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Research paper

Theoretical Smart Design and Control for an Atruamatic Grasper

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Abstract

Accurate knowledge of the grasping force is essential when avoiding tissue trauma during grasping and manipulation in abdominal surgery. The aim of this paper is to present a theoretical design of laparoscopic grasper complete with control system. Mechanically the design comprises of a load cell and actuator added to the traditional grasper. The original grasper was also modified slightly for example, the standard type of teeth were replaced with waveform teeth to maximise grip yet reducing the chance of tissue trauma. Control wise the grasper works by the load cell measuring the applied force which then controls the actuator via the control system. The applied force on the tissue either increases or decreases so that the demand force and the output force applied to the tissue are the same. To simulate the force the load cell would experience the Generalised Maxwell model was used to simulate the viscoelastic characteristics of a biological tissue.

1. Introduction

One of the current research areas in surgical technologies is Minimally Invasive Surgery (MIS). MIS is defined as “the use of flexible and rigid instruments inside any operative field” [1]. This form of operation reduces the need for multiple stitches due to the body not needing to be opened to a great extent. Due to this drastically reduced openness to the environment the chance of infection is greatly abridged. The disadvantage of this method however is that viewing the Viscera of the human body must be done indirectly via cameras. This reduces the surgeons awareness of what is going on. Therefore, three major requirements when performing MIS must be available: safety, efficiency and a clean environment [2]. In literature [3], minimally invasive (or access) abdominal surgery is described as a traditional surgical principle that minimalises trauma generated today by laparoscopic or videoendoscopically operative manipulations. The procedure of any MIS platform:

1. Access to a body cavity or it is known as intraluminal site.
2. Dissect the tissue to reach and manipulate the target organ.
3. Obliterate the tissue using focused energy delivery devices.
4. Reconstruction the destructive tissue using some techniques such as stapling and stitching.

There are a number of limitations when using of graspers [4]. The main limitation of using graspers instead of a surgeons own hands is that, by using a grasper as an intermediary, the tactile feedback a surgeon would normally feel is drastically reduced due to the losses caused through the grasper mechanics. Tissue trauma caused by excessive pressure is a possible by product of this lack of haptic feedback. Another limitation found in current grasper technology is rounded-off ends and sharp profiles of the grip. An example of this is colon surgery graspers. Due to poor design, issues with high pressure and/or compression peaks in the tissue caused by the graspers can lead to perforations during the operation and in some cases, after few days. Last but certainly not least, the present graspers have an unequal pressure distribution along the internal surfaces of the jaws since they possess only angular motion which is akin to crocodile jaws movement [5]. In other words, a tissue in the jaws closer to the shaft is subjected to a higher pressure compared with the tissue closer to the tip. Thus, to ensure safety of tissue during and after the procedure, it is important to identify the maximum safe force that is allowable without damaging the tissue or the tissue can recover to its original thickness after releasing from the jaws.

Pinch and pull forces are key considerations in grasper technology. The pinch force is required to provide enough friction to prevent the tissue from slipping whereas the pull force is concerned with tension of the tissue so as to be able to manipulate it from one place to another. The author [4] claims that the pull force causes a reduction the maximum permissible pinch force. Consequently, to achieve a safe laparoscopic grasper design for a surgical procedure, these two factors must be taken into account. The maximum allowable pull force that can be applied to the colon tissue of a pig was found to be 5 N. This force is sufficient to stretch the mesocolon during dissection process.

The main purpose of this paper is to produce a concept for the design and control of a laparoscopic grasper which can ensure the safety of the tissue. The concept will measure the pinch and pull forces via a load cell. The load cell will be part of a control system that will control what force is experienced by the tissue. The aim of the controller is to make the force experienced by the tissue equal to the force demanded by the surgeon. The control design will be built using MATLAB’s Simulink.

This paper is organised as follows: section II deals with computational modelling in SolidWorks and extracting the relationship between the horizontal movement of the slider shaft and the vertical motion of the jaws. Next section deals with a closed loop control system that compares the desired grasping force and the actual measured force to obtain minimum acceptable error. This is achieved through analysing the plots that shows the effect of applying force on the tissue.

2. Computational Modeling in Solid Works

A. The initial concept

The standard design includes four parts in SolidWorks. The first part is the body which is a U shape profile that contains the second part the slider shaft. This shaft moves from the initial position (far-left) to the end position (far-right) of the body. As a result of this movement, the third part (jaw) moves along the vertical axis from open to close simultaneously with the slider. Finally, each jaw has an inclined end with two holes across which the fourth part, link, is attached. Figure 1 below demonstrates the fundamental components of the preliminary mechanical design.

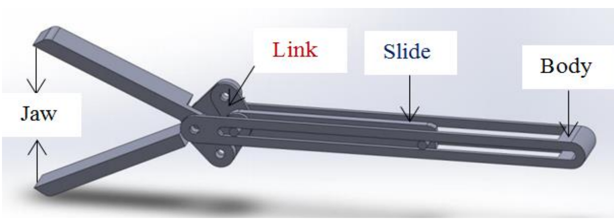

Figure 1: The basic mechanical arrangement of the grasper

B. The final design

The final design is almost same as the basic one. However, two things have been modified in the design of the jaws to increase the grip security. The first is a 2mm wave pattern has replaced the plain style of jaws. The advantage of this alteration is that it minimise tissue trauma and provide acceptable squeeze pressure on the tissue which leads to acceptable grip security [7]. The other change is to remove the solid jaws in the basic design with hollow jaws in order to reduce failure at the interface of the instrument-tissue. The final touches to the design can be presented in Figure 2 below:

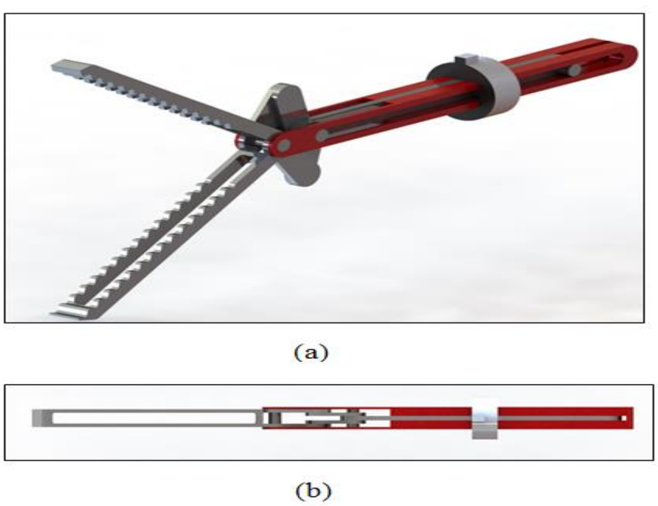

Figure 2: Final model of the laparoscopic grasper in SolidWorks: (a) isometric view of the system (b) Top view of the grasper

The final design also has load sensing capabilities through the load cell that surrounds the slider shaft and the body of the grasper. The purpose behind placing this sensor is to detect the amount of the force applied on the tissue. In addition, any closed loop control system must have feedback signal. Thus, this strain gauge load cell will provide the feedback signal to the controller to compare it with the desired force that entered by the surgeon. The situation of the load cell is important. Too close to the jaws, issues arise for example, a safety issue, the power for the sensor could electrocute the patient. Another issue is that the sensor would have to be very small as to not interfere in any way. This increases cost and complexity. Therefore the sensor should be removed from the jaws and placed elsewhere. Too far away from the jaws then more interference is introduced, for example, mechanical links. Each extra link increases calibration complexity hugely and the force measured by the load cell is less accurate [6]. The optimal place therefore is as close to the jaws as possible but not so closes as to increase cost and danger. This design therefore has located the load cell on the shaft.

C. Motion analysis

Motion analysis consists of capturing both the displacement of slider and the jaw. The two plots are exported from SolidWorks as data to an excel spreadsheet in the form of two columns. The first column represents the displacement of the slider while the second shows displacement of the jaws. The data is then imported into MATLAB (m-file script) which is used to combine both displacements in the form of a graph. A line of best fit is then used to obtain a polynomial that describes the movement of the jaw as result of the slider displacement. Subsequently a 4th order polynomial best defines this relationship between the two displacements. Figure 3 shows when the sliders at zero position, the jaws are opened fully and vice versa.

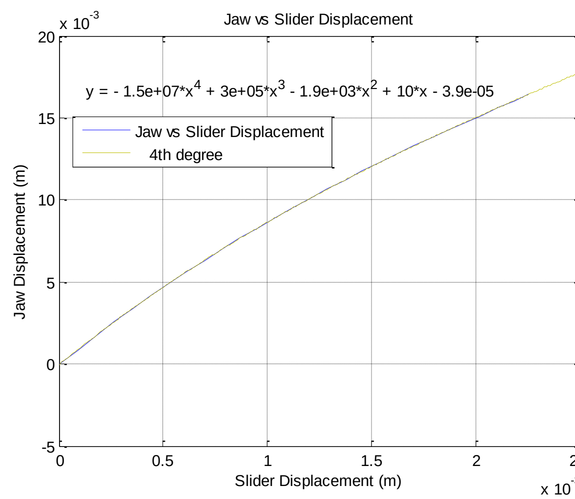

Figure 3: MATLAB Figure of (Jaws Vs Slider displacement)

3. Control and Simulation

A closed loop control system can be used to control the output signal (force experienced by the tissue) with respect to a demand signal (force required by surgeon).

The benefit of this kind of control system is that the difference between the demand signal and the output signal can be controlled. An ideal output signal would match the demand signal completely. In real life however this is impossible due to how the signal is manipulated and converted. In this design and electronic signal that gives a specific demand force is converted via a motor into a linear displacement witch via mechanical linkages is then converted to a force experienced by the tissue being grasped. The signal is manipulated so that certain criteria essential to for a good reliable signal are met. These are; minimal error between demand and output signals, robustness so that the system does not become affected by outside disturbances and finally stability in that at no point will the demand signal cause the output signal to become unstable. These criteria can be achieved by using the output signal in a feedback loop (hence closed loop system) complete with a PI controller. The closed loop control stem for this design is demonstrated below in Figure 4.

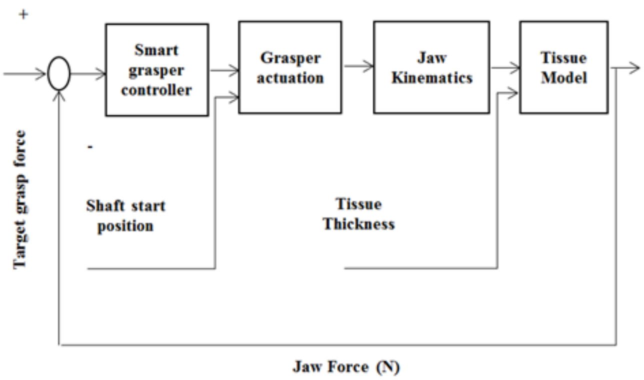

Figure 4: System block diagram of the grasper

The overall control system is made up of four subsystems identified above in Figure 4. The subsystems are; smart grasper control, grasper actuation, jaw kinematics and finally tissue model. The grasper controller subsystem is responsible for converting the error into DC voltage. The grasper actuation subsystem converts the DC voltage via a motor into shaft displacement. The Jaw Kinematics subsystem converts the shaft displacement into jaw displacement. The final subsystem, tissue model, converts the jaw displacement to force experienced by the tissue. The tissue model is in effect the load cell of the grasper.

D. Smart grasper control

The smart controller subsystem (Figure 5) has two inputs, demand force (demand signal) and jaw force (output signal). The error from these inputs is calculated then modified through a PI controller. The PI controller was tuned to give the control voltage shown in Figure 6. Due to the motor transfer function being 1st order the control voltage shows a first order response. Figure 6 shows that at a time of one second the voltage increases rapidly to overcome the inertia on the motor and shaft. Once the motor is moving the voltage is almost constant at 0.5V due to the jaws closing the distance between themselves and the tissue. Once the jaws have made contact with the tissue the motor requires a greater voltage to overcome the resistance of the tissue. The control voltage then levels off once the output force matches the demand force. A differentiator was not used due to it making the system exhibit 2nd order qualities,

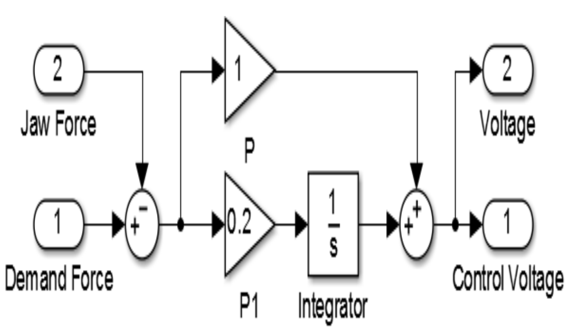

Figure 5: Smart controller subsystem

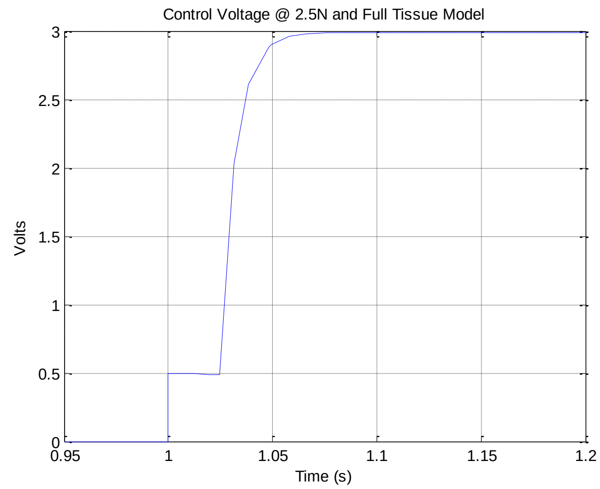

Figure 6: Control voltage at 2.5N and full tissue model

for example, an overshoot. For surgery this could be dangerous. The system also remained above the demand voltage creating an error the integrator could not eradicate. The gain could be used to increase the rise time or decrease the rise time. A gain of one was used as this gave a respectable rise time.

E. Grasper actuation

Figure 7 shows the grasper actuation submodule. As mentioned previously this module converts the control voltage into shaft displacement. The starting shaft position is set to zero. The transfer function is first order. This is very important as every other graph has a 1st order curve because of this. The value in front of the s values was picked to best replicate a motor with the correct characteristics. The characteristics are reasonable rise time without too much oscillation. A gearing system

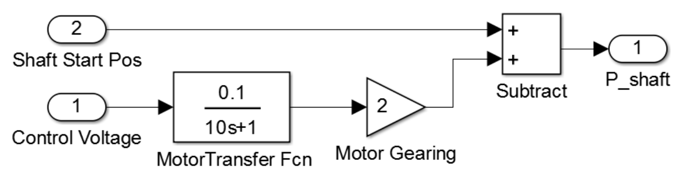

Figure 7: Grasper actuation

F. Jaw kinematics

The jaw kinematics subsystem, shown in Figure 8 below, converts the shaft displacement to jaw displacement. Before the polynomial is a saturation block. This is used to limit the shaft slider displacement as it can only move a finite difference. The polynomial block contains the polynomial gained from Figure 3 that converts the shaft displacement to jaw displacement.

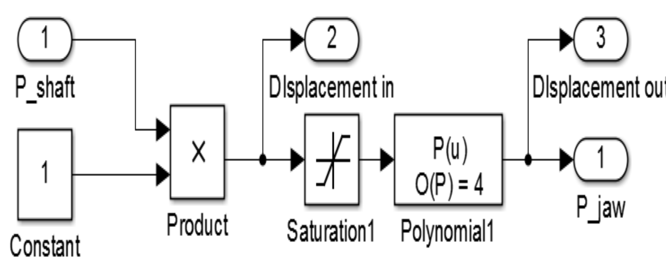

Figure 8: Jaw kinematics subsystem

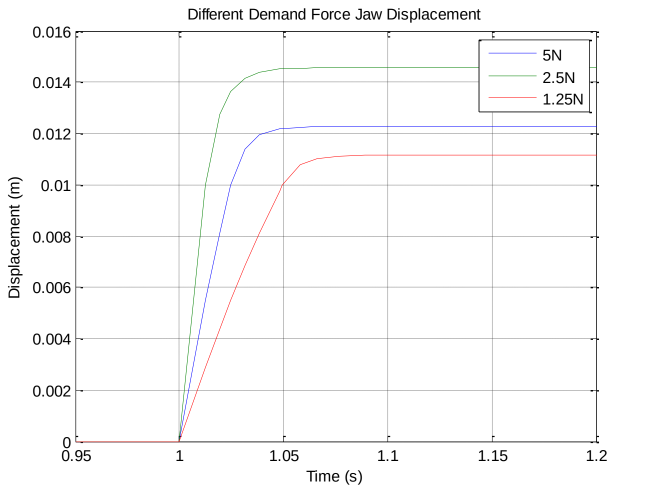

Figure 9: Different demand force jaw displacement (full tissue model used for each line)

The jaw displacement of different demand forces is shown in Figure 9. As the demand force is increased the maximum displacement increases as the tissue is compressed to a greater extent due to the greater force. It must be noted that there is a limit to the maximum displacement despite the demand force. This is due to the jaws becoming in contact with each other. Figure 9 does not show this the as the output force can match the input force for all demand forces shown. From 1.25N to 2.5N then 5N demand forces Figure 9 shows that the rise time increases as well as the displacement. This is as expected as the motor turns faster and with greater force due to the greater input voltage.

G. Tissue model

For the feedback of the system to be as accurate a possible, the forces the load cell will experience need to be as realistic as possible. To do this a tissue model, shown in Figure 10 (full tissue model), was used to replicate the forces the load cell would detect.

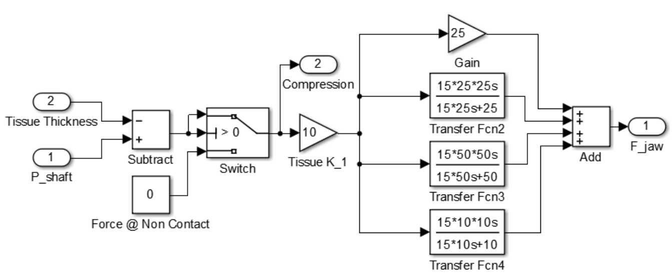

Figure 10: Full tissue model

A human tissue is a complex and difficult material to simulate due to it viscoelastic behaviour. A tissue is made up of a solid network that is swollen and surrounded by water. The solid part is mainly responsible for their elasticity characteristic while the viscosity characteristic is both from network mobility and an aqueous solution of water and different molecules [8]. These characteristics are sensitive to environmental conditions and pre-stress. Pre-stress include change water content over time, general degradation and irreversible deformation under small loads [9].

The model chosen to represent a tissue in this paper is the Generalised Maxwell (GM) model due to its simplicity and ease of implementation in

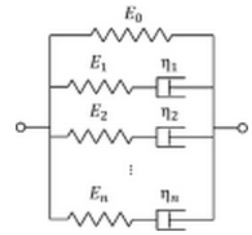

Figure 11: Generalised Maxwell model

Simulink. Another advantage of using GM is that instead of being one large complicated equation [10], it is built up of multiple simple equations, each representing a part of the whole. The GM uses a pure spring E_0 along with other springs E_i in series with dash pots η_i as shown in Figure 11. GM takes into account relaxation that occurs at multiple times. Each separate equation is a separate time. This system can be represented in Simulink as multiple transfer functions that take the form shown in equation 1.

$$H_{GM}(s) = E_0 + \sum_{i=1}^{\eta} \frac{E_i \eta_i s}{E_i + \eta_i s} \quad (1)$$

The spring's values are that of the material Young's modulus while the dash pot is equal to relaxation time multiplied by Young's modulus.

Three different models were tested to show the compression of three different tissues. Each model, except for the first tissue model which has only the pure spring and one spring dashpot, is made up of the previous tissue model (spring dashpot) plus another spring dashpot. The compression was recorded and is shown in Figure 12.

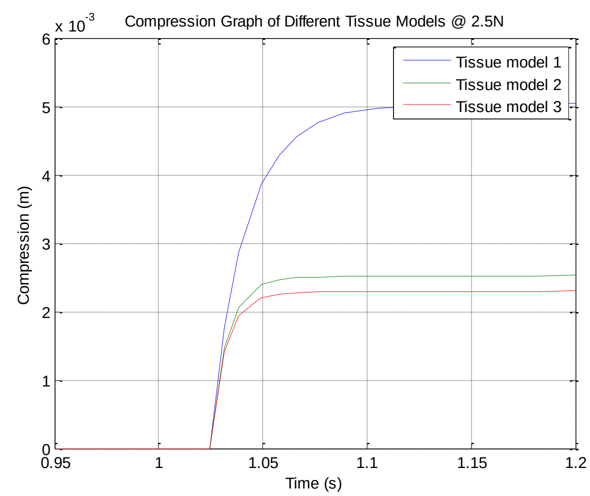

Figure 12: Compression graph of different tissue models at 2.5N

Tissue model 1 shows the greatest amount of compression then tissue model 2 followed finally by tissue 3. This is due to the varying Young's moduli of each transfer function. The greater the Young's moduli the stiffer, more spring nature materialises. When a lower Young's moduli the more spongy the hence greater compression [11]. The greater the number of equations, the smaller the amount of compression. This is due to the equations being summated. The greater the number of equations, the more accurate the model.

Increasing the relaxation time whilst maintaining Young's modulus increases the time taken to reach the maximum compression of the tissue.

Using the full tissue model the demand force was changed from a maximum force of 5N to 2.5N then finally to 1.25N. The signal was a step input signal where the step occurred at one second. The results of the corresponding output force are shown in Figure 13. As the demand force decreases the voltage applied do the motor is less hence the rise time increase. This is due to the motor taking longer to close the gap between the jaws and the tissue. It must be noted that the difference in rise time could be construed as negligible as they are separated by less than 0.05 seconds. This decreased rise time also means there is a great error initially between the step input demand force and the output force. The error then becomes vastly smaller when the demand force has been met.

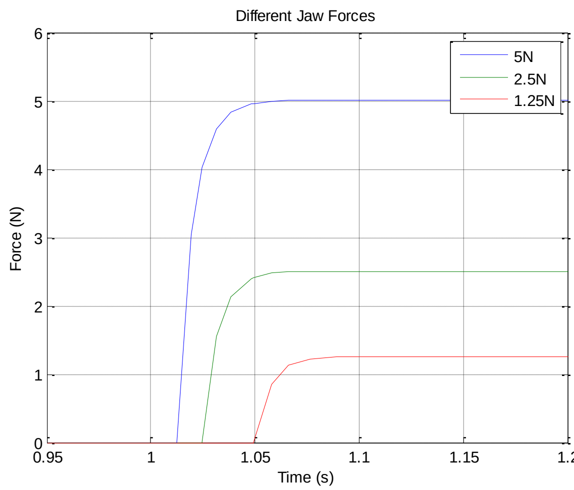

Figure 13: Different jaw forces

II. Discussion and Conclusion

This paper proses a design of a smart grasper complete with a closed loop control system that allows a secure grip that reduces the risk of trauma. The literature review pointed to using waveform teeth rather than jagged teeth as it reduces the risk of trauma whilst giving the surgeon ample friction to manipulate the tissue. This design uses waveform teeth. The load cell was placed in the middle of the shaft to reduce the inaccuracies caused by the force transmission through excess linkages. The load cell was also not placed directly on the jaws because of the interference it could cause and also the cost such a small load cell would be. The maximum safe force was taken from a specific operation on a specific tissue. This means that further research must be carried out to catalogue the variances in human tissue.

The closed loop control system proved to be very good at matching the output force to the demand force. By breaking down the whole control system down into subsystems the thought process of what must happen at each stage of the signal manipulation can easily be understood and flaws and errors can be resolved. An example of this was the use of the saturation block in the shaft to jaw displacement converter subsystem to control the progression of the polynomial. The control system uses a PI controller for a 1st order system. A more accurate approach would be to use a second order transfer function for the motor complete with a full PID controller for the control voltage. This would allow the error during the rise times to be reduced significantly however caution must be taken as overshoots do occur in 2nd order systems. Care must be taken as excess force could cause trauma. The tissue model used could be added too to make it more specialise towards a type of tissue. The model used was kept as general as possible to show the versatility of the control system in that it is easy to modify to an actual tissue. What was learned from the tissue model was that Young's modulus is the dominant variable in the GM that dictates the resultant signal

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