Haptic Interface for Surgical Manipulator System

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Background

The number of total hip arthroplasties (THAs) are expected to increase by over 174% in the next twenty years. Component wear and osteolysis, the active resorption of bone around components, are the primary phenomena responsible for the shortened life spans of total hip arthoplasty. Wear of the polyethylene liner of the implant causes macrophage activation and subsequent bone resorption. This osteolysis comprises the integrity of the bone and thus introduces the need for frequent revision surgery to remove the lesion and maintain the previously-used fixed acetabular component. Osteolytic lesions of the bone around the implant, if not removed, may lead to complications such as bone fracture or component loosening or disconnection [3].

Minimally-invasive approaches aim at replacing the polyethylene liner while preserving the acetabular and femoral components of the THA. In this manner, surgeons minimize the risk of introducing bone fracture. Minimal-invasiveness is achieved by accessing lesions through screw holes in the bone drilled from the original implant. A major challenge, however, is fully accessing the entire volume inside the lesion to clean the cavity; studies have shown that on average less than half of the lesion is grafted during manual procedures using curettes and other tools. Eventually, this lack of coverage forces the need for majorly invasive surgery in which the hip replacement is removed, the lesion is cleaned out, and another hip replacement is introduced [3]. Of course, an additional issue is that since the surgery site is being accessed through a screw hole, the surgeon also cannot visualize the lesion. He must use x-ray fluoroscopy, though this use must be limited to prevent overexposure to radiation. Therefore, the need for a highly dexterous manipulator that can cover the majority of the volume inside the lesion during the minimally invasive surgery as well as a way to track it is essential.

The Johns Hopkins University Whiting School of Engineering and Johns Hopkins Applied Physics Laboratory have developed a cable-driven surgical manipulator system. The snake-like cannula can access osteolytic lesions through the lumen of a larger, rigid guide cannula [3]. The actuation unit consists of a Z-θ stage with cable drive motors, which may be controlled using keyboard commands. Path planning algorithms of the system have suggested 85–95% coverage rates of surgically relevant osteolytic cavities [3], a significant improvement from traditional manual surgical methods.

Surgical control of the robot, however, is limited to MATLAB keystrokes with no visualization of the manipulator and no haptic feedback. Accurate and smooth operation is difficult, and the system lacks force feedback that allows the surgeon to “feel” his way around the cavity as he does during manual surgery. Since the system does not have a navigation system that allows the surgeon to orient himself within the lesion, he can only estimate where in the cavity the manipulator is currently located.

Prior research in the surgical value of haptic feedback has shown that robotic systems incorporating haptic feedback can significantly improve surgical performance. Shortened operative times; increased consistency, precision, and performance; and decreased frequency of surgical errors are all commonly demonstrated benefits drawn from comparing robotic systems with and without haptic feedback [8]. With no consensus as to how best implement haptic feedback, a variety of haptic-deliverance paradigms will need to be coded for and thoroughly evaluated. With the integration of haptics into the robotic control interface, we aim to bring the aforementioned benefits to the cable-driven surgical manipulator system during osteolysis revision surgery.

Our implementation of haptic feedback will rely on the use of the Sensable PHANTOM® Premium 1.5HF haptic device. This device allows for movements in 3-degrees of freedom as well as positional measurements and force feedback in 6-degrees-of-freedom. Studies using this system have shown the benefit of using it is two-fold: the applied forces can passively constrain hand-motion and also act as a guide to alter the intended motion [9]. In addition to the added haptics, we aim to add a more complete visualization system. Similar studies have shown that visual cues accompanying haptic feedback allows for a more complete feedback system and improved performance. These studies have gone further to suggest that auditory feedback may also a useful medium for conveying feedback information. This sort of sensory substitution will prove useful to compensate for the surgeon's lack of direct feedback during the surgery. Each of these feedback mechanisms will be explored to optimize surgical control and efficiency for the benefit of the surgeon and affected patients. [8]

Our goal is to develop an intuitive haptic interface for controlling the manipulator end-effector position that can relay force information to the user. We plan to create a mapping between the PHANTOM® Premium haptic device and the manipulator end effector. We will build a GUI that models the motion using a simplified kinematics model of the manipulator as well as display relevant information from the encoders to the user. The improved dexterity and incorporation of feedback will give us better coverage of the lesion, which may be verified via x-ray fluoroscopy, and decrease the total procedure time. We plan to demonstrate this through preliminary trials using a phantom.

Deliverables

Minimum:

- Develop a *well-defined, mathematically formulatable* interface coupling the workspace of a PHANTOM® Premium 1.5 haptic device (Sensable, Wilmington MA) to the workspace of the provided continuum surgical manipulator. This interface must be *reliable* and incorporate available force feedback from the provided manipulator actuation unit. This interface will be realized in hardware.
    - In this context, a *well-defined, mathematically formulatable interface* requires that the entire workspace of the fully actuated surgical manipulator is mapped (one-to-one and onto) a subset of the workspace of PHANTOM® Premium device. Additionally, the governing equations of this mapping must be documented highlighting any/all tunable (e.g. scaling) parameters. Note that, for the purposes of this work, a simplified model of the manipulator can be used for mapping workspaces. This model can assume simplified kinematics (i.e. 14-DOF) and evenly distributed bending (i.e. a constant curvature along the manipulators length [1]).
    - In this context, a *reliable* interface requires that, following documented hardware and software installation procedures, the system will "work every time." That is, upon starting up the interface, a user will be guided through the correct procedures to bring the manipulator and interface online without risk of unintended software or hardware behavior. Note that, given the overall scope and duration of this project, a fully debugged system may not be feasible. As such, all efforts must be taken to reduce, track, and document errors in the integrated system. Additionally, errors that endanger the user and/or system hardware must be addressed prior to final delivery.

Expected:

In addition to minimum deliverables,

- Develop and incorporate a 3D visualization of the manipulator for testing and training purposes.
- Increase interaction force estimation (utilizing simulation-based collision detection and/or additional sensors if available) to enhance/increase haptic feedback to the user.

- Schedule and document intermittent system trials with at least one mentor on a bi-weekly (i.e. every other week) basis to offer feedback on progress.
- Schedule and document a final system trial with a collaborating surgeon to provide qualitative feedback for future system enhancements

Maximum:

In addition to minimum and expected deliverables,

- Define and run quantifiable trials having inexperienced subjects learn to operate manipulator using the PHANTOM® interface, and perform a simple set of tasks. Compare multiple sets of scaling parameters and gestures to find best one for the specified task.
- Draft a preliminary conference paper documenting the use of this haptic interface to control the manipulator.
- Draft a preliminary conference paper describing outcome of user trials.

Milestones	Accomplished	Planned date	Expected date
Get PHANTOM® Premium 1.5 interfaced and running using provided Sensable software interface	Yes	20 Feb 2012	20 Feb 2012
Control software for PHANTOM®	Yes	22 Feb 2012	1 March 2012
Identify/create and implement test mappings from PHANTOM® to a graphical interface of the manipulator	No	28 March 2012	6 March 2012
Be able to control manipulator using keystrokes in MATLAB	Yes	28 Feb 2012	1 March 2012
Draft and submit IRB proposal for testing	No	7 March 2012	7 March 2012
Develop inverse kinematics model for the simplified manipulator model (given desired xyz coordinates of end-effector, how do we move the joints)	No	9 March 2012	9 March 2012
Develop initial PHANTOM®-manipulator mapping schemes incorporating haptic feedback on paper	No	29 Feb 2012	9 March 2012
Convert MATLAB interface to C++	No	16 March 2012	16 March 2012
Develop dynamic 3D visualization of the manipulator (eventually to become part of PHANTOM® GUI controller)	No	28 March 2012	28 March 2012
Control manipulator using PHANTOM® by implementing mapping schemes and be able to gather positioning/movement data from manipulator and import into MATLAB	No	28 March 2012	28 March 2012
Incorporate force feedback into mapping schemes	No	3 April 2012	3 April 2012
Complete preliminary testing and refine mapping scheme as necessary	No	17 April 2012	17 April 2012
Have surgeon provide qualitative feedback	No	20 April 2012	20 April 2012
Testing and trials with inexperienced users	No	27 April 2012	27 April 2012
Poster presentation	No	10 May 2012	11 May 2012

Technical Approach

The primary objective of creating a haptic interface for the dexterous manipulator (DM) is to convert the user's input into manipulator end behavior. Therefore, we seek to create a set of highly modular interfaces that 1) create a hierarchical system that abstracts away particular implementation details and 2) allow for more easily maintainable code. Our interface, therefore, will be controllable with different input devices (for example, the keyboard, another haptic device such as the PHANTOM® OMNI, or the SpaceNavigator® 3D Mouse), and can communicate with different motor controllers or even the manipulator itself. The ability to swap out different hardware and software components while still maintaining the same core functionality allows users to customize the system their needs.

The DM, the snake-like portion of the robot, is controlled using the PMX-2ED-SA 2-axis stepper motor controller from Arcus Technology, Inc. The controller is interfaced with the PC via USB and contains two 10-bit analog inputs [3] that measure the force from each of the DM drive cables (recall that the pull of each of the cables will "wiggle" the tip of the snake either left or right while constrained within a single plane).

Two additional degrees of freedom are provided by a stage on which the DM is mounted. The stage is composed of a translational (Z—forward and back) actuator and a rotational (θ) actuator, both of which are controlled by DMX-UMD-23-3 integrated stepper motors from Arcus [3]. These also interface with the PC via USB. An application may control the motors by invoking an ASCII command set on the PMX and DMX C++ dlls.

The PHANTOM® Premium's control functions are also exposed via a C++ API. It also connects to the PC via USB. The CISST library, a collection of libraries for aiding the development of computer assisted interventional systems, also has a C++ API. We plan on using CISST's mutex lock to ensure thread safety (since we'll be constantly reading from and writing to the motor data for position information).

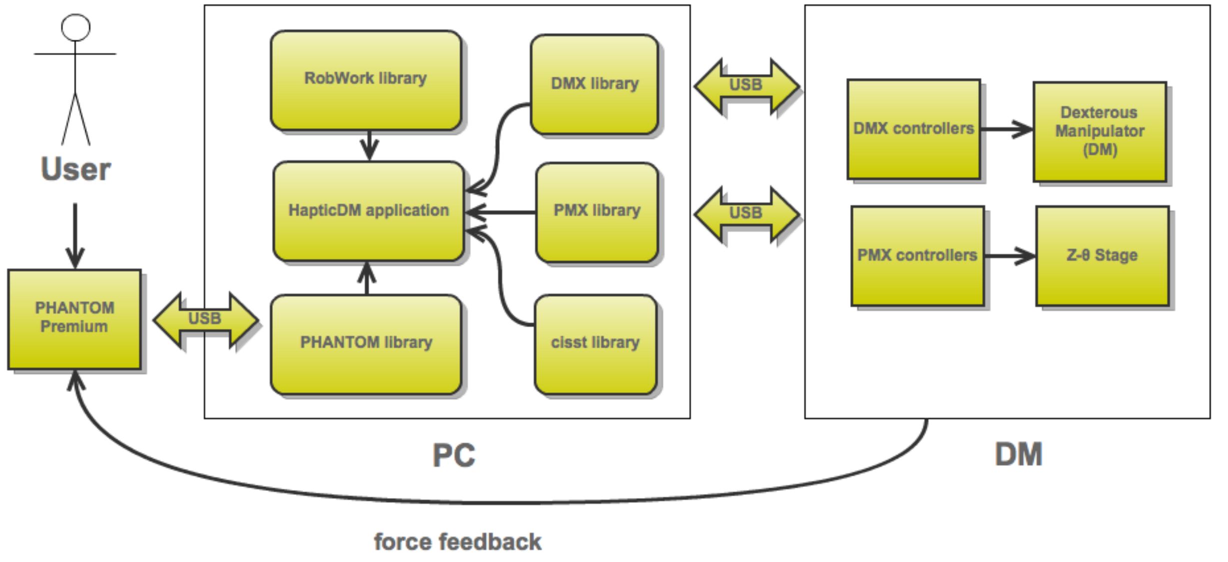
Currently, our collaborators at APL have developed a MATLAB application that controls the DM using keystrokes and a C++ application for PMX control. The PMX application was developed using Qt, a cross-platform application framework that is used for developing application software with a graphical user interface (GUI). Former students have developed a simplified forward kinematics model of the manipulator using RobWorks, a framework for simulation and control of robotics.

Since the existing APIs and the motor controller application (which we plan to build upon) are in C++, we plan to build our interface and our GUI in C++ using Qt on a Windows machine.

We first plan on running the demo applications for the DM, the PMX, and the PHANTOM® to familiarize ourselves with each system's command set. We then will develop the interfaces for the haptic DM system and the GUI. The haptic DM system interface that defines the manipulator model and the GUI interface that defines the applications look and feel will be separate. This will allow us to develop for each interface concurrently.

Each hardware component that we use will have its own separate implementation-specific class, which will inherit from a more general interface or class. For example, the InputDevice interface, which specifies the user's mode of input, may be implemented by either the Keyboard or Phantom class. The MotorController class may be implemented by either the DMXMotorController or DMXMotorController classes. Since the base ASCII command set used to control both types of motors are almost identical, inheritance of shared functions avoids duplicate code.

System Block Diagram

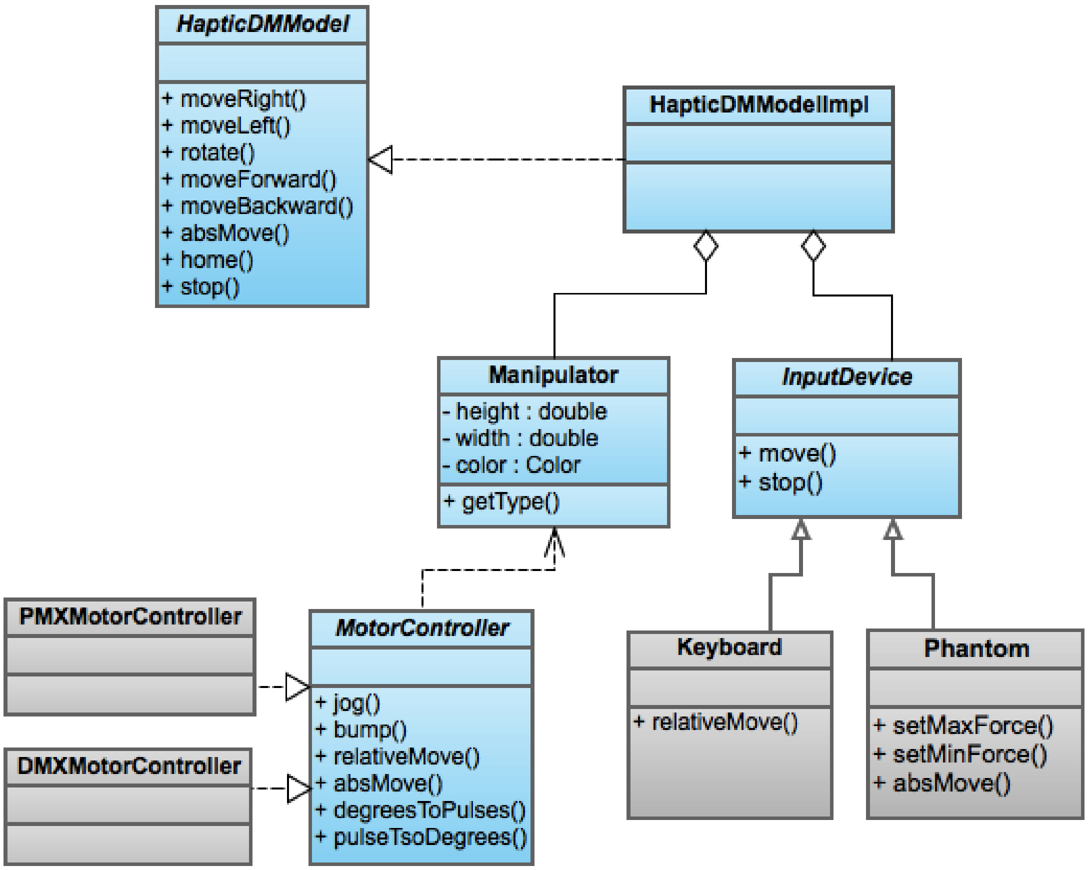


Next, we plan on porting selected MATLAB keystroke commands to C++. This will be a fairly simple process, since we will be calling upon the same ASCII command set to control the PMX and DMX dlls.

While developing the C++ keystroke program so that we may test the DM control in C++, we will concurrently develop a simplified inverse kinematics model based on the previous forward kinematics work done so that we may map the workspace of the manipulator to the workspace of the PHANTOM®. This will allow us to know what configuration of the manipulator will allow it to reach a desired position in space targeted by the PHANTOM® We will do this by making the simplifying assumption that all joint angles are equal—else the manipulator has 20 DOF. This information may then be used to develop various PHANTOM®-manipulator mapping schemes, each of which we will simulate dynamically (using RobWorks) before implementing in hardware.

After implementing the mappings, we will implement force feedback into the PHANTOM® to allow the user to haptically feel his way around the cavity in the osteolytic lesion without the use of non-intuitive kinematics readings. This will allow the surgeon to explore the inner cavity of the lesion similar to current manual procedures: when the DM is within the gelatinous cavity, the force the surgeon feels through the instrument held in his hand is minute compared to the force experienced when he comes into contact with the hard, bony boundary of the lesion. We plan on mimicking these forces by relaying the sensor measurements from the load cells on the DM back to the PHANTOM®, after applying some scaling factor.

Class Diagram for HapticDM



We further plan on performing unit testing, integration testing, and finally system testing on each of the classes that we develop. We will first test the keystroke controller, the DMX and PMX controllers, and the PHANTOM® controller independently, and then test each component as we incorporate it into the PhantomDM application.

To compare the efficacy and intuitiveness of the test mappings, we plan on conducting trials on subjects (a surgeon, Dr. Mears, as well as inexperienced users to assess the learning curve) who will use the PHANTOM® to control the DM. We will work on drafting, submitting, and obtaining IRB approval for these trials while concurrently working on our software. We will conduct trials using a control group composed of users who use the original keystroke control to explore a 3D volume and another group that uses the haptic device. Results will be assessed based on 1) coverage, 2) speed, 3) ease of use/intuitiveness, and 4) learning curve. Since in osteolysis procedures the coverage of the lesion, rather than accuracy of the tool (such as the curette) within the lesion, is the most important, we will assess coverage based on whether the user can touch several points at different locations and orientations in space as well as within a cavity; speed by comparing how quickly the user can hit the targets using the keystroke and the PHANTOM® interfaces; ease of use/intuitiveness by qualitative reports from the test subjects; and learning curve by the number of trials a subjects takes to decrease the time it takes to touch all targets below some threshold.

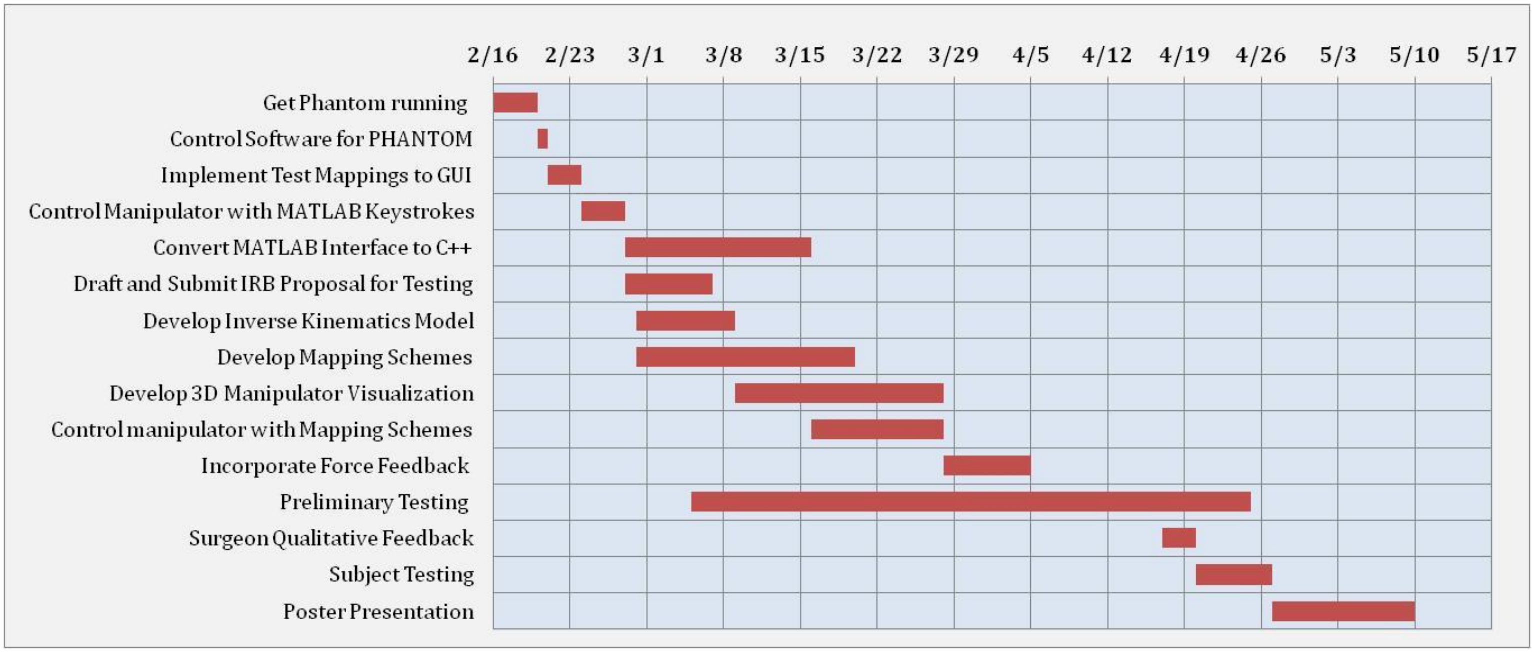
<u>Use Case</u>: Controlling manipulator using force-feedback integrated PHANTOM®

1. Start GUI
2. Follow instructions to turn on hardware (manipulator, PHANTOM®)
3. Move PHANTOM®
4. GUI: Maps PHANTOM®'s position (user input in xyz coordinates) to position of manipulator end effector using mapping and scaling function
5. GUI: Displays simulated movement of manipulator based on inverse kinematics model of manipulator
6. Manipulator moves
7. User feels forces (pushback) in PHANTOM® based on position of manipulator

Dependency	Resolved	Plan to Resolve	Resolve by	Contingency Plan	Affects
Access to BIGSS Lab	Yes	N/A	N/A	N/A	N/A
Access to PHANTOM®	Yes	N/A	N/A	N/A	N/A
Access to manipulator	Yes	N/A	N/A	N/A	N/A
Access to CISST library	Yes	N/A	N/A	N/A	N/A
Weekly meetings with mentors	Yes	N/A	N/A	N/A	N/A
Availability of test subjects	No	Recruit students (easily obtainable)	15 April 2012	Offer small rewards for participation (e.g. candy)	Expected deliverables: *(milestones 10--ability to refine model before presenting to surgeon--and 12--run trials with inexperienced users)*
IRB approval for trials	No	Submit plan proposal to IRB	15 April 2012	Talk to Mike about other ways to test device, perform limited testing on ourselves	Expected deliverables: *(milestone 10-- ability to refine model before presenting to surgeon--and 12--run trials with inexperienced users)*
Availability of surgeon	No	Ask Dr. Mears to come to Homewood and test out robot	19 April 2012	Reschedule to available date	Expected deliverables: *(esp milestone 11--have surgeon provide qualitative feedback)*

Management Plan

- Weekly in-person meeting with Michael Kutzer and Ryan Murphy to check in and ask questions along with constant email contact in lab pod depending on their availability
- Group meetings every Monday in lab pod from 8-9p to report status updates and assign tasks for the upcoming week
- Further group meetings throughout the week to work on project together
- Daily conference calls to update everyone on work and statuses
- Work will be done cooperatively for the most part, especially at first. In general, Jessie will mainly work with the simulation and kinetic model while Piyush and Manish work on interfacing the PHANTOM® and manipulator and testing various interfaces. Further delegation as project progresses will be considered as necessary.
- Revise Gantt chart and milestones as necessary



References/Reading List

[1] W.P. Liu, B.C. Lucas, K. Guerin, and E. Plaku, **Sensor and Sampling-based Motion Planning for Minimally Invasive Robotic Exploration of Osteolytic Lesions,** in Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on, Sept. 2011.

[2] S.M. Segreti, M.D.M. Kutzer, R.J. Murphy, and M. Armand. **Cable Length Prediction for a Compliant Surgical Manipulator,** in Proceedings of the 2012 IEEE International Conference on Robotics and Automation, May 2012, in Press.

[3] M.D.M. Kutzer, S.M. Segreti, C.Y. Brown, R.H. Taylor, S.C. Mears, and M. Armand, **Design of a new cable driven manipulator with a large open lumen: Preliminary applications in the minimally-invasive removal of osteolysis,** in Proceedings of the 2011 IEEE International Conference on Robotics and Automation (ICRA2011), May 2011, pp. 2913-2920.

[4] B. T. Bethea, A.M. Okamura, M. Kitagawa, T.P. Fitton, S.M. Cattaneo, V.L. Gott, W.A. Baumgartner, and D.D. Yuh. **Application of Haptic Feedback to Robotic Surgery**. in Journal of Laparoendoscopic Advanced Surgical Techniques 14.3, 2004, pp. 191-95.

[5] A.M. Okamura, **Methods for Haptic Feedback in Teleoperated Robot-assisted Surgery**. in Industrial Robot: An International Journal 31.6, 2004, pp. 499-508.

[6] C.R. Wagner, N. Stylopoulus, and R.D. Howe, **The Role of Force Feedback in Surgery: Analysis of Blunt Dissection,** Proc. Haptics Symp., Mar. 2002.

[7] G. Tholey , G.P. Desai, A.E. Castellanos, **Force feedback plays a significant role in minimally invasive surgery - results and analysis**, Ann of Surg, 2005;241(1): pp. 102–109.

[8] O.A.J. Meijden, M. P. Schijven, **The Value of Haptic Feedback in Conventional and Robot-assisted Minimal Invasive Surgery and Virtual Reality Training: A Current Review,** Surgical Endoscopy, 2009, pp. 1180-190.

[9] C.R. Wagner, R. D. Howe. **Mechanisms of Performance Enhancement with Force Feedback,** WHC '05 Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005, pp. 21-29.