Modeling of the System Dynamics during the Soft Contact between Rigid Body and the Soft Material Using Bond Graph Technique

Ankush Nandal\textsuperscript{1}, Lt. Yati Parjesh\textsuperscript{2}

\textsuperscript{1} M. tech, Scholar Department of Mechanical Engineering (Manufacturing and Automation), SBMNEC, Rohtak
\textsuperscript{2} Lt. Assistant Prof., Department of Mechanical Engineering (Manufacturing and Automation), SBMNEC, Rohtak

\textbf{ABSTRACT}

Soft finger contact mechanics plays an important role in grasping stability as well as safe object handling during manipulation. The estimation of grasping forces and their distribution requires knowledge of contact characteristics, including relationship between forces and contact area and pressure distribution profile at the finger-object interface. The contact model defines the connectivity at the contact area between a finger and the grasped object. The soft finger contact model provides more realistic results in grasping and manipulation. However employing the compliant (soft) material in between the contact surfaces introduces added complexity. Here Modeling of the system dynamics during the soft contact between the rigid body and soft material is done using the bond graph technique. Conventional techniques such as Finite Element methods are usually convenient for static analysis and linear problems. The Bond graph technique does not have this limitation.

Keywords: Soft finger contact, Rigid Body, grasping forces, FEM,

\textbf{INTRODUCTION}

The development of humanoid robots as well as the increasing interaction between human and robots are new challenging research topics towards which many efforts are directed. The skills of the robot are deeply affected by the contact interface through which robots interact with the environment. Generally there are three contacts models:

(1) Frictionless point contact,
(2) Point contact with friction (hard finger), and
(3) Soft contact.

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{Contact Type} & \textbf{Picture} \\
\hline
Frictionless Point Contact & \includegraphics[width=2cm]{Frictionless_Point_C} \\
Point Contact with Friction & \includegraphics[width=2cm]{Point_Friction_C} \\
Soft Finger Contact & \includegraphics[width=2cm]{Soft_Finger_C} \\
\hline
\end{tabular}
\end{center}

\textbf{Figure 1: Common Contact Types}
Objective of the current work:

Modeling of the system dynamics during the soft contact between the rigid body and soft material is the main objective of this thesis work. Here the modeling is done using the bond graph technique. Bond graph technique is a very useful, convenient and computationally advantageous for dynamic analysis. In this work, an effort has been made to integrate the bond graph formulation for dynamic modeling and analysis with the advantages of the finite element method. Finite Element methods are used for calculating the stiffness matrix and mass matrix for the soft material when the rigid body interacts with soft material. In finite element method Weighted Residual Approach is used to calculate the stiffness matrix and mass matrix for soft material. Soft material under the action of force, as shown in figure.

![Rigid Object, Soft finger Material, Robotic Finger](image)

Fig 2: A rigid body making contact with Soft Material on Robotic Finger

LITERATURE REVIEW

Van Anh Ho and Shinichi Hirai, 2010: In this they focused on the method to investigate the sliding motion of soft finger tip on the dexterous manipulation. To investigate the deformation of the fingertip during this process, they consider the soft fingertip as if it was composed of a finite number of plastic cantilevers which are compressible and bendable. After that, various experimental results will be shown to verify this model.

Kazuki Namima, Zhongkui Wang and Shinichi Hirai, 2009: In this paper they developed a new model to simulate contact and rolling motion between two soft fingers and an objective by using Finite Element and Constraint Stabilization Methods. This model is more efficient than the penalty method in connecting boundaries of objects through discrete models such as Finite Element models and particle models.

Hiroaki Yoshida, Mitsunori Tada and Masaaki Mochimaru, 2006: In this paper they developed a three dimensional Finite Element Model of the fingertip and performed a determination of material properties using an optimization technique so that the contact area of Finite Element Analysis corresponded with that of the experiment when a rigid plane was indented. The Finite Element Model slid on the rigid plane while indented using determined material properties and ABAQUS subroutine based on the rubber friction.

Paolo Tiezzi and Gabriele Vassura, 2005: In this paper they investigated the influence of the soft layer thickness on quasi static behaviour of rigid core fingertips with respect to different materials and loading conditions (pure normal load, normal and tangential load, normal load and torque). The experimental activity aims to outline the mechanical behaviour of hemispherical fingertips specimen made with constant external shape but variable size of inner core.

Anand Vaz and Shinichi Hirai, 2004: In this paper they presented a simpler model for such a joint which can still capture most of behaviour of the bone joint system. The model is applied to a ball and socket joint system with soft cartilage. The role of soft cartilage material is replaced by stiffness field, whose properties are defined with relation to ball position with respect to any fixed reference point within the socket. For study of dynamics they used the bond graph technique.

Imin Koa and Fuqian Yang, 2004: In this paper, they studied the nonlinear stiffness of contact for soft fingers under a normal load. This new theory relates the approach displacement of soft fingertips with respect to the
normal force applied. The nonlinear contact stiffness is found to be the product of an exponent and the ratio of the normal force versus approach displacement. Stiffness relationship of Hertzian contact for linear elastic materials is known to be a special case of the general theory presented in this paper.

Nicholas Xydas and Imin Kao, 1998: A new theory in contact mechanics for modeling of soft fingers is proposed to define the relationship between normal force and area of contact for soft fingers by considering the soft finger materials as nonlinearly elastic [7]. The results show that the radius of contact is proportional to the normal force raised to the power of $\gamma$ from (0 to 1/3).

Parsad Akella, Roland Siegwart, and Mark Cutkosky, 1991: In this paper they address the issue of controlling contact forces generated when the fingers of a dextrous device first close on an object [8]. The use of active fingertips is proposed to enhance the system performance and avoid contact instability problems resulting from non collocated sensors and actuators. A first step towards exploring this issue is the study of an idealized controllable fingertip making contact with an object.

C. Chang and Mark R. Cutkosky, 1995: In this paper they determined the kinematic effects of soft fingertips during manipulation with rolling [9]. The long term goal of this work is to produce a model of rolling with soft fingertips that can be incorporated into a real time control system to produce current best estimates of contact locations and velocities when planning and executing rolling maneuvers. They conducted experiments with a variety of sift materials and found that in most cases, for modest deformations on the order of 10% of the undeformed fingertip radius, the change in rolling distance or speed is small but noticeable and can be either positive or negative depending on the fingertip material.

K.B Shimoga and A.A. Goldenberg, 1992: In this paper, six chosen materials – plastic, rubber, sponge, a fine power, a paste and a gel are experimentally compared for their ability to overcome 1) the impact forces that result during grasping. 2) a hand with hard finger cannot securely grasp objects that have uneven surface due to the poor conformability of fingers. 3) Dissipation of strain energy. Results show that sponge is the most suitable and plastic is the least suitable for our application [10].

**METHODOLOGY**

Initially a small piece of soft material, Silica Rubber, of Robotic fingertip dimensioning 0.05m length, 0.01m width and 0.005m thickness is considered during this work. This material is divided into small 40 equal rectangular boxes of 0.0025m length and 0.005m width, considering the thickness as constant equal to 0.005m. Then each rectangular box is divided in two triangular parts. So small piece of soft material is discretized into 80 triangular elements. Here three cases will be considered, firstly force acting at a point, secondly a square box resting on soft material, thirdly a cylinder resting on the soft material. As at the initial stage the rigid body will make contact at one point, so during modeling it is taken as normal force acting at one point. Under the action of that forces the behavior and deformation of the material is analyzed. Using Finite Element Engineering the force–deformation relation and mass matrix is investigated. The values of Young Modulus of Elasticity (E) and Poisson’s Ratio ($\nu$) are considered, after going through the relevant literature survey, as 1000Pa and 0.48 respectively.

**Analysis by Finite Element Method:**

Finite element formulation of 2-D problem using triangular element and its analysis is introduced in this chapter. Finite element method is a powerful tool to find the solution of a complicated problem by replacing it by a simpler one. Since the actual problem is replaced by simpler one in finding the solution, we will be able to get the approximate solution rather than exact solution. Finite element method is very advantageous to solve the boundary value problem. Boundary value problem consist of differential equations with some boundary conditions. The F.E.M. converts the partial differential equations into a set of algebraic equations.

From 1960 to 1975, the FEM was developed in the following directions:

1. FEM was extended from a static, small deformation, elastic problems to
   - dynamic (i.e., vibration and transient) problems,
   - small deformation fracture, contact and elastic - plastic problems,
Non structural problems like fluid flow and heat transfer problems.

(2) In structural problems, the integral form of the balance law namely the total potential energy expression is used to develop the finite element equations. For solving non-structural problems like the fluid flow and heat transfer problems, the integral form of the balance law was developed using the weighted residual method.

Analysis of Soft Material under Consideration by F. E. M:

In this analysis, a small part of Robotic Fingertip of dimensioning length 0.05 m, thickness 0.01 m and width 0.005 m is considered. The choice of material depends upon the type of application. This material is divided into small 40 equal rectangular parts of 0.0025 m length and 0.005 m width, considering the thickness as constant equal to 0.005 m and further each part is discretized in two triangular elements for Finite Element Analysis (EFA). Base of the material is taken as fixed (Dirichlet boundary condition). At the initial stage the rigid body will make contact at one point, so during modeling, it has been assumed that a normal force is acting at one point. Under the action of that force, the behavior and deformation of the material is analyzed. Using Finite Element Engineering the force deformation relation is investigated. Finite Element method has been integrated with Bond graph for dynamic analysis. During Finite Element procedure, for the development of stiffness matrix and mass matrix, the weighted residual approach has been used. The values of young modulus of elasticity (E) and Poisson’s ratio (v) are considered after going through the relevant literature survey. Here in this analysis, young modulus of elasticity and Poisson’s ratio (v) of the soft material taken as:-

Young modulus of elasticity (E) = 1000 N/m² and Poisson’s ratio (v) = 0.48

The first step is to calculate material matrix D. It is a symmetric (3x3) material property matrix, given by

\[ D = \frac{E}{1 - \nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1 - \nu}{2} \end{bmatrix} \]

Integration with Bond Graphs:

Finite element analysis in widely used for static analysis and linear problems. But in case of dynamic analysis it fails. So for dynamic analysis we have to integrate FEM with other tool. In this work, Finite Element method, integrated with Bond graph, has been used for dynamic analysis of the soft material during contact interaction. The global stiffness matrix, formulated by adding up the stiffness matrix of each element, with the help of elemental connectivity, has been used for force-displacement relationship. Similarly the global inertia matrix, formulated by adding up the mass matrix of each element, with the help of elemental connectivity, has been used for flow-momentum relationship. Bond graph Modeling is used to represent system dynamics. A bond graph model is based on the interaction of power between the elements.

Bond graph Modeling:

So far global stiffness matrix and mass matrix of relevant problem has been calculated. Now for dynamic analysis of contact between the soft body and hard body, bond graph modeling is to be done. For modeling a small part of Robotic Fingertip dimensioning length 0.05m, thickness 0.01m and width 0.005m of the soft material (Silicon Rubber), is considered during this work. This material is divided into small 40 equal rectangular blocks of 0.0025m length and 0.005 m width, considering the thickness as constant equal to 0.005m and the base of the material is fixed (Dirichlet boundary condition). At the initial stage, the rigid body will make contact at one point, so during modeling it is taken as a normal force is acting at one point. The material is divided in 80 elements for Finite Element analysis. Numbering of each node and its position by coordinates. This is done by asking following two basic questions.

1. What do the elements (all) give to the system?
2. What does the system give to the storage elements with integral causality?

**SIMULATION RESULT**

The term simulation described as a procedure of establishing a model and deriving solution from it covers the whole gamut of physical, analogue, and analytical and numerical investigations. Geoffrey Gorden has defined system
simulation as “The technique of solving problems by observation of the performance, over time, of a dynamic model of the system.” Thus the dynamic model and the time element are two important components of system simulation. In many situations, the time element may not be significant parameter. System behavior may not be a function of time, but still the system is analyzed by step-by-step calculations of the successive stages of the system. Simulation models can be classified as being static or dynamic, deterministic or stochastic and discrete or continuous.

Parameters used in Simulation:

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>UNITS</th>
<th>SIGNIFICANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>1000 N/m²</td>
<td>Young Modulus of Elasticity</td>
</tr>
<tr>
<td>ν</td>
<td>0.48</td>
<td>Poisson’s Ratio</td>
</tr>
</tbody>
</table>

Link Properties

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.005 m</td>
</tr>
</tbody>
</table>

Derivation of System Equations

Equations in the state space form for the system are taken by Bond Graph Technique and discussed above on page by two questions

1) What do the elements give to the system?
2) What does the system gives to the elements with integral causality?

Simulation Results and Discussions:

The models have been tested through simulation. Simulation is done using MATLAB and results are discussed here. The total simulation time is taken as 10 seconds. The results are shown graphically at 10 intermediate instances of time.

CASE 1:- Here initially a point load of 2N is assumed acting on node 11, i.e 11th point of first layer. Deformation of the layer is analyzed at equal interval of time. This deformation of layers at different intervals of time is shown in Figures from 1.1 to 1.5. The damping is also considered as R=10N-s/m.
Figure 1.2

Figure 1.3

Figure 1.4: Deformation of layer at each interval of time
CONCLUSION AND FUTURE SCOPE

Modeling of contact interaction is one of the most important subjects in dexterous manipulation because grasping and manipulation are dictated by contact behavior. It has been established that the deformation effect of soft fingertips plays an important role in the manipulation of an object by the hand. It is therefore necessary to consider the deformation effect of soft fingertips for successful soft-fingered object manipulation tasks. In case of rigid or hard bodies, contact interaction can be considered to occur at a point. However in case of soft contact, the contact force is distributed over an area of contact due to the effect of material compliance. Modeling of this aspect is indeed a challenging task.

- Modeling of soft material during contact interaction is carried out in this thesis work using Bond graphs. Conventional techniques such as the Finite Element method are usually convenient for static analysis and linear problems. The Bond graph technique does not have this limitation. It is especially convenient and computationally advantageous for dynamic analysis. The Bond graph models are further useful for control system analysis and design.

- An effort has been made to integrate the bond graph formulation for dynamic modeling and analysis with the advantages of the finite element method. Finite Element methods are used for calculating the stiffness matrix for the soft material or the force-deformation relationship during contact, as the deformation occurs when the rigid body interacts with soft material.

- The models have been tested through simulation. Simulation code has been developed using MATLAB and results are plotted, analyzed and discussed. The graphical results obtained by changing various parameters and conditions, show the behavior of soft material during contact interaction. During deformation of the material, the effect of compliance under compatibility conditions is observed.

The future scope of this work is to develop dynamic models for contact based manipulation. Manipulation, in general, includes both translational and rotational movements. Contact manipulation includes rolling with soft fingertips. The analysis of contact area as it continuously changes during manipulation is an interesting and open problem in robotics at present. The development of forces and moments at the contact interface due to the change in the contact area during manipulation also needs analysis. The models are of special significance for (1) design and analysis for robotic hand development for dexterous manipulation, soft fingertips, etc. (2) the control of robotic manipulation and prosthesis.
REFERENCES


