic adhesion	Magnetic grippers, vacuum suction

Table 1. Table of Gripping methods along with the non-penetrating and the penetrating examples. [19]

4.3.1 Impactive grippers

Impactive Grippers make the use of impact of jaws and the object to be grasped through the motion of solid jaws in order to produce the necessary grasping force.

4.3.2 Ingressive grippers

Ingressive grippers deform or penetrate the surface to some predefined depth (force shape mating).

4.3.3 Contigutive grippers

Contigutive type of gripping means that there is a direct contact to facilitate the gripping. For example: chemical adhesion.

4.3.4 Astrictive grippers

Astrictive grippers make use of the binding forces between the surfaces. For example: magnets or electrostatic adhesion. Some of these types of grippers do not even have physical contact with the grasped object.

4.3.5 Importance of gripper

The end effector that is usually used by the manipulator is the gripper. There are a lot of Grippers having different mechanisms and design that exist in the industry. Grippers essentially replace most of the work that is done by the human hand. If the gripping abilities of a mechanical five-finger "hand" are denoted as 100%, then a four-finger hand has 99% of its ability, a three-finger hand about 90%, and a two-finger hand 40%.

4.4 Taxonomy of common end effectors

Nowadays Robotic end effectors include everything from simple two-fingered grippers and vacuum attachments to elaborate multi fingered hands. Perhaps the best way to become familiar with end effector design issues is to first review the main end effector types.

Figure 2 is taxonomy of common end effectors. It is inspired by an analogous taxonomy of grasps that humans adopt when working with different kinds of objects and in tasks requiring different amounts of precision and strength .The left side includes "passive" grippers that can hold parts, but cannot manipulate them or actively control the grasp force. The right-hand side includes active servo grippers and dexterous robot hands found in research laboratories and teleoperated applications.

4.4.1 Passive end effectors

Most end effectors in use today are passive; they emulate the grasps without manipulating it in the fingers. However, a passive end effector may (and generally should) be equipped with sensors, and the information from these sensors may be used in controlling the robot arm. The left-most branch of the "passive" side of the taxonomy includes vacuum, electromagnetic, and Bernoulli-effect end effectors. Vacuum grippers, either singly or in combination, are perhaps the most commonly used gripping device in industry today. They are easily adapted to a wide variety of parts from surface mount microprocessor chips and other small items that require precise placement to large, bulky items such as automobile windshields and aircraft panels. These end effectors are classified as "no prehensile" because they neither enclose parts nor apply grasp forces across them. Consequently, they
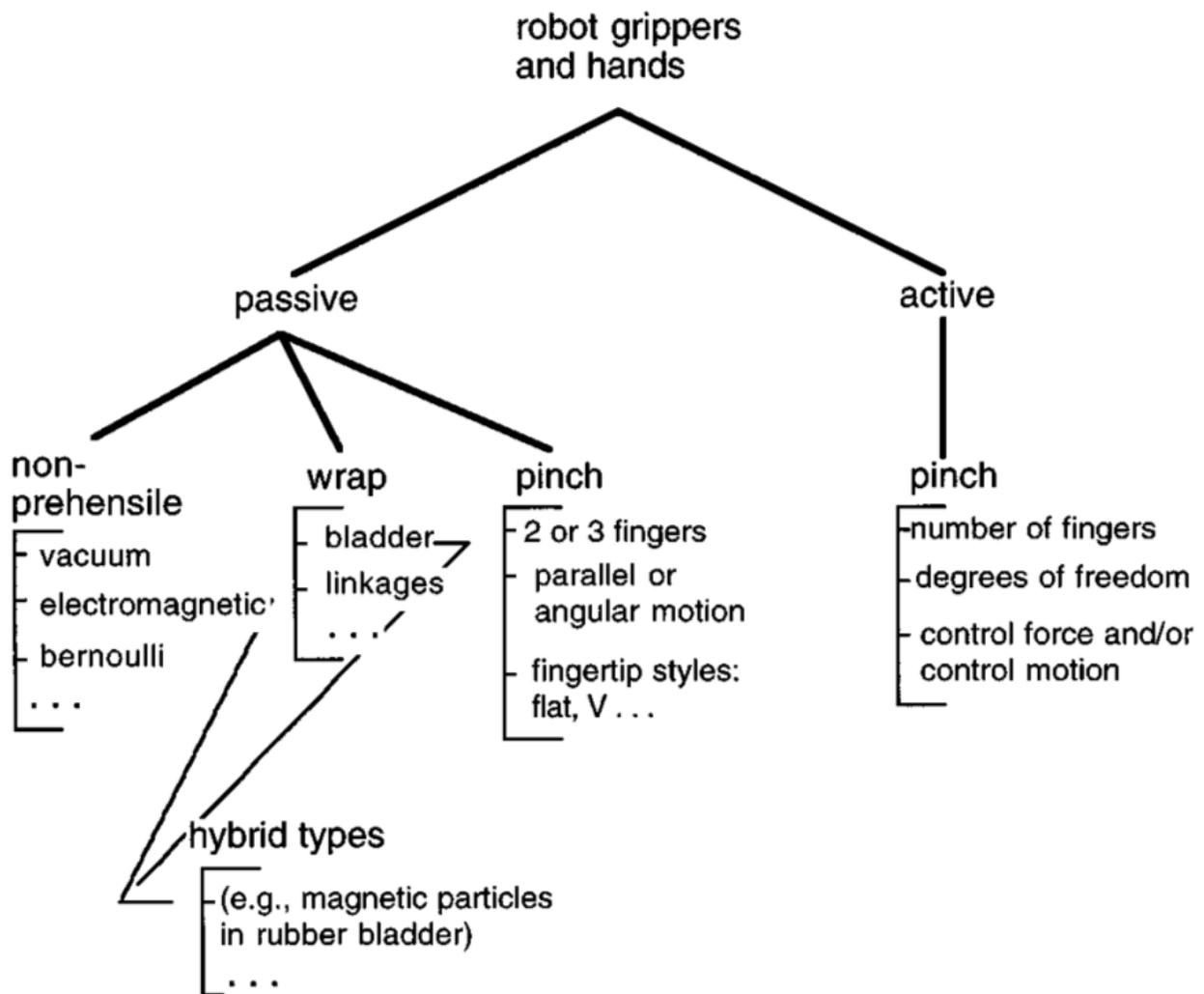
Fig. 2. A taxonomy of the basic end effector types. [20]

are ideal for handling large and delicate items such as glass panels. Unlike grippers with fingers, vacuum grippers do not tend to "center" or relocate parts as they pick them up. If difficulties are encountered with a vacuum gripper, it is helpful to remember that problem can be addressed in several ways, including increasing the suction cup area through larger cups or multiple cups, redesigning the parts to be grasped so that they present a smoother surface (perhaps by affixing smooth tape to a surface), and augmenting suction with grasping. The second branch of end effector taxonomy includes "wrap" grippers that hold a part in the same way that a person might hold a heavy hammer or a grapefruit. In such applications, humans use wrap grasps in which the fingers envelop a part, and maintain a nearly uniform pressure so that friction is used to maximum advantage.

Another approach to handling irregular or soft objects is to augment a vacuum or magnetic gripper with a bladder containing particles or a fluid. When handling ferrous parts, one can employ an electromagnet and iron particles underneath a membrane. Still another approach is to use fingertips filled with an electro rheological fluid that stiffens under the application of an electrostatic field. The middle branch of the end effector taxonomy includes common two-fingered grippers. These grippers employ a strong "pinch" force between two fingers, in the same way that a person might grasp a key when opening a lock. Most such grippers are sold without fingertips since they are the most product-specific part of the design. The

fingertips are designed to match the size of components, the shape of components (e.g., flat or V-grooved for cylindrical parts), and the material (e.g., rubber or plastic to avoid damaging fragile objects). Note that since two-fingered end effectors typically use a single air cylinder or motor that operates both fingers in unison, they will tend to center parts that they grasp. This means that when they grasp constrained parts (e.g., pegs that have been set in holes or parts held in fixtures) some compliance must be added. [21]

4.4.2 Active end effectors and hands

The right-hand branch of the taxonomy comprises of servo grippers and dexterous multi fingered hands. Here the distinctions depend largely on the number of fingers and the number of joints or degrees of freedom per finger. For example, the comparatively simple two-fingered servo gripper is confined to "pinch" grasps, like commercial two-fingered grippers, shown in figure 3:. Servo-controlled end effectors provide advantages for fine-motion tasks. In comparison to a robot arm, the fingertips are small and light, which means that they can move quickly and precisely. The total range of motion is also small, which permits fine-resolution position and velocity measurements. When equipped with force sensors such as strain gages, the fingers can provide force sensing and control, typically with better accuracy than can be obtained with robot wrist or joint-mounted sensors. A servo gripper can also be programmed either to control the position of an unconstrained part or to accommodate to the position of a constrained part .The sensors of a servo-controlled end effector also provide useful information for robot programming. For example, position sensors can be used to measure the width of a grasped component, thereby providing a check that the correct component has been grasped. Similarly, force sensors are useful for weighing grasped objects and monitoring task-related forces which can help in checking the weights of the objects.
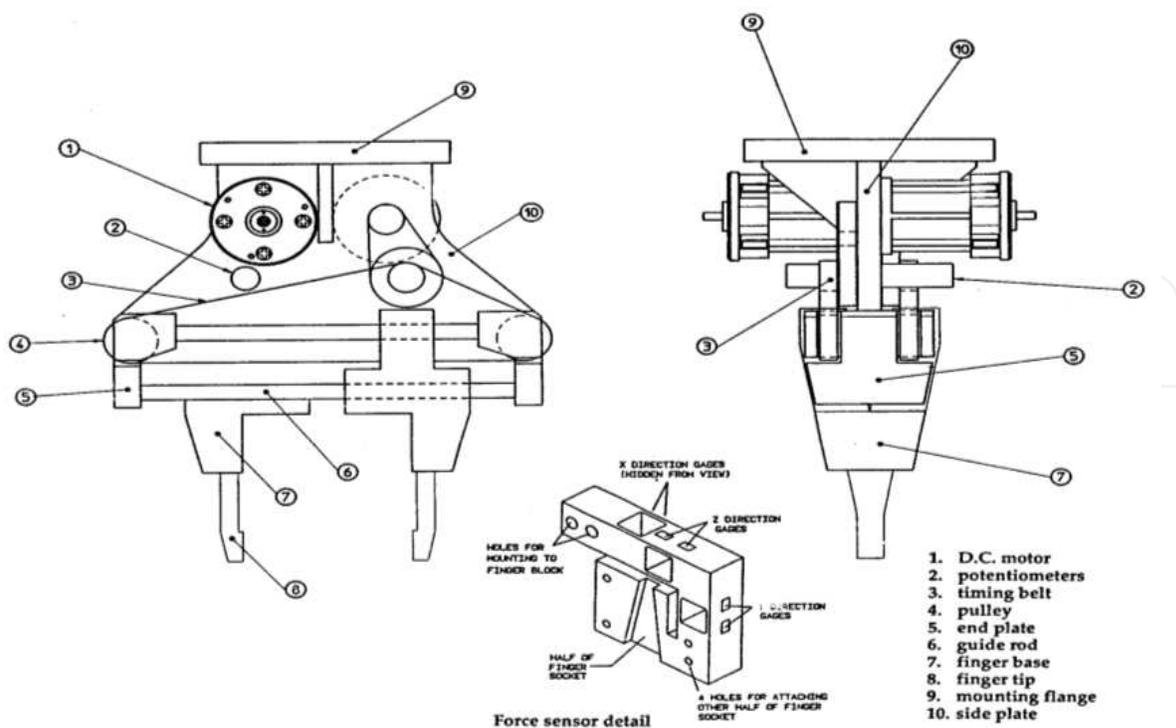

Fig. 3. A two-finger servo gripper with force sensing and changeable fingertips. [3]

For a wide range of applications requiring a combination of dexterity and versatility for grasping a wide range of objects, a dexterous multi fingered hand is the ultimate solution. A number of multi fingered hands have been described in the literature and commercial versions are available. Most of these hands are frankly anthropomorphic, although kinematic criteria such as workspace and grasp isotropy (basically a measure of how accurately motions and forces can be controlled in different directions) have also been used. Despite their practical advantages, dexterous hands have thus far been confined to a few research laboratories. One reason is that the design and control of such hands present numerous difficult tradeoffs among cost, size, power, flexibility and ease of control. For example, the desire to reduce the dimensions of the hand, while providing adequate power, leads to the use of cables that run through the wrist to drive the fingers. These cables bring attendant control problems due to elasticity and friction .A second reason for slow progress in applying dexterous hands to manipulation tasks is the formidable challenge of programming and controlling them. The equations associated with several fingertips sliding and rolling on a grasped object are complex, the problem amounts to coordinating several little robots at the end of a robot. In addition, the mechanics of the hand/object system are sensitive to variations in the contact conditions between the fingertips and object (e.g., variations in the object profile and local coefficient of friction). Moreover, during manipulation the fingers are continually making and breaking contact with the object, starting and stopping sliding, etc., with attendant changes in the dynamic and kinematic equations which must be accounted for in controlling the hand.

When the fingers are soft, during holding and for manipulation of the object through precise dimensions, their property of softness maintains the area contact between, the fingertips and the manipulating object, which restraints the object and provides stability. In human finger there is a natural softness which is a combination of elasticity and damping. This combination of elasticity and damping is produced by nature by putting flush and blood beneath the skin. When it holds the object due to the applied force reaction comes according to 3rd law of Newton and presses the skin and when it rotates the object for manipulating, skin comes back to its original state softly and the other portion compresses against the object. This keeps the contact firm and helps in holding the object firmly and stably. The setup shown in figure 4 is an example of such grasping. It is being modeled in figure 5.
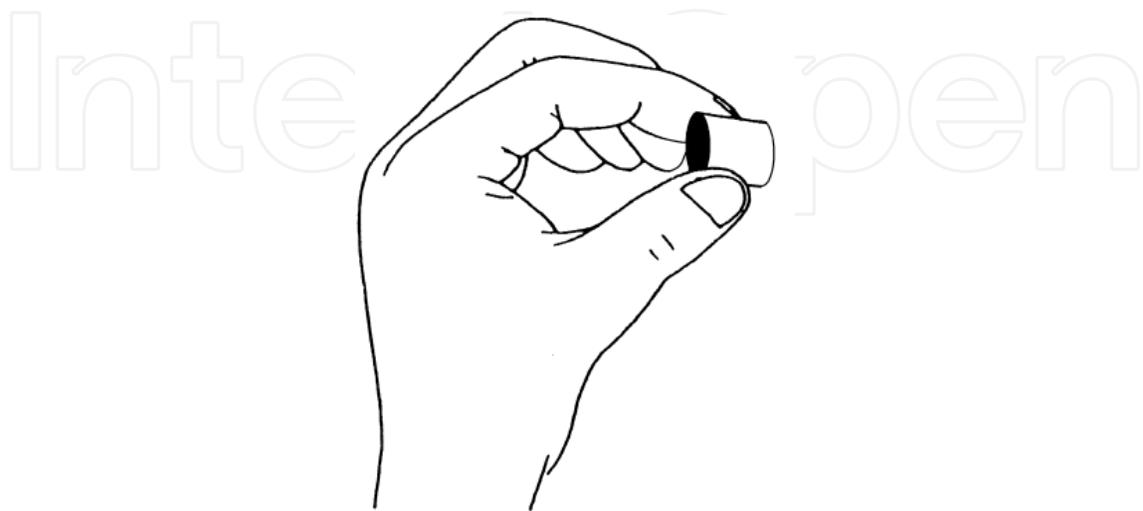

Fig. 4. A set up showing two soft fingers grasping a knob.

To analyze the stability of dynamic control through a *soft interface* that is the viscoelastic material between manipulating fingers and a manipulated object, we have to model dynamic control through the soft interface.

Thus we have to find out:

- How to make the robotic fingers soft?
- The method for measuring the soft fingers grasping force
- Their modeling and simulation
- Analyzing the stability effect due to soft fingers
- Role of springs and dampers in providing stability and accuracy in dexterous manipulation

We shall show that system stability depends on the viscoelasticity of the soft interface for feedback control. The relationship between material viscoelastic property and the settling time shall be analyzed by root locus. Stability analysis is done by using bondgraph methodology to precisely model the situation and then simulating based on Runge-Kutta method.

4.5 Work objective

During grasping the weight of the object being grasped is controlled from slipping downward with the friction between the grasping fingers and the object. This friction further depends upon the applied force. For securing the object from damaging, the contact fingers are made soft by introducing springs and dampers at contacts.

Human finger tips are fleshy, soft and deformable. They locally mold to the shape of a touched or grasped object due to their viscoelastic behavior, and for these reasons, are capable of extremely dexterous manipulation tasks. Viscoelastic materials have an interesting mix of material properties that exhibit viscous behavior (like the gradual deformation of molasses) as well as elasticity (like a rubber band that stretches instantaneously and quickly returns to its original state once a load is removed). The clearest way to visualize the behavior of a material containing both elastic and viscous components is to think of a spring (exerting forces to return to its unstressed state) in series with a dashpot (a damper that resists sudden motion, similar to the pneumatic cylinder that prevents a storm door from slamming shut).

Most robot fingers are crude and therefore rather limited in capability. This realization has led to the investigation of robotic manipulation with soft, human like fingers, for example, Sun and Howe [22], Trembley and Cutkosky[23], Howe and Cutkosky [24], Russel and Parkinsan[25], and Shinofa and Goldenburg[26] report on experiments in which either foam-backed or fluid-filled fingers successfully enhanced dexterous capability. Therefore, in this work, the robot fingers are made soft by introducing springs and dampers at contact. Thus by varying the damping and stiffness, control of the grasped object is achieved.

In the first step we put spring and damper to provide this viscoelastic effect in the grasping finger tips to make the grasping dexterous. Then we made its precise mathematical model by using BGM and put it in virtual environment. Then by using 20-Sim software we have studied by modeling and simulation different experiments in virtual environment the behavior of springs and dampers during grasping. Then we came to this conclusion that by changing spring stiffness and damping coefficient of damper the object can be grasped effectively. They influence the friction between the fingers and the object which plays a vital role in grasping stability. Figure 5 shows this setup.
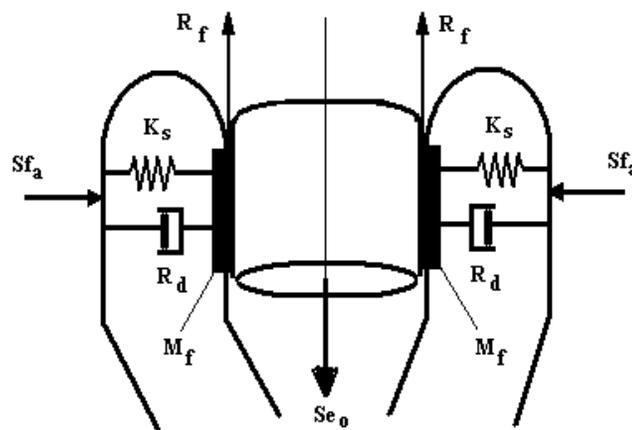
Fig. 5. Model of two soft fingers grasping the object.

Bond-graph modeling and simulation methodology is an attempt to explore the modeling intricacies encountered in the system, using an alternative but powerful modeling technique. The bond graph technique is a graphical representation of the power flow using bonds. It can be very helpful in the preparation of the equations of motion for digital simulation. This method is especially powerful when several physical domains have to be modeled within a system simultaneously. Although the bond graph is of relatively recent origin, it has been widely used in the simulation of system dynamics.

The bond graph is a graphic language for modeling dynamic systems. It displays, by letter elements and half arrows, the energy phenomena modeled in a system and the topology of the energy transfer between these phenomena. The bond graph representation of a system may be constructed in total abstraction from the mathematical model of the system. Even the individual phenomena may be graphically represented without considering the characteristic laws. This constitutes the physical level of the description contained in the bond graph representation.

A.Khurshid and M A Malik [27-29] have used bond graph techniques for modeling and simulation of different dynamic systems. Bond-graphs represent the dynamics of the system pictorially and are extensively used for the modeling of physical system dynamics in multiple energy domains, as discussed by A.Khurshid and M A Malik [30]. A bond-graph model is based on the interaction of power between the elements of the system. The cause-effect relationships help in deriving the system state equations. Further, the model yields insight into various aspects of the control of the system [31, 32].

The effects due to softness of the finger tips while manipulating an object and due to the friction at the finger contacts, and their internal damping and stiffness are modeled and successfully analyzed.

We have modeled dynamic control through a soft interface and formulate system dynamics through a soft interface represented by continuous-discrete time. Taking as an example force control based on the linear mass-damper-spring model.

4.6 Modeling the soft interface

Figure 5 shows a simplified model for a soft interface using linear mass-damper-spring components. The model describes soft robotic fingertips holding an object.

It consists of two fingers which are used to manipulate the objects as done by human fingers. The two fingers are made soft by introducing *linear mass, spring, and damper effects* in

these. Force Sf_a is applied to both fingers for the grasping of the object. The weight of the object tries to slip it from the grasping of fingers, whereas the friction between the fingers contacts surfaces with the object balance it. Friction is represented as damping by R_f at the finger's contact surfaces with the object and two dampers are part of the fingers having damping R_d. The stiffness of the springs used in the fingers is K_s. The mass of the outer surface layers of the fingers in contact with the object is M_f. The mass of object is M_o and its weight is taken as Se_o. *We have assumed that the soft material shows linear viscoelasticity. Parameters R_f, K_s, and R_d are time-invariant and positive.*

4.7 Bond-graph model and state space equations

The physical system shown in figure 1 is converted into bond graph shown in figure 6. A bond graph model is a precise mathematical description of the physical system in the sense that it leads to the state space description of the system.
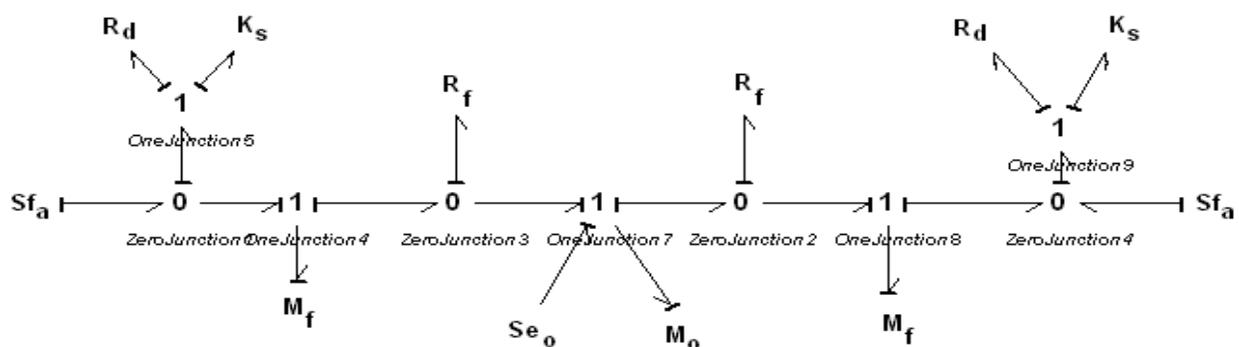

Fig. 6. The bond graph model of two fingers grasping an object as shown in fig-5.

The bond graph model shown in figure 6 leads to the following state space equations from 1-5 of the soft finger system:

$$\dot{p}_f = R_d*(Sf_a - p_f/M_f) + K_s*q_s + R_f*(-p_f/M_f - p_o/M_o) \tag{1}$$

$$\dot{p}_f = R_f*(-p_o/M_o - p_f/M_f) + K_s*q_s + R_d*(-p_f/M_f + Sf_a) \tag{2}$$

$$\dot{p}_o = R_f*(-p_f/M_f - p_o/M_o) + Se_o + R_f*(-p_o/M_o - p_f/M_f) \tag{3}$$

$$\dot{q}_s = -p_f/M_f + Sf_a, \tag{4}$$

$$\dot{q}_s = Sf_a - p_f/M_f \tag{5}$$

The description of different variables and parameters appearing in the above equations is given below.

$\dot{p}_f$ = force on finger by the object (N), $\dot{p}_o$ = force on object by the fingers (N)

$\dot{q}_s$ = velocity of spring in finger (m/s), Sf_a = applied force on finger (m/s)

R_d = damping in soft finger (Ns/m), R_f = friction at soft finger contact (Ns/m)

M_f = mass of finger & M_o = mass of object (kg),

The state variables are q_s = displacement of spring (m), p_f = momentum on finger (kg m/s), p_o = momentum on object (kg m/s). Total five state variables, for both the fingers q_s and p_f are assumed same.

Se_o = weight of object (N), K_s = spring stiffness (N/m)

4.8 Simulation and results

For simulation of the state space equations of the physical system, we have used 20-sim computer software [33]. The results of grasping the object by soft contact fingers and their corresponding root locus, based on BGM modeling and simulation are shown in figure 7-9. The flow signal on each finger is 0.1 m/s.
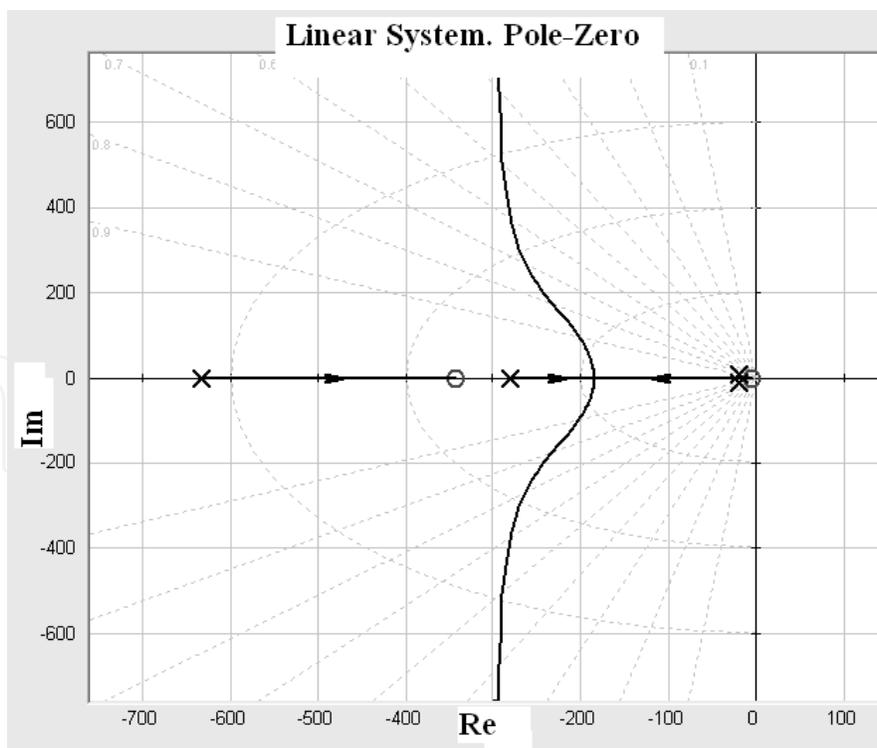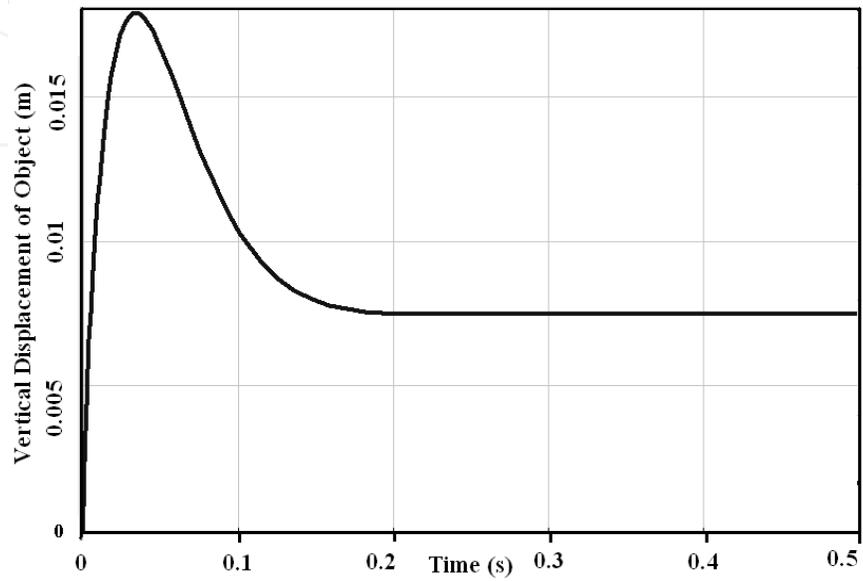

Fig. 7. The vertical displacement of object vs time adjusting stiffness and corresponding rootlocus of the dynamic system.
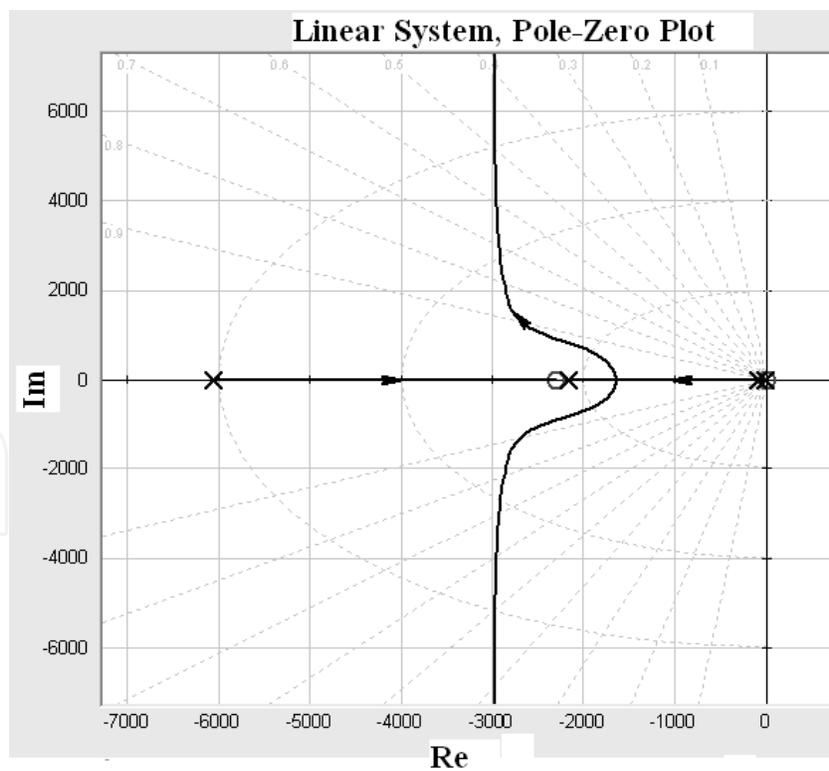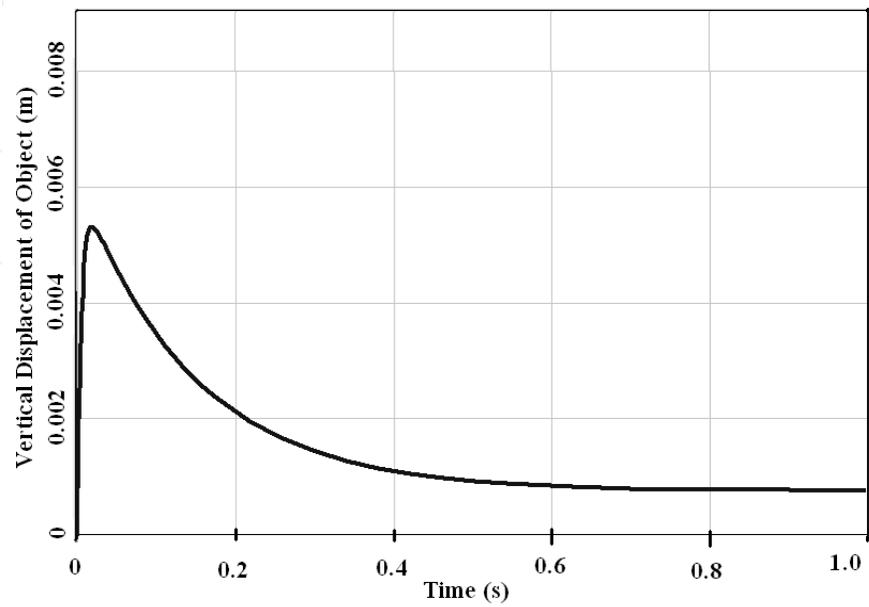
Fig. 8. The vertical displacement of object vs time adjusting finger damping and corresponding rootlocus of the dynamic system.
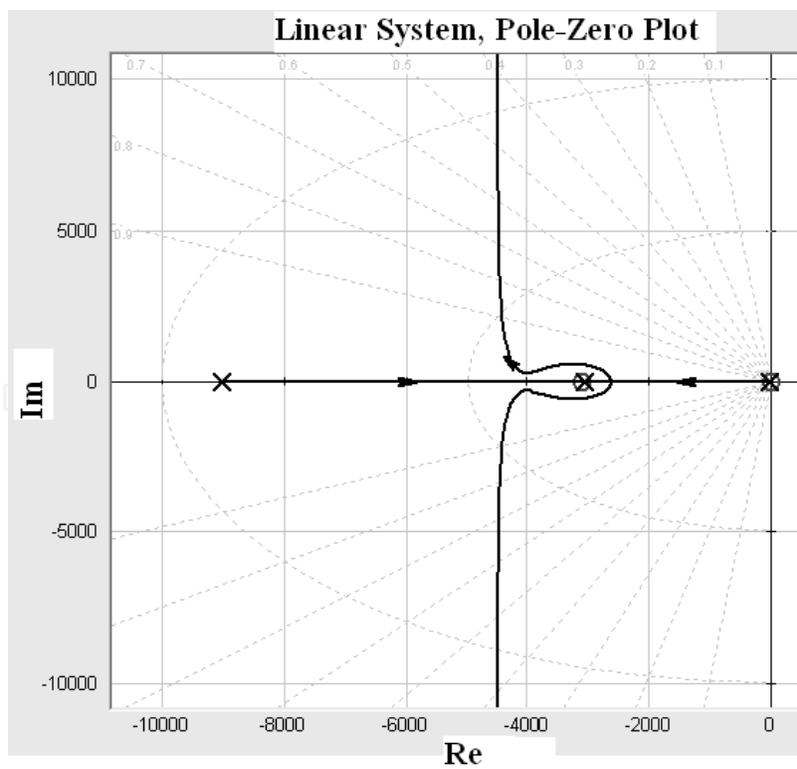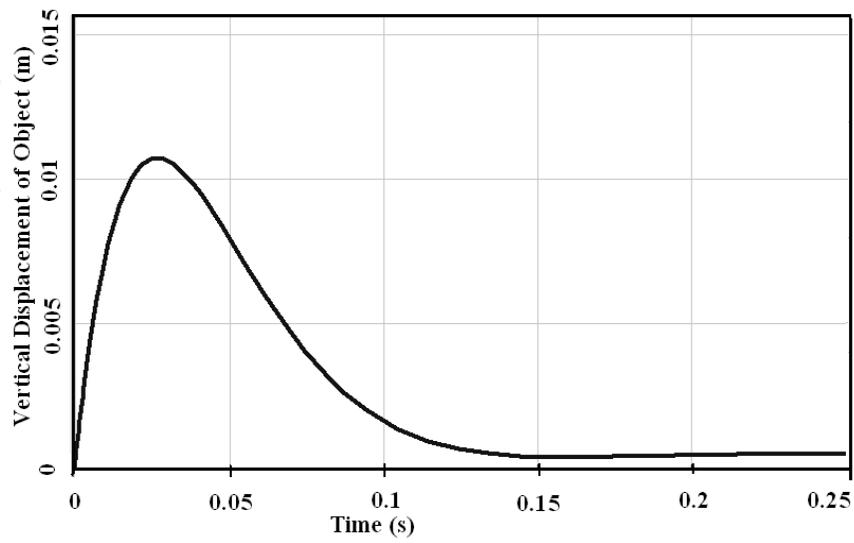
Fig. 9. Final adjusted vertical displacement of object vs time and corresponding rootlocus of the dynamic system.

5. Discussion

The objective of this work is to design and develop a robotic gripper which has soft fingers like human fingers. Soft fingers have ability to provide area contact which helps in dexterous grasping, stability and fine manipulation of the gripping object. This work is a step towards this final goal. We have carried out a detailed parametric study of the dynamic system and have observed the effects of changing material properties on the dynamics of the soft contact grasping system. In this work my objective is to optimize the values of spring stiffness and damping in the soft finger for an effective grasping. This has been achieved by making many simulated experiments.

The poles of the system have negative real parts *(-0.9017, -0.3050, -16.59+23.3j, -16.59-23.3j)* thus the exponential terms will eventually decay to zero. Since, for the springs and the dampers which specify the viscoelastic property of the soft contact fingers, the poles have negative real parts, the system is stable. *Table 2 to 5 show the consolidated results found from the simulated experiments shown in figures 7-9.* The left side curves present the response of the object vertical displacement with respect to time and the right side curves present the root locus for the corresponding system poles. Initially the system was settling down slow as the dominant poles are very close to the imaginary axis. Thus a zero is introduced to cancel the effect of dominant pole as seen by comparing the figures 7 and 9, and the root locus is pulled away from the imaginary axis to settle down the system quickly.

Sr #	$K_{s_1} = K_{s_2}$ [N/m]	$R_{d_1} = R_{d_2}$ [Ns/m]	$R_{f_1} = R_{f_2}$ [Ns/m]	Peak value [mm]	Peak Time [ms]	Steady State Displacement Value [mm]	Settling Time [s]
1	10	10	20	21.7	73.5	7.67	4.4
2	25	10	20	20.9	67.7	7.5	2.2
3	50	10	20	20.2	56.0	7.5	1.06
4	100	10	20	19.2	44.4	7.5	0.5
5	200	10	20	17.5	26.8	7.5	0.19

Table 2. Results of the simulated experiments by varying stiffness of springs and keeping damping and friction constant.

Sr #	$K_{s_1} = K_{s_2}$ [N/m]	$R_{d_1} = R_{d_2}$ [Ns/m]	$R_{f_1} = R_{f_2}$ [Ns/m]	Peak value [mm]	Peak Time [ms]	Steady State Displacement Value [mm]	Settling Time [s]
1	200	15	20	15.3	33.5	7.5	0.276
2	200	20	20	13.7	31.5	7.5	0.412
3	200	25	20	12.7	29.2	7.5	0.519
4	200	30	20	11.9	24.2	7.5	0.604

Table 3. Results of the simulated experiments by varying damping and keeping stiffness of springs and friction constant.

Sr #	$K_{s_1} = K_{s_2}$ [N/m]	$R_{d_1} = R_{d_2}$ [Ns/m]	$R_{f_1} = R_{f_2}$ [Ns/m]	Peak value [mm]	Peak Time [ms]	Steady State Displacement Value [mm]	Settling Time [s]
1	200	30	50	7.5	22.9	3.05	0.679
2	200	30	100	6.06	19.4	1.53	0.76
3	200	30	150	5.56	19.2	1.03	0.759
4	200	30	200	5.3	18.14	0.79	0.699

Table 4. Results of the simulated experiments by varying friction and keeping damping and stiffness of springs constant.

Sr #	$K_{s_1} = K_{s_2}$ [N/m]	$R_{d_1} = R_{d_2}$ [Ns/m]	$R_{f_1} = R_{f_2}$ [Ns/m]	Peak value [mm]	Peak Time [ms]	Steady State Displacement Value [mm]	Settling Time [s]
1	200	10	200	11.36	31.8	0.74	0.224
2	250	10	200	10.9	28.8	0.64	0.176
3	250	10	250	10.8	25.2	0.47	0.155
4	250	10	300	10.4	25.2	0.17	0.154

Table 5. Optimum results of the simulated experiments.

6. Conclusion

A new approach to design an effective soft contact grasping system is presented in this research work portion. The parametric study is made to evolve suitable values of material properties for an effective grasping. The bond graph modeling technique has been applied to obtain the precise mathematical model of the two soft contact robotic fingers. The two fingers are made soft by introducing linear mass, spring, and damper effects in them. The object is controlled by the friction between the fingers from slippage. It would have taken a lot more effort to get these results using traditional methods.

From the simulated results presented in Table 2 to 5, it is concluded that the friction, when increased between the contact surfaces, reduces the displacement of the object. Secondly the damping of the soft fingers when increased controls the peak value of displacement of object and also brings the stable value close to zero. Thirdly the stiffness of the spring effects the settling time of the object. Therefore, the damping of soft finger and the stiffness of the spring in the soft finger and the friction between the soft contact surfaces effects considerably in manipulation of the object. Combination of the stiffness and the damping is the viscoelastic property of the material. The flow signal is produced due to the applied forces on the fingers by some separate mechanism which is not the part of this work but may be designed or procured for experiments.

7. Acknowledgement

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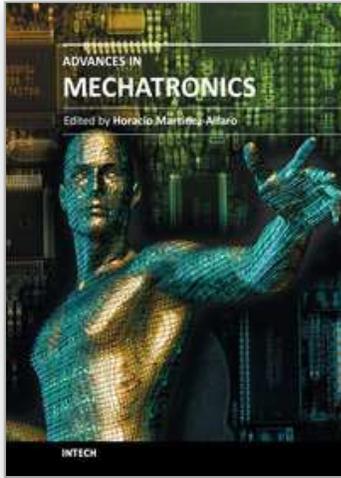
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