Flexible Endoscopic Robot

B.Tech. Project Mid-Term Evaluation Report

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Abstract

A simulation of the navigation of an endoscopic device inside a human body has been attempted on SPACAR. The human tissue has been modelled using force fields based on the Hertzian contact model. We will be finding adequate parameters for friction and damping coefficients in order to develop a realistic model of the internal organs of the human body. The endoscope has been modelled as multiple finite planar beam elements for optimally calculating the deformation and forces endured during operation.

1 Introduction

Modern surgery has progressed rapidly with advancement in technology and medication. Earlier, treating or observing any internal part of the body required a surgeon to make large incisions resulting in excessive blood loss, pain, infection and a longer recovery period. The introduction of Minimally-Invasive-Surgery in recent years had greatly reduced damage to tissues leading to faster recovery. Further advancements to this field in terms of endoscopes and colonoscopes now give rise to the possibility of observing and treating diseases with almost no blood loss and damage to the tissue.

These endoscopic instruments allow the surgeon to deploy cameras to observe the intestine of the patient and check for ulcers, tumours, inflammation etc; they can be used to place the ultrasound probe closer to organs that can be difficult to image, such as pancreas; finally, endoscopes can also be used to carry out surgery such as removal of gallbladder, sealing/ tying fallopian tubes and removal of tumours.

The use of robotics systems in surgery allow for more precision, miniaturization and smaller incisions. Further, these robotic systems allow the surgeon to control instruments in a more convenient working position, it scales his movements and improve visualisation by showing enhanced three-dimensional magnified images. Naturally occurring tremors are filtered out by the robot automatically decreasing chances of human error.

In our project we want to focus our attention on the interaction between multiple soft bodies allowing us to simulate the movement of a soft robotic endoscope/ colonoscope inside a human body. Just like the current medical procedures where the doctor is physically controlling only one end of the endoscope, we are also constraining the translational and rotational motion of only one end of the device.

An accurate modelling of the characteristics of the motion of a robot inside the human body is critical for further development of these robots as well as proper training of medical professionals. Modelling these interactions however is extremely complex and challenging. Machado et. al. [1] talk about how geometry, kinematics and nature of the contacting body all play a critical role in determining the stiffness and damping coefficient of the contact. Further, non-smooth systems also exhibit nonlinearities and discontinuities such as those caused by intermittent contact, nonlinear material properties etc.

As a first step in our project, we have started off by studying Hertz contact forces wherein we ignore energy transfer and focus on linear elastic bodies. To represent the endoscopic tube, we have made use of multiple planar finite beam elements while surrounding objects have been defined as force fields. We are currently accounting for only reaction forces between the bodies in contact, but we aim to include friction forces as well towards end of this term. We further plan to use more involved variations of Hertz contact forces which have been further discussed in theory. If time permits, we aim to carry out tests and make prototypes to improve our simulation further.

2 Literature Survey

Over the last few decades, several contact models have been proposed, most of which have the Hertzian model as their foundation. The classical Hertzian theory states that contact force is a nonlinear function of the depth of indentation, assuming the bodies are perfectly elastic and there is no energy dissipation. However, this model has many limitations and is not suited for any practical application. Machado, et al. [1] in *Compliant contact force models in multibody dynamics* describe various compliant force, i.e. based on indentation and contacting bodies' properties, formulations which try to deal with the problems associated with the Hertzian model. Two widely used models are Kelvin Voigt model which includes a damping term which is dependent on contact velocity and Lankarani-Nikravesh model which accounts for permanent deformations using a hysteresis damping coefficient. Kelvin Voigt model too has a serious drawback, i.e., the force at the beginning of the contact is not zero due to a non-zero velocity term. Continuous contact forces for soft bodies have been comprehensively described in a review paper by Paulo Flores [2], et al. who gives an overview of three approaches:

a. Dissipation with coefficient of restitution involving balance of energies and momentum.
b. Storage of a part of kinetic energy as elastic energy which would lead to deformations.
c. Dissipation through internal damping.

Most of the work being done in endoscopy nowadays focus on either creating physical models or simulations using computer graphics and virtual reality for the training of the practitioners. There are numerous papers like Tingxi Wen et al. [3] and MacIntosh et al. [4] which focus purely on virtual reality training based on a real-time computational approach.
Woojin Ahn, et al. [5] describe a contact model which calculates forces given displacement measurements by a virtual reality-based colonoscopy simulator. Levin J. Sliker et al. [6] present a frictional resistance model for tissue-capsule endoscope sliding contact. The model outputs the drag force required to move the endoscopic capsule through the gastrointestinal tract. However, this model is limited to interaction between a stiff small capsule and incompressible tissue. Many authors have also attempted to develop friction models based on Lankarani-Nikravesh forces.

Some work has also been done on simulation-based in relatively more conventional settings. Alexander Verl in his book, *Soft Robotics: Transferring theory to Applications*, describes some state-of-the-art simulation techniques for soft body robotics and the basic concepts of e-Robotics, which provides a comprehensive software environment suited for such applications. Khatait et al. [7] use a simulation software *SPACAR* to model the sliding contact forces of a flexible endoscope inside a comparatively rigid tube. The rigid tube is described with multiple beam elements whereas the tube is essentially a force field in a 3-D Bezier curve form. The endoscope is held at its rear end where no rotation is allowed and as the instrument enters the tube, it experiences a force depending on the contact penetration and damping coefficient of the tube wall. The force field is a slight variant of Kelvin Voigt contact model and is divided into two regions:

a. Transition region, where the indentation term is a second-order polynomial and the damping term is third order.
b. Full contact region with linear polynomials.
c. A simple friction term is also incorporated in the given approach.

Charles R. Welch and John D Reid did colonoscopy simulations in a slightly more sophisticated software *LS-DYNA*. The tissues here are modelled through adjusted Mooney-Rivlin rubber model and the results are obtained for different parameters iteratively. The simulation attempts to show the looping phenomenon, a phenomenon in which the endoscope forms a loop along the walls of the colon due to the application of larger forces which leads to more difficulty in manoeuvring and poses a significant challenge to overcome for the doctor.

3 Project Objectives and Work Plan

3.1 Motivation

Modern day endoscopic operations entail a lot of problems; even the most experienced surgeons find it difficult to navigate inside the complex structures of the body or to avoid the chances of loop formation. The problem in hand is to accurately simulate the navigation of a flexible endoscopic robot using multielement formulation. This not only involves modelling the motion of the endoscope but also suitably defining the interacting environment. The simulation shall enable us to study the forces involved in endoscopic surgeries and their effect on the motion of the front tip and if possible, the phenomenon of looping. Further these simulations can be used to train surgeons as well.

However, to accurately model and verify these simulations is extremely difficult because it is almost impossible to obtain any real-world data. Fan etal. [8] do talk about carrying out tests on rats, however doing such a detailed study is beyond the scope of this paper. We aim to develop and perfect simulations of interaction of beam elements with various simple shapes and build further on that. We have talked about this in more detail in the section 4.2.

3.2 Objectives

a. To simulate the navigation of a flexible endoscope inside a human oesophagus/ colon using a simulation software. The interaction between the soft bodies will be broadly based on Hertzian contact force models. We plan to select a force formulation which will appropriately model the effect of wall damping and hysteresis and consider the frictional forces involved.
b. To model the human oesophagus/ colon using simple geometries where forces are defined as force fields. These fields shall accurately model the nonlinearity in the stiffness and damping properties of the walls.
c. The endoscope on the other hand will be modelled using Finite Element Analysis, which would allow us to focus our computation on the deformation of the endoscope while closely mimicking actual forces acting upon it.
d. To observe the forces, deformation and stress endured by the endoscope during the procedure. This shall allow us to ascertain the range of suitable material properties for a soft surgical robot.

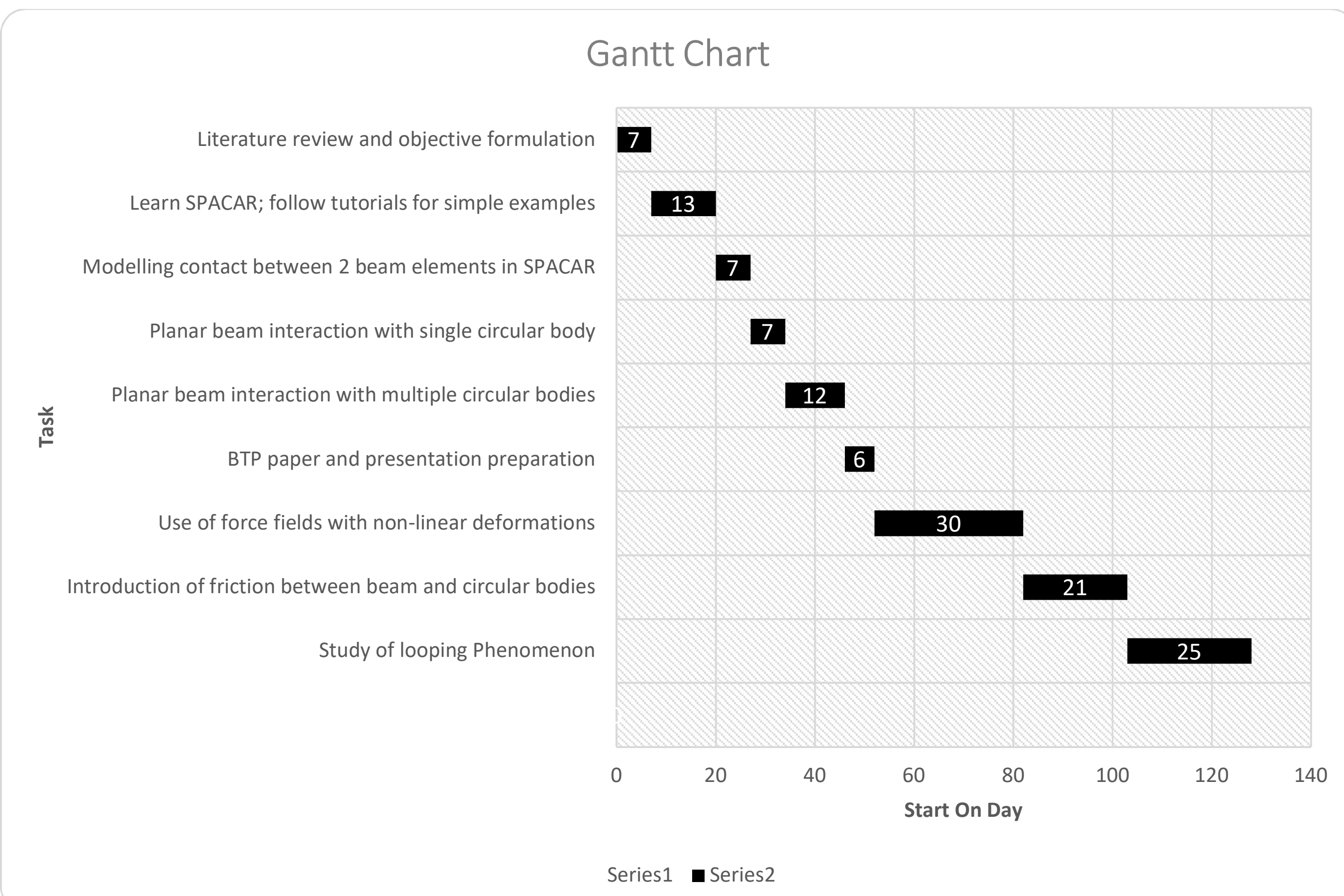
3.3 Additional Objectives

e. Once the model is complete, we wish to study more about the phenomenon of looping, its correlation with the forces applied at the end of the endoscope and its prevention.
f. We further wish to develop a simple prototype that can verify the results of our simulations for the interaction between the beam and simple deformable geometries.

3.4 Methodology

To carry out our simulations, we are making use of the software SPACAR. SPACAR is based on the non-linear finite element theory and is well suited for the analysis of rigid and flexible structures in both 2-D and 3-D environments. It is computationally efficient and allows for a detailed visualisation of the endoscope in the environment using tools like SPAVISUAL.

As mentioned earlier, force fields are based on analytical force models, while the endoscope is finite element based. So, SPACAR essentially takes care of the overall motion of the beam once we define the forces fields. The force model being developed by us will be a variant of Hertzian contact formulation. Currently we have only assumed a linear force field, however we aim to include damping and friction due to the walls of the organs as well. Also, the parameters have been chosen such that the surrounding organs are more flexible than the robot itself.



4 Work Progress

4.1 Theory

The relevant theory is described in following two sections: 4.1.1. FEA of the endoscope (made of beam elements), 4.1.2. Contact force fields

4.1.1 Endoscope

The endoscope is made up of planar beam elements which are already defined in the simulation software SPACAR. A 2-D flexible beam element has two nodes and 6 degrees of freedom. It is therefore defined by x and y coordinates of the two nodes and the angle of rotation at the two nodes. JB Jonker in his book Dynamics of Machine [9] defines the flexibility of the beam element in terms of three ‘deformation modes’ (**e**). The first deformation mode represents the elongation in the beam, while the other two capture the bending angle at the two ends. The deformation modes can thus be defined as follows:

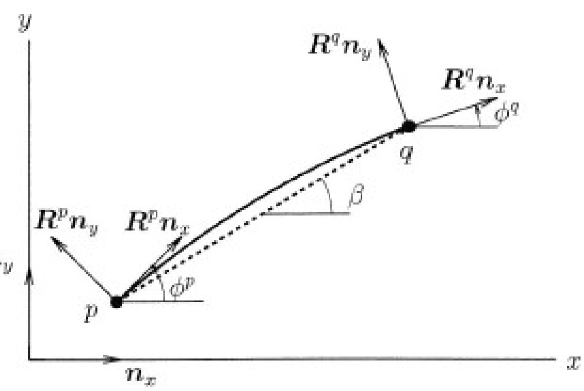


Figure 1: Planar beam element

$e_1 = l - l_0$ (elongation) (i)

$e_2 = -(\mathbf{R}^p\mathbf{n}_y, l)$ (bending at end 1) (ii)

$(=(x^q-x^p)\, sin\emptyset^p - (y^q-y^p)\, cos\emptyset^p)$ (iii)

$e_3 = (\mathbf{R}^q\mathbf{n}_y, l)$ (bending at end 2)

Here, l is the length of the beam element, l_0 the initial length, R^p and R^q are the rotation matrices at the two ends, i.e,

$\mathbf{R}^p = \begin{bmatrix} cos\emptyset^p & -sin\emptyset^p \\ sin\emptyset^p & cos\emptyset^p \end{bmatrix}$

$\mathbf{R}^p\mathbf{n}_y$ represents the vector perpendicular to the end ‘p’.

After defining the beam elements, its inertial properties and external forces/ velocities, the software handles the kinematic and dynamic analysis part. A node or a deformation mode can be either independent ($\mathbf{x}^m$, prescribed dof), dependent ($\mathbf{x}^c$) or fixed ($\mathbf{x}^o$). For the kinematic analysis part, each deformation mode **e** is written as a function (***D***) of x (the expression for planar beam is given in (iii)). In a nutshell, **x** and **e** of the element are defined in terms of the generalised coordinates **q**, i.e. the complete motion is described with respect to the motion of the independent coordinates $\mathbf{x}^m$ through functions called geometric transfer functions (***F***) and their derivatives are taken to calculate the velocities and accelerations. For dynamic analysis, the software uses the principle of virtual power and the principle of d’Alembert. Further discussion on kinematics and dynamics is beyond the scope of the report.

4.1.2 Contact Forces

To revisit and formalise some of the concepts discussed in Section 2, Hertzian contact forces are given by:

$$F = K\delta^n$$

where K is the contact stiffness parameter and n is the nonlinear coefficient, δ is the depth of indentation.

The Kelvin-Voigt model is an improvised model which considers damping forces proportional to the indentation speed. It is given by:

$$F_N = K\delta + D\dot{\delta}$$

where D is the damping coefficient and $\dot{\delta}$ is the velocity/ rate of indentation.

As was mentioned, these models suffer from some major issues and are not in much use. It was further refined by Lankarani-Nikravesh [10] who included hysteresis damping coefficient:

$$F_N = K\delta^n \left[1 + \frac{3(1 - c_r^2)\dot{\delta}}{4\,\dot{\delta^{(-)}}}\right]$$

Here, c_r is the coefficient of restitution and $\dot{\delta^{(-)}}$ is the relative approach velocity.

As can be seen, there is no damping for perfectly elastic system (c_r = 0). The damping coefficient is written as D = $\mu\delta^n$, since damping should be zero for zero indentation (unlike Kelvin-Voigt model). This equation is obtained by equating kinetic energy losses to the work done by the deformation forces. Work done is described as a hysteresis loop, i.e.,

$$\oint D\dot{\delta}\, d\delta = 2\int_0^{\delta_m} \mu\delta^n\, \dot{\delta}\, d\delta$$

The change in kinetic energy is simply:

$$\frac{1}{2} m^{eff} \dot{\delta^{(-)}}(1 - c_r^2)$$

where m^{eff} is the effective mass of the system.

4.2 Work Done

We have studied various variations of the Hertz contact forces looking at both linear and non-linear models. In this project, we want to focus on the force endured by and deformations of the endoscopic beam in more detail. We are also interested in looking at how it navigates along a sinuous path. Therefore, we have modelled the endoscope as a beam element to get a more realistic behaviour. At this stage, we have accounted only for reaction forces between bodies in contact; we look to include a more comprehensive model to represent human tissue as well.

We had started off working on interaction between two rods composed of planar beam elements. It is to be noted that in a basic simulation setting, the ‘no penetration’ condition is not defined; that is to say that a rod will simply move past the other rod if their nodes are not in contact. Following this, one possibility was to use the relatively complicated idea of floating nodes which would ensure that a node is created wherever the two rods are in contact. We, however, went ahead with defining analytical contact forces which would take into account the crucial element of flexibility and non-linearity in the system.

Currently the endoscope is composed of 20 planar beam elements which share the rotation component with their adjacent element. A constant velocity is being given at its rear end which is restricted from rotating. We have defined force fields in three circular regions, details of which will be provided in the section below. The force fields as of now follow simple Hertzian model with n = 1 (linear model with no damping). The material properties of the environment have not been considered yet, but the endoscope has certain damping and stiffness constants.

4.3 Simulation Details

The various parameters currently being used, and the simulation results are described in this section:

4.3.1 Endoscope

Type of Elements	Planar Beam
Number of Elements	20
Length	5 m (from x=0 to 5)
Mass per unit length	0.001532 kg/m
Rotational Inertia J	0.00000000002393 kg-m^2
Axial Stiffness (EA)	69300 N/m
Bending Stiffness (EI)	0.00164 N/m
Longitudinal Damping	0.000001 N-s/m
Bending Damping	0.000001 N-s/m

4.3.2 Force field

<u>Field 1</u> Centre: X – 8m | Y - 0.75m Radius: 1m k: 0.05 N/m	<u>Field 2</u> Centre: X – 7.5m | Y - -1.2m Radius: 1m k: 0.05 N/m	<u>Field 3</u> Centre: X – 8.5m | Y - -0.95 Radius: 0.55 k: 0.05 N/m

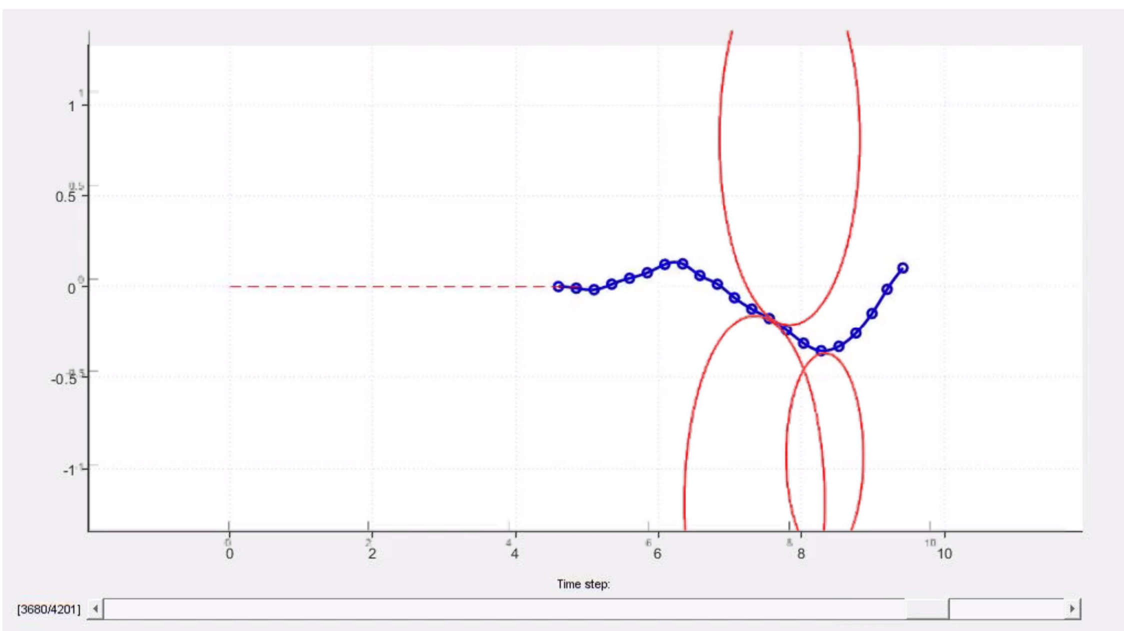


Figure 2: Snapshot from simulation

4.3.3 Discussions and Results

The simulation consisted of an endoscope represented by 20 planar beam elements. To drive this endoscope forward, a constant velocity of 1m/s was provided to the left most node. Additionally, the rotation and translation at this node were restricted as well. For all beam elements except the first, all 3 deformations, i.e. elongation, bending at first node, bending at second node were allowed.

Depending on the position of each of the nodes (42 in total) with respect to the centre of force fields, the force acting on them was calculated. The simulation environment provided by SPACAR determines the correct position of each node for each time step by running an optimisation algorithm. This simulation ran for a total of 20 seconds and had 1,00,000 time steps. The software also provides us with a log of the forces endured and deformation of each node at any given time point.

The deformation and final shape taken by the endoscope has been shown in the figure 2. We are still analysing the log files of the simulation to get information about the forces and deformations endured by all nodes and will publish those results in the final project report.

Some of the limitations of the simulation presented by us include:

a) The force field strength needs to optimised further to represent the material properties of human tissues in a more realistic manner. Further, we need to include non-linear behaviour and introduce damping and friction as well.
b) The parameters of the endoscope, namely density, stiffness need to be refined to bring them inline with the materials used for endoscopes today.
c) Further, there is a limitation on the number of elements we use for the beam. Currently, the force acts on only 42 nodes to represent a beam defined for it, leading to non-smooth motions and interactions.

5 Conclusion and Further Work

We plan to experiment with various force fields and choose parameters for the interactions involved. Current model is based on linear Hertzian formulation but, we will try to move towards more useful models such as Lankarani-Nikravesh. Friction forces will also be considered once we are able to resolve the complexities involved. For instance, the oesophagus wall is made of four different layers, each with its set of stiffness parameters. We will try to vary the parameters iteratively to report results and choose different geometries to describe the environment more accurately.

We also plan to experiment with the FE model by varying the number of nodes, the number of deformation modes and the way of manoeuvring the rear end (constant force or constant velocity).

6 References

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