Kangsan Kim
Kevin Yee
02/25/2016
CIS II

Project #10: Real Time Motion Reflexes for Robotic Hip Surgery
Project Proposal

Team Members
Kangsan Kim, Senior Biomedical Engineering and Applied Mathematics & Statistics
Kevin Yee, Senior Electrical & Computer Engineering

Mentors
Andrew Hundt, Ph.D. Student in Computer Science
Dr. Peter Kazanzides, Research Professor in Robotics

Topic and Goal

This project involves a next-generation orthopedic surgical system called Robone that is currently in development. Robone will be used for hip replacement surgery. One of the components of this surgical system is the Kuka LBR iiwa robotic arm that accurately mills the femur bone into the shape of the hip transplant. The robotic arm has many joints that allows it to position itself in a wide range of orientations. Every joint in the arm contains torque sensors, but these sensors are not currently being utilized in the Robone system. The aim of this project is to use the data from these torque sensors to improve Robone. There are two main goals to achieve this: develop a force controlled velocity algorithm for the cutting speed of the robot and implement null space compliance for the arm while the arm is performing the milling operation. The force controlled velocity algorithm should decrease the robot's cutting speed when the cutting tool tip experiences increased resistance due to higher bone density and vice versa. The null space compliance capability should allow to robot arm to reposition itself during the milling operation in response to external forces, such as the surgeon pushing it out of the way, without altering its cutting speed or trajectory.

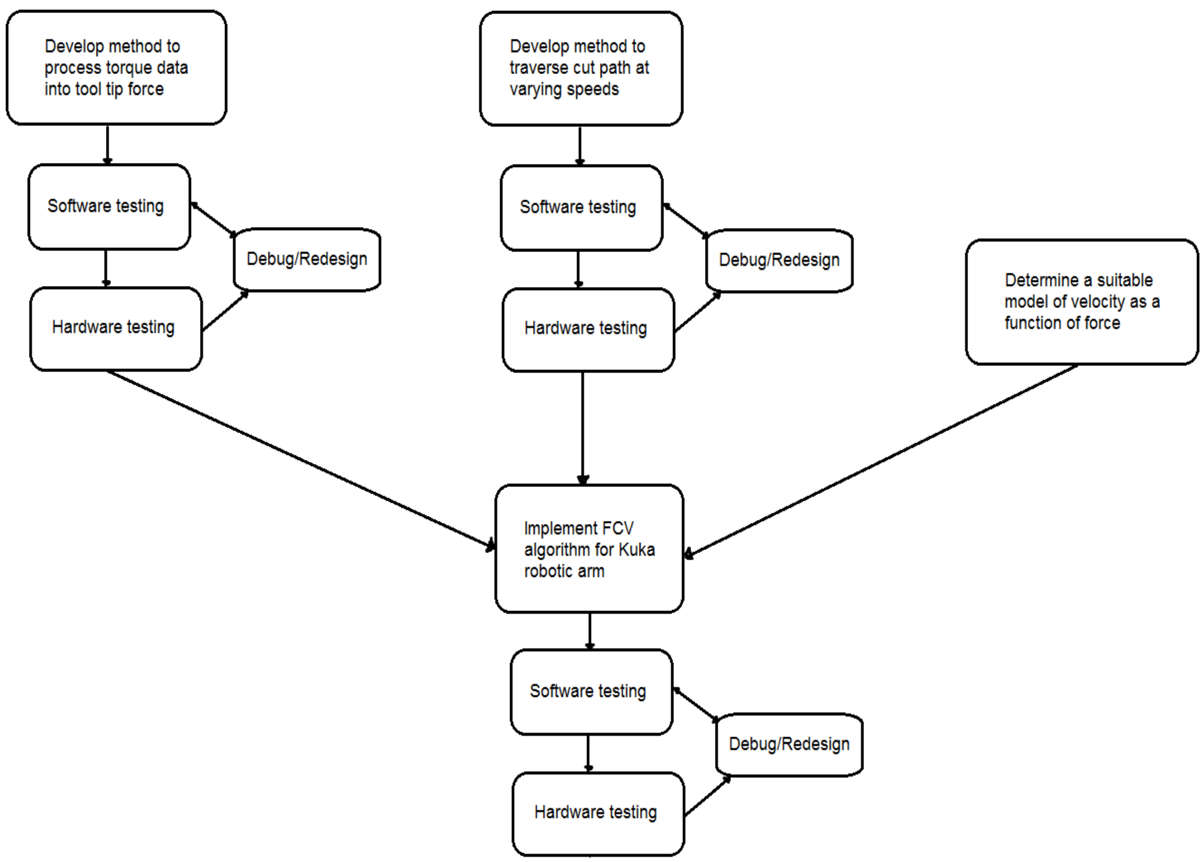
Project Relevance

A force controlled velocity algorithm is necessary for a safe, efficient, and accurate milling operation. The milling speed is limited by the maximum applicable force at the tool tip, as well as the density of the material being cut. Exceeding this allowed milling speed would cause tool chattering, resulting in damage to the tool tip and workpiece. In addition to the damage to the device, attempting to cut through high density areas of the femur beyond a safe speed will result in a less clean cut, decreasing the quality of the transplant fit. It is also important that the robotic arm increases its speed when cutting through low density areas. An unnecessarily low cutting speed will result in a longer surgery, thus increasing the cost of the operation. The benefits of robotic hip surgery must outweigh the costs.

Null-space compliance will allow the surgeon to move certain joints of the robotic arm without negatively affecting the milling operation. This provides the surgeon with better visibility and comfort during surgery. There is an existing implementation of null-space compliance for the Kuka robotic arm, but there are two issues. One issue is that the existing implementation cannot react to real-time changes in the cutting path, which is needed if the patient changes position during the surgery. The other issue is that the existing implementation uses a Java application program interface. This interface can only provide feedback once every ten milliseconds. In situations involving surgery, much faster feedback is a necessity. Thus, this project's implementation of null-space compliance will use the Fast Robot Interface, which provides feedback every millisecond.

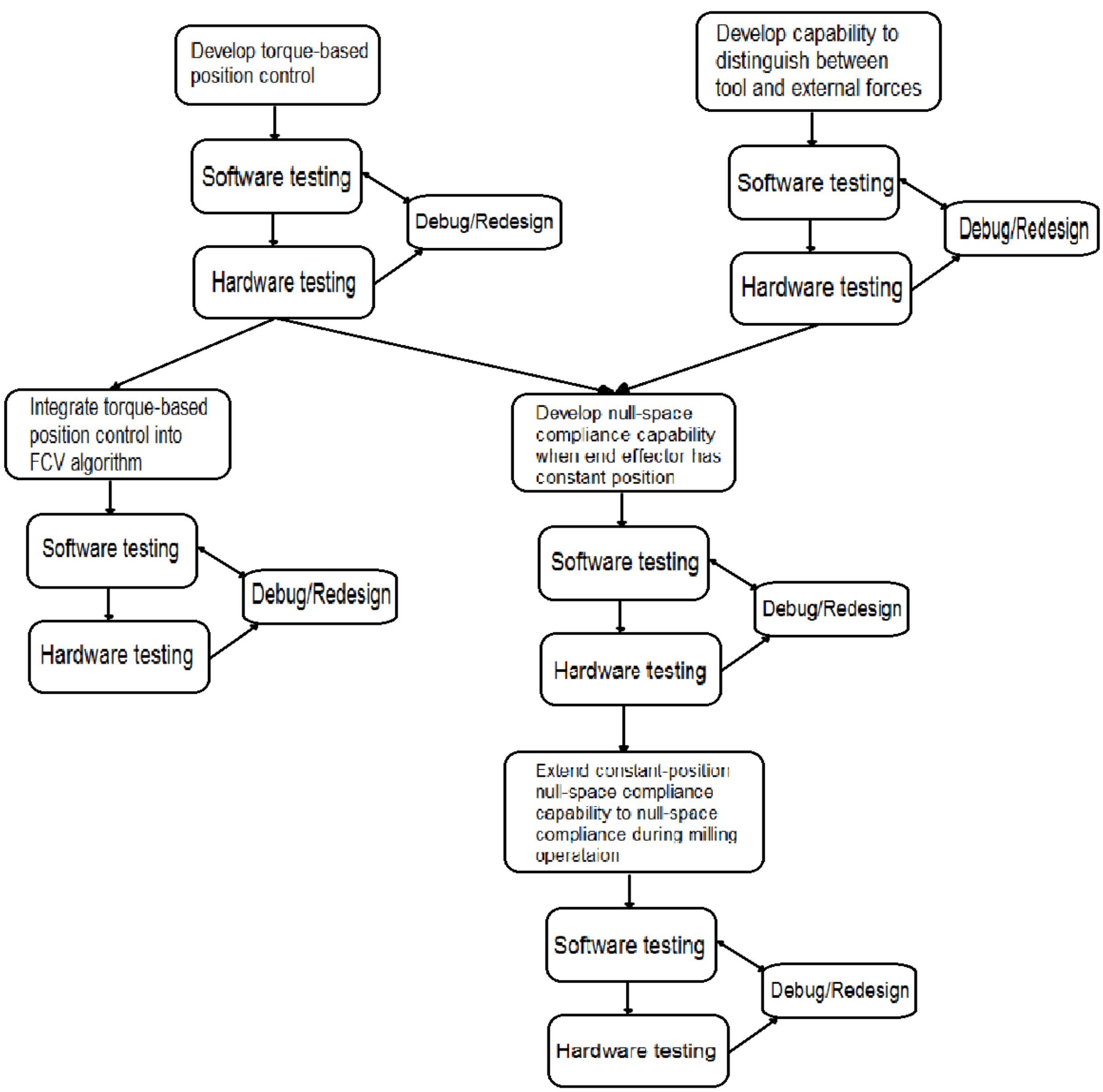
Technical Approach

Force Controlled Velocity Algorithm:
To approach the force controlled velocity algorithm, three independent components must first be addressed. The first component is a method that will receive the raw torque sensor data from every joint and process the data to return the force on the tool tip. The second component is a method that allows the robot arm to vary its cutting speed as it traverses its cut path. Currently, the robot can only traverse its cut path at a constant velocity that is given as an input before it starts the milling operation. These two components will be tested in a robotic simulation called Virtual Robot Experimentation Platform (v-rep) until they are fully functional in the software, after which they will be tested on the actual Kuka robotic arm. If the hardware test is unsuccessful, the code will be debugged and/or redesigned, tested in software again, and then tested on the hardware again. This cycle will repeat until the hardware tests provide the desired results. The third component of the force controlled velocity algorithm is to determine an appropriate model for the damping of cutting speed as a function of force. An exponential model will be used as an initial estimation because this will make the cutting speed less sensitive to force variations at low forces than at high forces. Changes in force at low forces should be treated as noise.
Once all three components are addressed, they will be integrated into our force controlled velocity algorithm and it will be tested in the same manner as the other two components.
Below is a diagram of the technical approach.



Null-Space Compliance:

There are two factors that must be integrated in order to accomplish null space compliance: control the robot using “torque-control” mode and distinguish between internal and external forces. Everything up until this point has been leveraging the “position-control” mode of the robot. In this phase of the project, we intend to use “torque-control,” in which we give each joint a torque value, as opposed to an angle relative to the parent joint. This mode is not essential for null space compliance, but it should simplify commands moving forward. Secondly, the robot must be able to distinguish between forces from different bone densities and forces from a surgeon pushing on the robot. Once these forces are isolated, we can move the robot to minimize these forces. We will first demonstrate null space compliance on a fixed tool position. When that is up and running, it will be integrated into the force controlled velocity algorithm. This technical approach is summarized in the flowchart below.



Deliverables

The table to the right depicts our minimum deliverables. The first of which is to develop an algorithm to traverse the cutting path at varying speeds. This addresses the constant velocity problem described earlier. The next minimum deliverable is to demonstrate our force controlled velocity algorithm in a V-REP simulation. Once the algorithm succeeds in software, our last minimum deliverable will be to demonstrate the algorithm on the physical robot using a simple test.

Minimum Deliverables
Implement an algorithm to traverse cutting path at varying speeds
Position control force controlled velocity implementation in software
Demonstrate position control on hardware (robot)

Expected Deliverables
Factor in end effector mass into calculations
Test force control based on known resistance

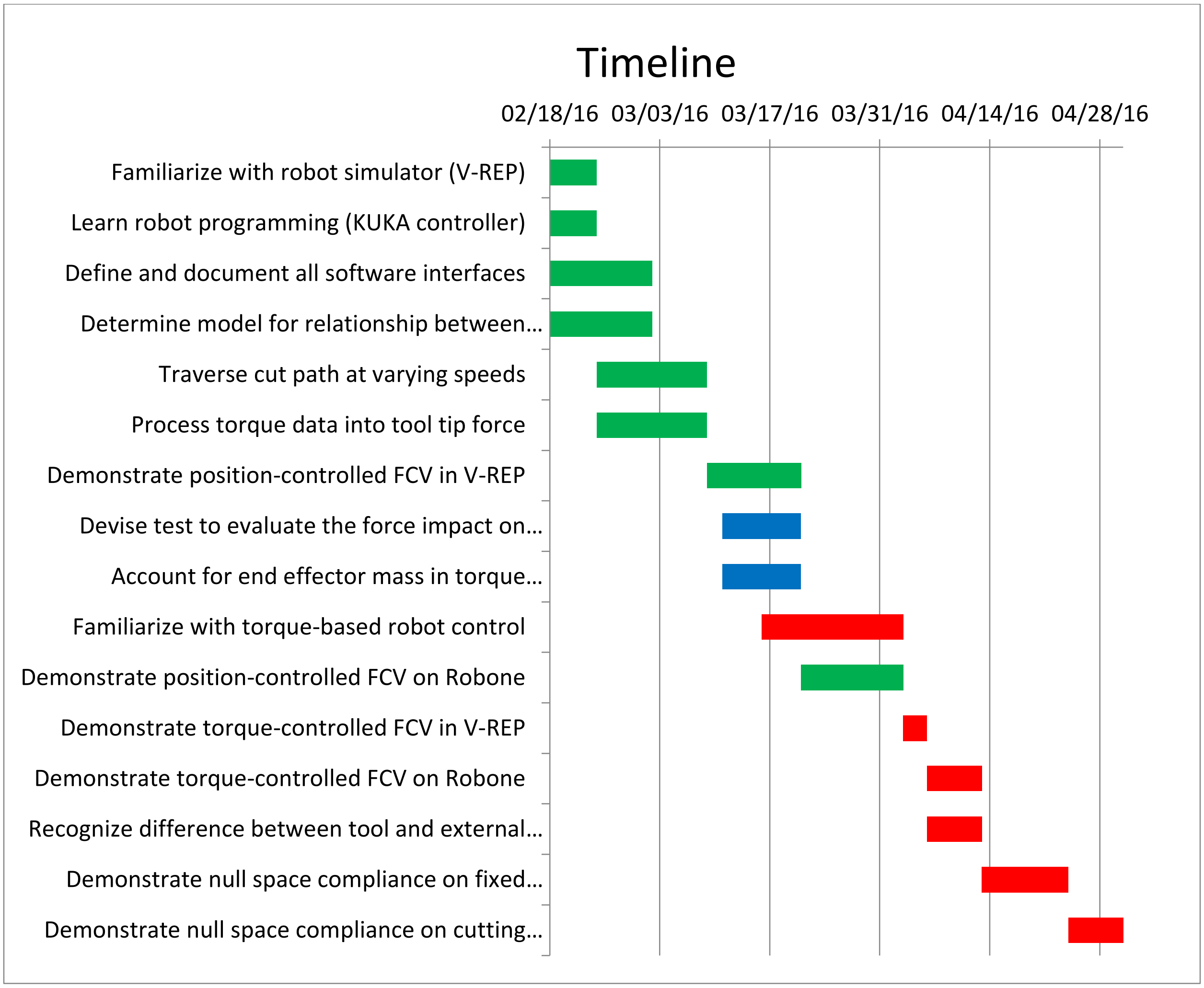
The table to the left summarizes our expected deliverables. Firstly, we must factor in the end effector mass into the torque calculations. The robot arm is aware of the torques that each child arm exerts on its parent joint. However, the mass of the tool may exert some torque on the robot joints. For example, the robot may cut at a slower rate when it is going up than when it is going down because the force of gravity on the tool may be interpreted as the tool encountering denser bone. This must be accounted for. Additionally, a more thorough test must be designed to evaluate the performance of the force controlled velocity model. One reasonable method to test this is to make several gelatin molds of different densities and measure the quantity of time required to cut a fixed distance. Denser molds should take longer to cut than those less dense.

The final table lays out our maximum deliverables. Torque control and null space compliance fall into this phase. Additionally, the accuracy of the torque sensors will be tested. It is appropriate to wait until this far into the project to perform this test because there are multiple examples of the adequacy of the torque sensors.

Maximum Deliverables
Demonstrate torque control in software
Demonstrate torque control on hardware
Human force null space compliance (fixed and cut path)
Quantify accuracy of robot arm torque sensors

Key Dates

The included Gantt chart graphically depicts a timeline of our project. The minimum, expected and maximum deliverables are found in green, blue and red, respectively. The minimum deliverables are scheduled to be completed by the end of April, the expected deliverables by mid-March and the maximum deliverables by the end of May.



Management Plan & Assigned Responsibilities

Weekly mentor meetings have been scheduled for Wednesdays at 4:30. We will also have team meetings on Sunday and Tuesday evening. Kangsan has a more mathematical background so he will be handling the force-cutting speed model and processing the torque data. Kevin, on the other hand, will tackle the solving the variable cutting speed problem and develop a test to evaluate the performance. Together, we'll take on the robot simulation and hardware programming.

Dependencies

The adjacent table is a list of our dependencies. Fortunately, most of these dependencies are resolved. There is currently some software to access the torque data from the robot arm, but if we need access to something else we will rely on our mentor to resolve that deficiency. We only expect to need funding to build something to test the efficacy of the robot with our modifications. We have not agreed to a dollar figure that we are budgeted, but we do have a handshake agreement that we may spend on the order of $100. We will estimate the cost of materials as soon as possible in order to finalize that agreement.

Dependencies
Access to lab
Access to robot arm & mentors
Access to Robone Git repository
Access to Linux machine to drive robot
API access to torque data
Funding

Reading List

Our reading list can be found below. It includes some papers that were recommended to us by our mentors and some that we found in our own independent research.

- Zuhars, J.; Hsia, T.C., "Nonhomogeneous material milling using a robot manipulator with force controlled velocity," in *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on* , vol.2, no., pp.1461-1467 vol.2, 21-27 May 1995
- P. Kazanzides, J. Zuhars, B.D. Mittelstadt, R.H. Taylor, "Force Sensing and Control for a Surgical Robot", Proc. 1992 IEEE Internat. Conf. on Robotics and Auto., Nice, France, May 1992
- Whitney DE. Force Feedback Control of Manipulator Fine Motions. ASME. *J. Dyn. Sys., Meas., Control.* 1977;99(2):91-97.
- Plaskos, C., Hodgson, A.J., Cinquin, P. Modeling and optimization of bone-cutting forces in orthopaedic surgery. *Lect Notes Comput Sci*. 2003;2878:254–261.
- H. Sadeghian, L. Villani, M. Keshmiri and B. Siciliano , "Task-space control of robot manipulators with null-space compliance" , *IEEE Trans. Robot.* , vol. 30 , no. 2 , pp.493 -506 , 2014
- Petrovic, Petar B., Ivan Danilov, and Nikola Lukic. "Nullspace Compliance Control of Kinematically Redundant Anthropomorphic Robot Arm."
- Pearlman, J.J. Cutting Velocity Effects in Bone Sawing. Tufts University, Medford. MA, USA; 2011