CIS II: Paper Presentation Report

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Group 5

Project: Haptic Interface for Surgical Manipulator

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Relevant Paper Source:

Kutzer, M. D. M., S.M. Segreti, C.Y. Brown, M. Armand, R.H. Taylor, and S.C. Mears. "Design of a New Cable-driven Manipulator with a Large Open Lumen: Preliminary Applications in the Minimally-invasive Removal of Osteolysis." *International Conference on Robotics and Automation* (2011): 2913-920. *IEEEXplore*. Web. 12 Apr. 2012. <http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5980285&tag=1>.

Project Summary

For the semester project, we are aiming to develop an intuitive, haptic interface that will allow for improved control over a surgical manipulator designed for application in removal of osteolysis. Current surgical options for osteolysis removal require manual surgery that often leaves much of the lesion unexplored, and, thus, researchers at the Applied Physics Lab and Johns Hopkins University have developed a dexterous manipulator with an open lumen that aims to improve the efficacy of this surgery. This manipulator, however, can currently only be controlled using a keystroke controller in a MATLAB interface. Given the robot's multiple degrees of freedom and given the lack of haptic feedback offered with a keystroke controller, effective and intuitive control of the robot is difficult. Thus, using the SENSABLE Phantom Premium haptic controller, we aim to develop a more intuitive interface for the developed dexterous manipulator that incorporates force feedback in attempt to ultimately provide the surgeon with a more effective means of performing osteolysis surgery.

Necessary Background

Total hip arthroplasty surgeries often suffer from shortened life-spans. One of the primary causes of this is the wear of the components as well as the active resorption of the bone surrounding these components. This wearing often leads to macrophage activation and osteolysis surrounding the hip implant. If this degradation is not treated in a timely matter, the surrounding bone may fracture or the implant may even separate from the bone itself. To remedy this, the current standard of care aims to remove these osteolytic lesions and replace the worn polyethylene liner via revision surgery. To avoid the need of removing the acetabular components of the hip replacement, a minimally-invasive surgery exists that aims to only replace the polyethylene liner while keeping the other components intact and in-place. In these approaches, the lesions are accessed through the existing screw holes of the acetabular component of the replacement. Even this minimally-invasive approach, however, suffers from challenges. Effective debridement of the lesion and monitoring of progress are both significant challenges that remain in these manual revision surgeries. In fact, studies have shown that less than half of the lesion is grafted when performed manually. Thus, a dexterous manipulator with robotic assistance may greatly benefit the efficacy of these revision surgeries.

Paper Purpose and Relevance

The purpose of the paper is to present the design, the fabrication, the kinematic modeling, and preliminary testing of a newly developed dexterous manipulator designed for use in osteolysis removal. This paper is of strong relevance to our chosen project as we are aiming to design an intuitive controller for the very manipulator discussed in this paper. Apart from offering the larger context of the purpose of the project, this paper outlines the design considerations that went into its manufacturing. The paper also goes through many of the manipulators physical dimensions and constraints. Keeping these different considerations in mind is crucial in optimally designing an effective, intuitive, and safe interface for the user and patient. Further, the paper outlines a few testing protocols from which we may be able to draw experimental techniques from in testing our own interface implementations.

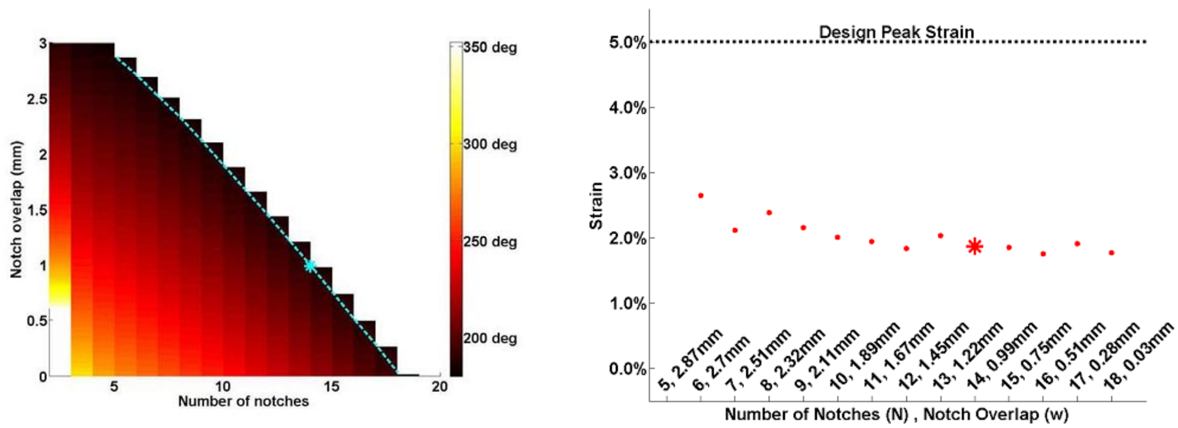
Design, Theory, Methods, and Experiments

The following will present a summary of the different aspects of the dexterous manipulator as presented in the paper. The topic outline is as follows—intended work-flow, manipulator design, fabrication methods, actuation and sensors, calibration, kinematic modeling, and experimental testing.

Work-flow: A typical workflow using the developed dexterous manipulator would likely involve a series of outline steps. First, the lesion is accessed through the existing screw hole (or holes are drilled in the cortical bone of the pelvis). Second, a guide cannula is inserted into the hole for a reliable point of access. Third, the dexterous manipulator is inserted through the guide cannula. Fourth, various tools are inserted and used as the manipulator is moved to different points in the lesion. Fifth, a final cleaning and inspection is performed. Lastly, the surgeon delivers the bone graft or bone cement through the lumen of the manipulator.

Manipulator Design: In designing the manipulator, there were a number of design constraints. The main requirements were that 1) the size was compact enough to maneuver within the existing holes of acetabular THA components 2) the manipulator featured an open lumen to allow for tool entry and removal 3) the design and fabrication process was scalable so it could be adapted for different component sizes and brands 4) the manipulator was highly-dexterous to allow for effective tool manipulation and wide-spread exploration and lastly 5) the manipulator can produce high end-effector forces to effectively scrape, brush and curette during the procedure.

To accomplish these goals, many considerations were made into the design of the manipulator. The manipulator was made to have an outer-cylinder of 5.99 mm (as compared to the hole size of 6.60 mm of the acetabular shell they designed the initial system for). Notches in the manipulator were in a common plane to constrain bending to a single plane to allow for simple control and modeling as well as to produce higher end-effector forces. Bending was performed in a marionette-like fashion via the tensioning and slackening of two drive cables threaded 180° apart between channels cut between inner and outer nitinol tubes. Initial modeling of bend showed that the total bend could exceed 180°. To determine the number of notches and the overlap between left and right notches, a strain test was performed. Realizing that a higher bend angle generates higher-strain, they chose only to consider the lower-bend angle candidate dimensions (as seen in the blue-dashed line in Figure 1a). Since there were no significant differences between the strains of these candidates, an intermediate candidate was arbitrarily chosen (14 notches and 0.99 mm notch ovelap) as seen in Figure 1b.



Figures 1a (left) and 1b (right): (left) The effect of notch-overlap and count on bend angle (right) and the simulated strain of different ~180° total bend dimension candidates

<u>Fabrication:</u> Fabrication of the manipulator is relatively straightforward. First, the inner and outer tubes are cut to the appropriate length. The inner tube is then mounted and the channels (for the drive cables) are cut on its outside. The outer tube is then mounted and channels are cut on the inside of this using an Electrical Discharging Machine. These two tubes are then nested together using a machine vice. Finally, the notches are cut using the Electrical Discharging Machine.

<u>Actuation and Sensors</u>: Actuation is performed using four stepper motors. These motors control the driving of cable lengths, the linear actuations about the unbent manipulator axis (Z translation), and the spinning around the unbent manipulator axis (θ $rotation$). Z translation and θ translation is done using DMX-UMD-23-3 motors and cable length actuation is done using PMX-2ED-SA motors from Arcus Technology Inc.

To characterize actuation during actuation, sensors are embedded into the system. Namely, each drive cable is connected with a tension/compression load cell that interfaces via USB to allow measurement of the force at each drive cable. Secondly, a CMOS FireWire camera with ultra-low distortion is mounted to the translating component to maintain constant view of bending and rotation of the manipulator tip.

<u>Calibration:</u> To reliably define the zero-position of each actuator, a calibration method is needed. Calibration of the Z-axis relies on actuation between the front and back limits of movement. Limit switches on both ends of the translational component would signal the translational limits and a fixed point between these positions can be used as the zero position.

θ-calibration is performed by bending the manipulator to an arbitrary position and then rotating 360° with an image being obtained at each step. Using intensity-based segmentation, the distance between the base and the left and right end-pixels of the manipulator is measured. The images containing the largest left and right distances were set to be 180° apart and thus the system rotates so that the bend-plane is orthogonal to the principal camera axis.

Lastly, drive-cable length calibration is performed by first estimating the total bend angle of the manipulator using the end-effector points. The bend-ward side cable is slacked by the steps proportional the bend-angle while the opposite cable is maintained at its 4.4N counter-tension. The cable on the bend-ward side is then counter-tensioned and the angle is estimated again. This is repeated until the bend angle is about 0 with each cable showing a counter-tension of 4.4N.

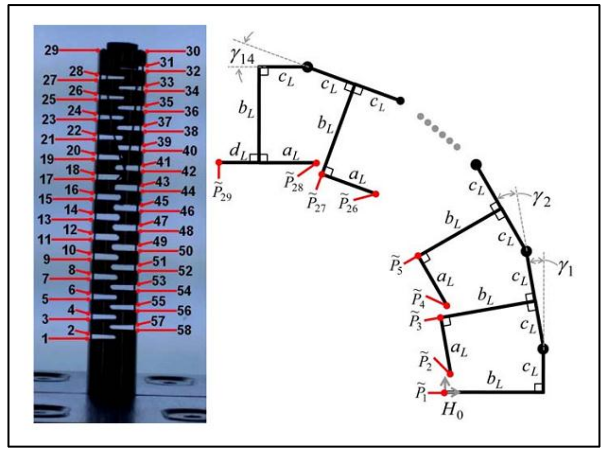
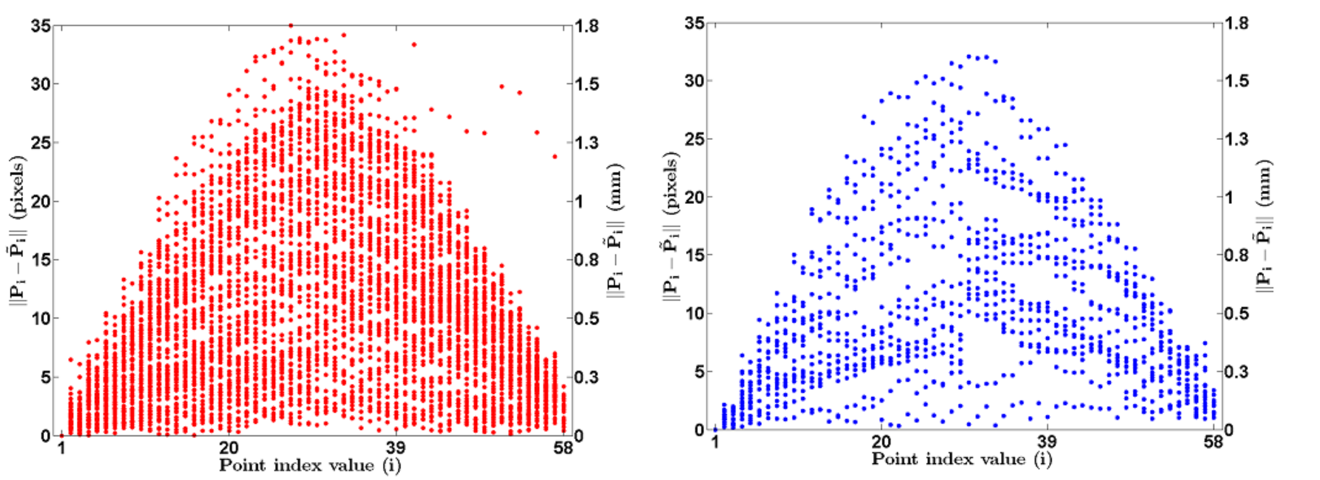


Figure 2: (left) Image of Manipulator showing the 58 identifiable points. (right) Kinematic Diagram with relevant variable.

<u>Kinematic Modeling:</u> A kinematic model would be helpful in motion planning and further design optimizations. Thus, a model was developed that views the manipulator as a series of pin joints that connect a series of rigid vertebrae. Using the aforementioned image-segmentation, the 58 points demarcated in Figure 2 can be reliably identified. The complete model fully describes the motion of the manipulator using 35 total terms.

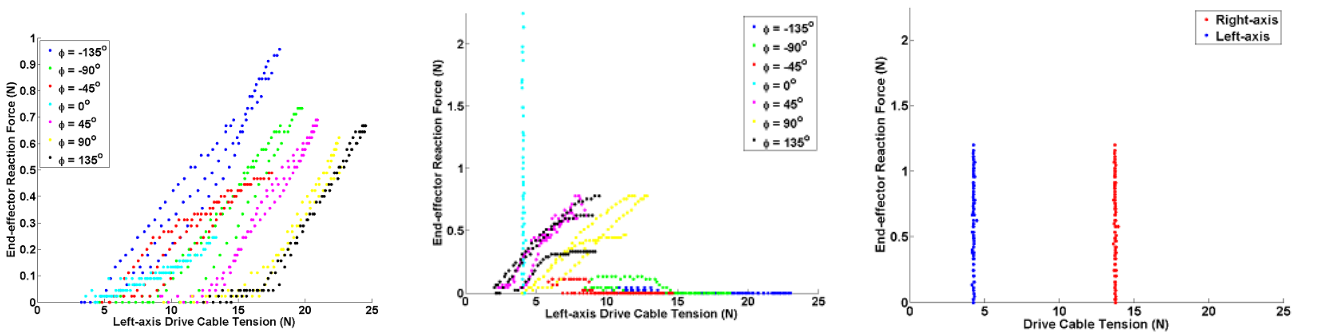
<u>Experimental Testing:</u> Two basic sets of experiments were performed to verify operation of the manipulator. The first experiment investigated the accuracy of the developed kinematic model and the second defined an end-effector force and drive cable tension relationship in various configurations in and out of the bend plane.

To evaluate the kinematic model, 120 images were taken in freely bent configurations and the aforementioned identifiable 58 points on the manipulators were obtained. Using linear least squares on the first 100 images, the constant length parameters ($a_L, a_R, b_L, b_R, c_L and\ c_R$) were forced to be constant, allowing calculations of γ_i. Plot 3a below shows the error between the image position and the calculated kinematic position. The error results of applying the same values for those length parameters to the next 20 test images are shown in Figure 3b.



Figures 3a (left) and 3b (right): Plot indicating error between point position in image and calculated kinematic position from 100 training images. (Left) Plot indicating same error using same parameters at 3a for next 20 test images

The second test involving seven manipulator bend configurations ($\phi = \{-135°, -90°, -45°, 0°, 45°, 90°, 135°\}$) were tested. At each of these angles, a digital force gauge was loaded in one of three loading conditions, eastward, southward, or westward. The force gauge was first brought to a position of visual contact with the manipulator, but to a point where there was a 0.00N force reading. At that point, the corresponding cable was stepped and data from the load cell, the force guage, and camera were taken. This was repeated for 30 points and three total trials were performed at each configuration. For the southward configuration, separate trials for left and right cable were performed. To summarize, some of the results are shown in Figures 4a and 4b. To test out-of-plane bending, the manipulator was bent 90° and rotated 90° and the manipulator was rotated as the same data was recorded. The results are seen in Figures 4c.



Figures 4a (left), 4b (center), and 4c (right): (left) Results given an Eastward pointing reactor force. (center) Results given southward pointing reaction force with tension left-axis drive cable (except 0° bend where Z-axis translation increased force) (right) Results given perpendicular reaction force out-of-bend plane.

Conclusions

The results from these tests show that the kinematic model is fairly accurate yielding a peak error of approximately 1.8 mm. The pointed shape of the graph can be attributed to the distance from the "origin". Since the error is additive with each step taken, the maximum error is expected to be at the point furthest away from the reference point (points 29 and 30). Further, no additional error was seen in applying the same parameter values to the next 20 images.

The results from the force tests show a near proportional relationship between cable tension and end-effector reaction force dependent on configuration and loading condition. For the southward condition, coupling between end-effector forces and tension occurs only when the bend-ward cable is tensioned. For forces outside the bend-plane, as expected, the left and right cable tensions remained constant with rotation.

Other drawn conclusions were that all of the design objectives were met. During the extensive number of trials, there were no signs of fatigure or failure. The authors did note that there was some variability between identical trials. Path-planning work, however, did indicate 85%-95% percent coverage rates of relevant osteolytic lesions.

Possilbe next steps in this research may include further optimizing the geometry of the manipulator, introduction of three-dimensional bending by adding drive-cables, predicting cable lengths from a known-position and vice-versa.

Personal Assessment

I found this paper to be very strong. One of its strong points was its breadth of information. The paper started with discussing the overall problem statement and then proposed a solution. Further within the solution, the design, fabrication, kinematics, actuation, and experimentation were all discussed. Thus, the paper served as a strong overview of the entire manipulator system. Second, I thought the experimental data was strengthened by the number of trials and data points taken. In the end-effector force and cable tension relationship experiments, over 30 points were taken in each trial and 3 trials were performed for each configuration at each force direction. This large data set gives additional validity to the data. On a more general note, the paper was very well-written. The language was clear and concise and each figure was clear and contributed to the understanding of the material.

While most of the paper was strong, there were a few minor points that could have been improved upon for the sake of clarity and completeness. Some features were not explained in depth, such as the image-based segmentation, the current control interface, or the work that resulted in the 85%-95% coverage estimates. Also, some of the explanations of the techniques could have been more clearly explained, namely the development of the kinematic model and the drive-cable length calibration methods.

On the whole, this paper was very relevant to our semester project. Apart from imparting a solid background of the problem, it helped gives us a better sense of the overall purpose. The paper gives insight into what considerations were involved with the design. In designing our interface, we must respect these considerations and realize the limits of movement and possibly make use of the proposed calibration methods. Further, we may implement some of the kinematic modelling and testing protocols in evaluating and testing the newly developed interface.