Synthetic Tracked Aperture Ultrasound Imaging:
Virtual Fixtures and Force Control

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Motivation

Ultrasound imaging is widely used in the clinical setting to visualize a patient's anatomy quickly, easily, and at a low cost. However, the main problem with ultrasound imaging is due to the aperture size of the transducer, which limits image quality in deep tissues. Synthetic aperture ultrasound imaging (STrAtUS) is a technique that synthesizes data from multiple sub-apertures using tracking data and has been shown to provide an improvement in image quality. The current synthetic aperture system uses a UR5 robot arm to autonomously scan the desired trajectory on the patient. This presents problems for clinical translation due to patient safety, ease of use by the sonographer, and force control requirements for anatomy-specific imaging.

Goals

Our goal is to bring the current system from autopilot to co-robotic freehand. This will be done by implementing guidance virtual fixtures, force sensing, and compliance force control. This will assist the operator in completing a safer and more accurate procedure.

Relevance

Achieving these goals will essentially bridge the gap between an autonomous robot and direct control by the user. First and foremost, this project will ensure patient safety. Secondly, it will allow for ease of use by the sonographer. Additionally, the force sensing and control component will allow for higher quality imaging of more complex regions, such as the abdomen, by guaranteeing a constant amount of force exerted.

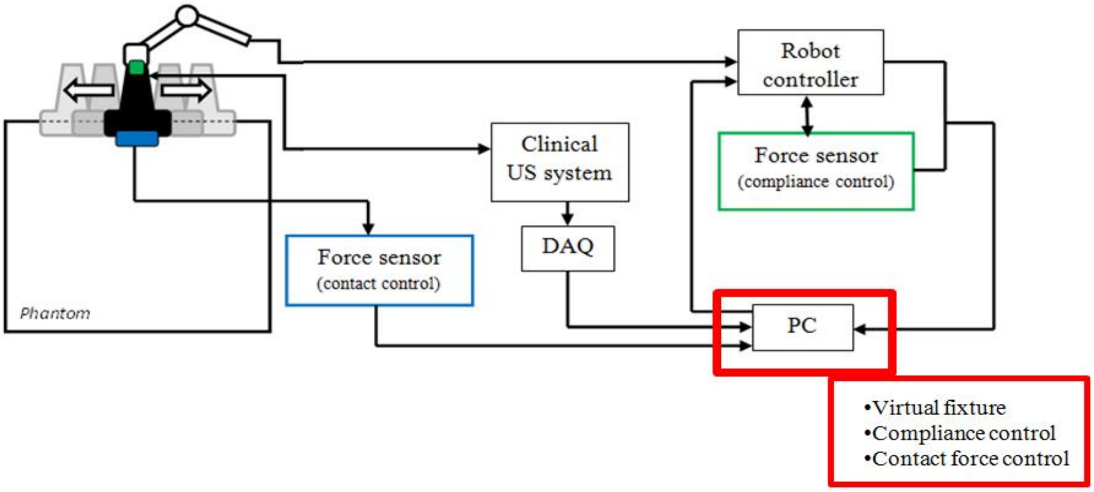
Technical Approach

<u>Proposed system architecture</u>

The currently proposed system is outlined in Figure 1. Two force sensors are highlighted in blue and green. Data flows from these two sensors to the PC, and back to the robot controller.

The blue force sensor is proposed to be placed on the probe to detect the contact force with the phantom or patient, while the green force sensor is proposed to be placed at the wrist of the UR5 arm for compliance control. We currently possess the sensor highlighted in green, which is the Robotiq FT150, a 6-axis force-torque sensor. We have also been given permission to use the Futek LSB 200 from the AMIRo lab, run by Iulian Iordachita. This device is a uni-directional load cell that can measure forces up to 10 lbf (~44.5 N). For this project's requirements, it may prove unnecessary to have both of these sensors since it might be preferable to pre-set a constant desired contact force. If this route is selected, the Robotiq FT150's measuring capabilities will be sufficient and the Futek LSB 200 will not be required.

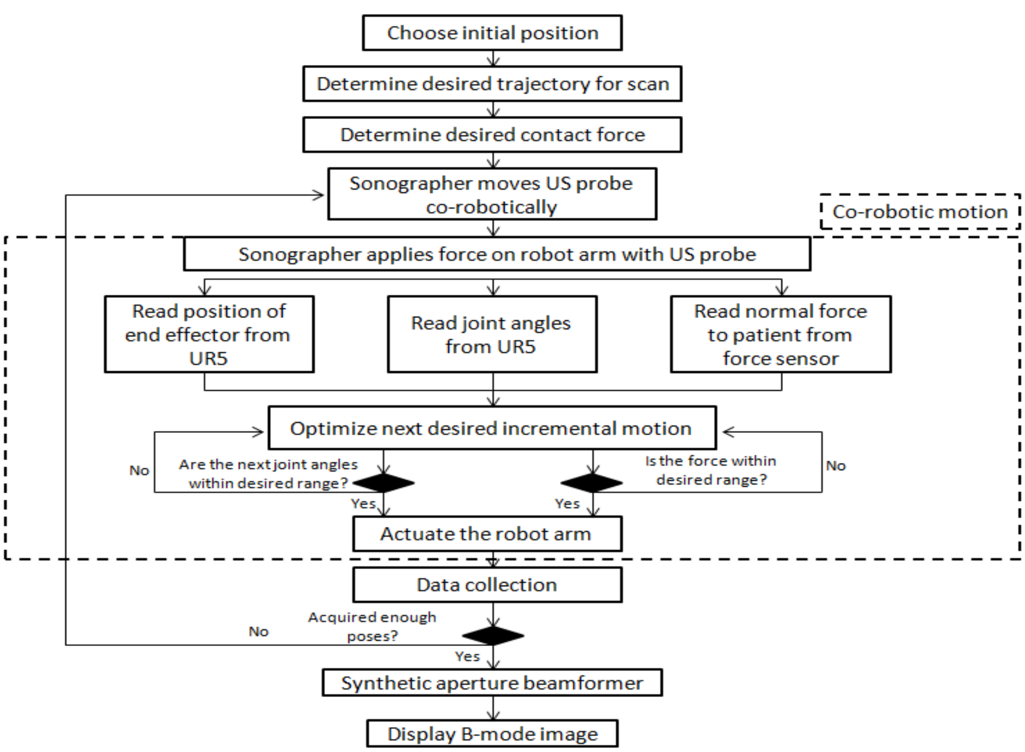
Figure 1. Proposed system architecture



<u>System Flowchart</u>

The following flowchart in Figure 2 represents how our virtual fixtures and force sensing will integrate with the current STrAtUS system. It demonstrates how the improved system with co-robotic control will be used together with input from the sonographer and creating the output of the B-mode image. Each of the components that are essential to this co-robotic control and how they serve to assist in image formation will be outlined in detail below.

Figure 2. System flowchart



Virtual Fixtures

We propose to use a linearized, constrained optimization approach to implement the desired virtual fixtures. The idea of this approach is to lead the sonographer along the trajectory while providing haptic feedback to discourage deviation from the desired path. This will be done through the information gathered on the instantaneous kinematics of the manipulator, in addition to physical and geometric constraints.

The objective function of the optimization problem generally takes the form $\operatorname{argmin}_{\Delta q}\|W(J\Delta\vec{q} - \vec{x}_d)\|$, where W is a diagonal weight matrix, J is the manipulator Jacobian that relates task space to joint space, q is the vector of joint variables, and x_d is the desired Cartesian position. A general form of the constraints is given as $H\Delta\vec{x} \geq \vec{h}$. The desired behavior of the system will be used in defining the linearized subject functions for H, the constraint coefficient matrix and h, the constraint vector. As mentioned, we want to guide the sonographer in moving the probe along a line. This is done by defining the equation of the line to be followed, calculating the error in each incremental motion, and bounding that error using the form outlined above.

A similar method will be applied for constraining joint limits, following a curve instead of a line, and/or constraining the contact force on the patient. This simple formulation will allow us to add more constraints as we see fit over the course of our development.

Compliance Control

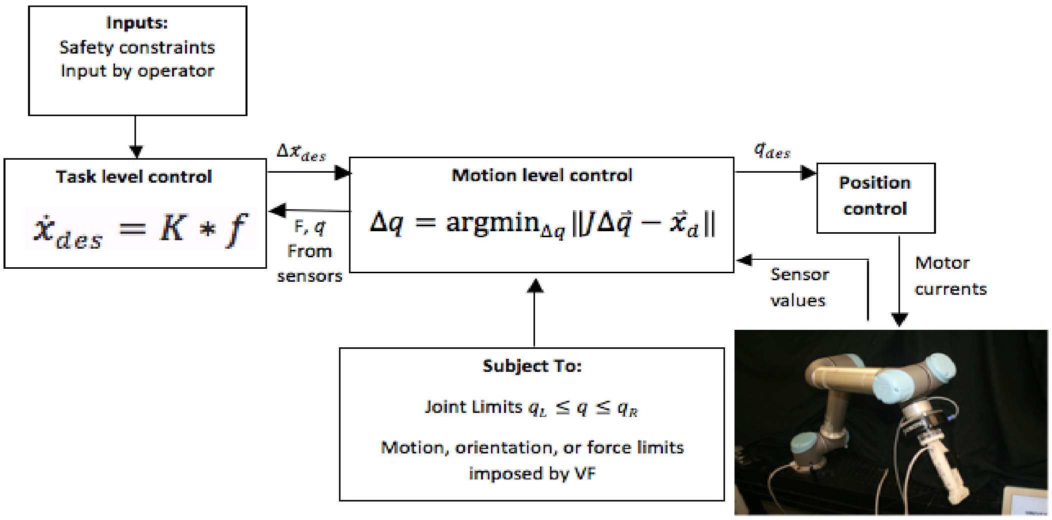
We additionally propose to implement compliance robot force control for the use of ultrasound probe guidance in synthetic aperture applications. This component will be similar to the work being implemented for a master's thesis project by Rodolfo, one of our team members. A more detailed explanation of the relationship and differences between this project and Rodolfo's thesis project is described in the "Assigned Responsibilities" section below.

In short, force and torque readings acquired through the Robotiq FT 150 sensor will be translated into incremental joint motions of the UR5. The relationship between the forces exerted by the clinician against the robot end effector (EE) when manipulating the ultrasound probe takes the form $\dot{x}_{des} = K * f$ where K, typically determined experimentally, is a coefficient matrix that scales the input force to an appropriate EE velocity in Cartesian coordinates. From this EE velocity vector, the corresponding joint velocities are calculated using $\dot{x} = J\dot{q} \rightarrow \dot{q} = J^{-1}\dot{x}$ where J is the robot Jacobian matrix. As seen on the right-hand side of this equation, the inverse of the Jacobian must be calculated to determine the joint velocities. However, to avoid cases where the Jacbobian cannot be inverted, an optimization method can be employed, resulting in the formulation $\dot{q} = \operatorname{argmin}_{\dot{q}}\|J\dot{q} - \dot{x}\|$ where the joint velocity vector that minimizes the objective function is calculated.

For safety purposes, it is important to consider the situation in which the connection between the robot controller and the computer sending the velocity commands is broken. In particular, if the connection is broken while the robot is in motion due to a previously received velocity command, the UR5 will not receive any new commands and will continue to move at the same velocity. In order to avoid this, a common technique is to instead send the robot incremental joint angle commands. This is done by changing the optimization problem to $\Delta q = \operatorname{argmin}_{\Delta q}\|J\Delta\vec{q} - \vec{x}_d\|$ where x is the desired end effector position and Δq is the resulting incremental joint commands. This results in the objective function shown in the "Virtual Fixtures" section above.

Figure 3 shows the relationship between the robot, force sensor, and probe. Overall, this method will be used to allow for smooth and intuitive clinician-robot interactions and will allow the user to have control of the velocity at which the probe moves down the desired trajectory. Combined with virtual fixtures, this collaborative control will ensure smooth, accurate, and safe ultrasound image acquisition at a velocity that is most comfortable for the sonographer.

Figure 3. Data flow diagram



<u>Image formation</u>

The details above highlight the important components of using co-robotic control for STrAtUS imaging. The main goal of improving ultrasound image quality is obtained through tracking the transducer, which in this case is achieved through the inherent and highly accurate mechanical tracking properties of a robotic arm. This tracking of the ultrasound probe allows for data from multiple poses to be reconstructed to form a single, higher resolution image. As can be seen in the flowchart in Figure 2, the sonographer determines the initial pose, which will serve as the base image frame during reconstruction, and then collects data aided by the virtual fixtures and compliance control in order to construct the desired image.

Deliverables

Minimum

- Code implementing virtual fixtures

  To implement the guidance and forbidden region virtual fixtures mentioned above, the constrained optimization algorithms must be formulated as described in the "Virtual Fixtures" section above. Once this has been done, the MATLAB optimization toolbox will be used to solve for the desired joint commands
- Code implementing compliance force control

  The optimization problem's objective function will be set up to translate the force input of the user to incremental joint position commands with the equation $\Delta q = \text{argmin}_{\Delta q}\|J\Delta\vec{q} - \vec{x}_d\|$ as described in the "Compliance Control" section above.
- Comparison of actual trajectory of robot with planned trajectory

  Using commands provided by the Universal Robots interface, the actual position of the end effector will be collected. These values will be compared to those expected from the implementation of the virtual fixtures and this comparison will allow for validation of the guidance and forbidden region virtual fixtures.

- Demonstration of translational path in water tank using co-robotic control

  In order to show the effectiveness of the guidance virtual fixtures in improving control for synthetic aperture imaging, the ultrasound probe will be placed inside a water tank containing a single wire target. A synthetic aperture image will be created by moving the probe down a linear translational path while keeping its orientation constant. The full width at half maximum of the resulting image will be compared to that of images collected when the robot is run on autopilot without virtual fixtures.

Expected

- Demonstration of rotational path in water tank using co-robotic control

  The same experiment described immediately above will be conducted, this time allowing the orientation of the probe to vary in real time. This will allow us to determine if we are able to keep the orientation of the probe pointing in the direction of the target, thereby allowing us to further increase the synthetic aperture.

- Demonstration of translational path on general US phantom

  This experiment will require use of contact force control on a planar phantom. This will be used to ensure that the probe is maintained at a constant and safe force against the phantom surface, while acquiring quality images. In this case, the contrast to noise ratio of the image collected with synthetic aperture using virtual fixtures and force control will be compared to that collected when the robot was on autopilot.

Maximum

- Demonstrate control on more anatomically accurate path using rotation and force control on abdominal phantom

  The same experiment described immediately above will be conducted, this time with the added requirement that the robot is able to account for sudden changes in the topology of the object being scanned. Both translational and rotational positions of the end effector, along with the compliance and contact forces will have to be controlled.

Dependencies and Plan for Resolution

<u>UR5 robot and force sensors</u>

In our project plan, we assume that we will have access to the UR5 robot and the necessary force sensors. We have obtained access to the MUSiiC Lab’s Google calendar so that we can schedule times to test our software and produce the necessary deliverables in a timely manner. We plan to schedule these times in advance, but we both have flexible schedules if any problems arise.

<u>Sonix Touch ultrasound system</u>

Similarly, we have access to the ultrasound system through the Google calendar. While it is not necessary for our software development, it will be required for our experimental protocol and demonstration of our functional system. Again, these times will be planned in advance.

<u>STrAtUS real-time visualization system</u>

Kai has walked us through his software. However, we will still depend on him to aid in the image formation portion of this project. When this becomes necessary after our first experiment in the water tank in mid-March, we will schedule extra time with him to produce the necessary images.

Access to water tank & phantoms

These are available in Dr. Boctor's lab, and can be requested as necessary. We plan to reserve access to them within a week of when we would like to test our system.

Access to mentors

We have scheduled a weekly meeting with Kai on Mondays at 4 pm. We will use this time to review our weekly progress and answer any questions or problems with our software development. Additionally, we have had a preliminary mentor meeting with Dr. Taylor on 2/17, and will schedule time with him as needed.

Deeper understanding of virtual fixtures and implementation

Our first 3 weeks have been dedicated to literature review and meeting with experts in the field to gain a better understanding of virtual fixtures. This is an ongoing process. We have already met with Paul Wilkening, Tutkun Sen, and Dr. Taylor, and can schedule additional time as necessary. Additionally, we are doing a thorough literature review, as can be found on our reading list.

Familiarity with CISST libraries

This is also an ongoing process. However, we have been given an overview of the libraries and sample code by Tutkun Sen. We have also reviewed the GitHub Wiki pages for SAW and the Constraint Controller. Paul Wilkening is a very good resource for this, and we have given him an overview of our project and he has offered his help when necessary.

Management Plan

Assigned Responsibilities

In order to ensure our deliverables are completed on time, we have split up the major tasks of the project, with the lead for each based on his or her previous experience and knowledge. However, it is important to note that we will be in constant communication with each other and our mentors, keeping each other updated on our status and assisting one another as required. We plan on having bi-weekly team meeting on Mondays and Thursdays and weekly meetings with our mentor, Kai Zhang on Mondays. Both team members will work on the phantom experiments and data collection and analysis.

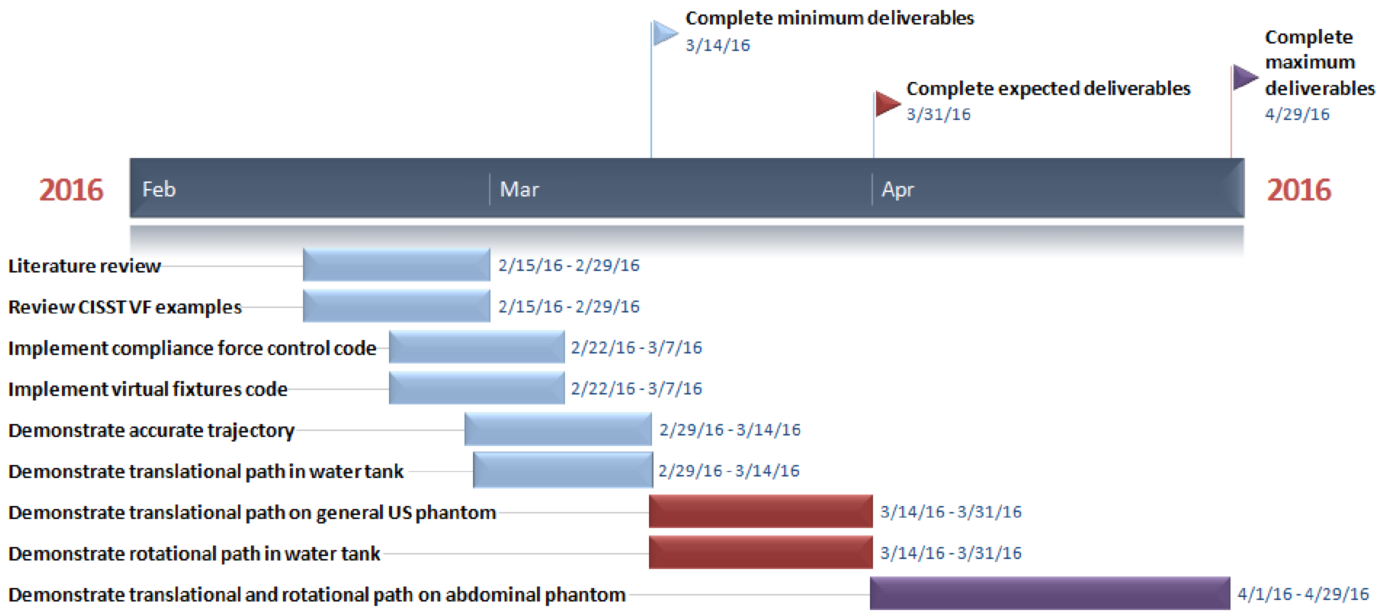
Kalyna, who has a stronger mathematical background and experience with optimization methods, will lead the research behind and implementation of the virtual fixture algorithms. Additionally, given her knowledge of medical imaging, she will take the lead on the image analysis involved with our deliverables where image quality with and without virtual fixtures will be compared.

Rodolfo has experience with mechanical systems and robotic control. He will focus on the research and implementation of the compliance and contact force control relevant to synthetic aperture imaging. It is important to note that this project relates to work he has simultaneously been developing for a thesis to satisfy the requirements for his MSE in Robotics. In this separate project, Rodolfo is also implementing compliance force control with the aim of assisting sonographers apply the force required to scan targets deep in a patient's anatomy. This method will be particularly useful in use with obese patients where the sonographer might have to apply up to 250 N of force to traverse the extra layers of fat. The system he is implementing resembles power steering systems used in the automotive industry, in which the effort of the steering wheel rotation by the driver is augmented. Part of his deliverables for this will consist of a set of experiments that compare the ergonomics and image quality of the assistive system to freehand ultrasound. Additionally, the focus is on the augmentation of forces normal to the patient's surface, which can change dynamically through a procedure. It makes use of a custom ultrasound holder Rodolfo has designed to measure this contact force in real time. Compared to the project described herein, Rodolfo's main thesis project does not make use of virtual fixtures and does not involve synthetic aperture imaging. Additionally, in this project, the contact force will be expected to remain constant, while the robot is allowed to move freely in every other direction, according to a number of constraints.

Milestones

Our plan for completing our deliverables is as follows. We will have our minimum deliverables complete by March 14th, 2016. This includes functioning code implementing compliance force control, force sensing, and virtual fixtures, as well as a demonstration of a translational path in a water tank. Our expected deliverables will be complete by March 31st, 2016. This is simply an expansion of our previous implementation onto a different phantom, and including a rotational path in addition to a translational path. Our maximum deliverable is a combination of all of the above on a more complicated abdominal phantom and is projected to be complete by the end of April.

It is important to note that we will be keeping our future deliverables in mind while working on current ones, so that we are not limited to a short amount of time for a new task. Additionally, we will ensure that these milestones are met by evaluating our timeline each week and adding or subtracting work where necessary. This approach will aid us in making sure that we don't fall behind, but if we do, we will decide with our mentors where we can make up for it. As can be seen, we have dedicated all of April to our maximum deliverable, so there is room to complete other tasks if necessary in a worst case scenario.



Reading List

Kalyna

Abbott, Jake J., Panadda Marayong, and Allison M. Okamura. "Haptic virtual fixtures for robot-assisted manipulation." *Robotics research*. Springer Berlin Heidelberg, 2007. 49-64.

Funda, R. Taylor, B. Eldridge, S. Gomory, and K. Gruben, "Constrained Cartesian motion control for teleoperated surgical robots," *IEEE Transactions on Robotics and Automation,* vol. 12, pp. 453-466, 1996.

A. Kapoor and R. Taylor, "A Constrained Optimization Approach to Virtual Fixtures for Multi-Handed Tasks," in IEEE International Conference on Robotics and Automation (ICRA), Pasadena, 2008, pp. 3401-3406.

M. Li, M. Ishii, and R. H. Taylor, "Spatial Motion Constraints in Medical Robot Using Virtual Fixtures Generated by Anatomy," *IEEE Transactions on Robotics*, vol. 2, pp. 1270-1275, 2006.

M. Li, A. Kapoor, and R. H. Taylor, “A constrained optimization approach to virtual fixtures,” in IROS, 2005, pp. 1408–1413.

S. Payandeh and Z. Stanisic, "On Application of Virtual Fixtures as an Aid for Telemanipulation and Training," *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2002.

R. H. Taylor, J. Funda, B. Eldgridge, S. Gomory, K. Gruben, D. LaRose, M. Talamini, L. Kavoussi, and J. anderson, "Telerobotic assistant for laparoscopic surgery.", IEEE Eng Med Biol, vol. 14- 3, pp. 279-288, 1995

Rodolfo

Ankur Kapoor, *Motion Constrained Control of Robots for Dexterous Surgical Tasks*, Ph.D. Thesis in Computer Science, The Johns Hopkins University, Baltimore, September 2007

A. Kapoor, M. Li, and R. H. Taylor "Constrained Control for Surgical Assistant Robots," in *IEEE Int. Conference on Robotics and Automation*, Orlando, 2006, pp. 231-236.

R. Kumar, An Augmented Steady Hand System for Precise Micromanipulation, Ph.D thesis in Computer Science, The Johns Hopkins University, Baltimore, 2001. - cannot find

M. Li, *Intelligent Robotic Surgical Assistance for Sinus Surgery*, PhD Thesis in Computer Science Baltimore, Maryland: The Johns Hopkins University, 2005.

J. Roy and L. L. Whitcomb, "Adaptive Force Control of Position Controlled Robots: Theory and Experiment", IEEE Transactions on Robotics and Automation, vol. 18- 2, pp. 121-137, April 2002

R. Taylor, P. Jensen, L. Whitcomb, A. Barnes, R. Kumar, D. Stoianovici, P. Gupta, Z. Wang, E. deJuan, and L. Kavoussi, "A Steady-Hand Robotic System for Microsurgical Augmentation", International Journal of Robotics Research, vol. 18- 12, pp. 1201-1210, 1999

Both

sawConstraintController *and* Constrainted Optimization JHU-saw library page on Virtual Fixtures