ME 328 MEDICAL ROBOTICS NIH R21 PREPROPOSAL

PROJECT TITLE:

ULTRASOUND GUIDANCE OF AUTONOMOUS ROBOTIC PERCUTANEOUS INTERVENTIONS

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SPECIFIC AIMS

Percutaneous interventions have many potential advantages when compared with alternative open or minimally invasive surgical approaches, including reduced blood loss, scar tissue formation, and hospital stay. Robotic systems designed to steer flexible needles through tissue have the potential to enable a host of new percutaneous procedures that are not possible using current manual methods and straight needles. Unfortunately, while extensive work on the design of robotic needle steering systems has been described in the literature (see references in [8]), actual in-vivo studies and descriptions of practical clinical systems have been extremely limited. The overall goal of this project is to translate robotic needle steering to actual clinical practice by overcoming two of the largest remaining obstacles: intraoperative medical image guidance of steerable needles and steerable needle position control in 3D.

Specific Aim 1: Automatically localize curved needles in 3D ultrasound. Ultrasound is a useful intraoperative imaging modality that can be easily integrated into existing OR's. The automatic localization of needles in ultrasound images is an important unsolved problem in image-guided intervention, with many applications beyond robotic needle steering. Although algorithms exist, they are generally too computationally intensive to run in real time, and have poor accuracy and robustness. We plan to leverage the robotic needle steering system to reduce the complexity of the image analysis task. We will use the robot to generate controlled motion of the needle which can be recognized in the ultrasound data. We will experimentally validate our methods in simulated tissues and ex-vivo tissue samples.

Specific Aim 2: Control the position of flexible needles in tissue in 3D. Flexible needles with beveled or bent tips follow curved trajectories as they are inserted into tissue, with a fixed radius of curvature defined by the tip geometry. As described in [6], intermittently spinning the needle during insertion leads to a trajectory with a new radius of curvature that is dependent on the fraction of time spent spinning. This "duty cycle" technique allows one needle to be steered on paths of arbitrary radius. An alternate approach that involves flipping the needle between discrete orientations can also be used to control curvature of the needle path. For both of these approaches, trajectory tracking error accumulates over the course of insertion, and increases with the ratio of insertion velocity to maximum rotation speed. We will evaluate these two approaches and develop an open-loop controller to compensate for motor speed limitations and the torsional dynamics of the tissue. Such a controller will allow greater access to obscured regions of the body with simpler path planning algorithms.

Specific Aim 3: Integrate the methods developed for SA1 and SA2 into a system for image-guided placement of steerable needles. We will develop a controller for steerable needle placement that minimizes open-loop tracking error, while at the same time generating motion that allows localization of needles in 3D ultrasound. Real-time imaging will then provide feedback for closed-loop control of the needle position in 3D. We will validate our system in phantom and ex-vivo tissue experiments.

Our application is appropriate for R21 funding because it is *high risk*; we will develop novel algorithms for ultrasound image segmentation and registration, as well as methods for position control of robotically-steered needles. This project is also *high impact.* By combining the repeatability and precision of a robotic needle insertion system with the real-time patient specific information provided by ultrasound imaging, our work has the potential to improve a wide variety of clinical applications, from breast cancer biopsy to liver ablation.

RESEARCH STRATEGY

A. Significance

Percutaneous interventions have advantages when compared with alternative open or minimally invasive surgical approaches, including reduced blood loss, scar tissue formation, and hospital stay. In many percutaneous interventions such as biopsy, brachytherapy and ablation, clinicians manually insert straight needles to a target point under medical image guidance. These procedures are very challenging for clinicians. They must manually register the medical image data to their own movements while actively compensating for motion of the tissue and deflection of the needle. As a result these procedures in general are very time consuming and suffer from limited accuracy.

Robotic systems designed to steer flexible needles through tissue have the potential to overcome the limitations of manual needle insertions and enable a host of new percutaneous procedures that are not possible using current manual methods and straight needles. Unfortunately, while extensive work on the design of robotic needle steering systems has been described in the literature (see references in [8]), actual in-vivo studies and practical clinical systems have been limited. The overall goal of this project is to translate robotic needle steering to clinical practice by overcoming two of the largest remaining obstacles: intraoperative medical image guidance of steerable needles, and steerable needle position control in 3D.

Previous studies have described robotic systems for image-guided percutaneous intervention. These studies have largely focused on magnetic resonance imaging (MRI) [10], likely because MRI offers high spatial resolution, and can discriminate both soft tissues and interventional tools. Unfortunately MRI has drawbacks that prevent widespread adoption. MRI equipment is costly, must be situated in special suites, and is incompatible with existing interventional equipment. Unlike MRI equipment, ultrasound imaging equipment is portable and relatively inexpensive, and can be readily integrated into existing operating rooms. On the other hand, ultrasound is limited in its ability to localize interventional instruments with respect to anatomy. Some typical metal instruments generate substantial imaging artifacts, while others may be partially or totally invisible.

Long-term, we will develop methods for ultrasound image guidance of surgical robots in a variety of possible procedures, including laparoscopic surgery, endovascular interventions, and percutaneous interventions. For the exploratory work described by this R21 application, we will focus on needle insertion. We believe our current approach offers the most potential benefit for procedures that require multiple precise insertions to deep targets, such as percutaneous ablation for hepatic carcinoma.

B. Innovation

Our work will enable a new paradigm in image-guided intervention. Robotic needle insertion systems will use real-time ultrasound guidance to semi-autonomously reach targets deep within the body with greater accuracy than is possible for a human clinician. This goal requires innovation in two areas: ultrasound segmentation of curved needles and robotic control of steerable needles in 3D.

Methods for localizing needles in ultrasound data that are described in the literature generally involve complex image analysis algorithms such as the Hough Transform [7] or parallel projection [1]. Applying these complex algorithms to a large, noisy dataset is not currently practical for a clinical system. Rather than further develop complex image analysis algorithms, we will use the robotic platform to generate known motion to be recognized in the ultrasound data. Investigatory studies have applied a similar concept by using high-frequency vibration and existing ultrasound Doppler protocols to highlight tool tips in images [5]. As described in the following section, we will create novel Doppler imaging techniques based on a model of the tissue velocity field around a moving needle. The described work will be the first to use Doppler techniques to highlight the entire body of a curved surgical instrument.

While previous researchers have developed and implemented methods for straightening the path of a bent or bevel-tipped needle by precisely spinning it at various increments, steering a needle along complex trajectories in tissue remains a relatively unexplored problem. This work will expand upon previous strategies and explore new options for controlling needle position, while also testing their effectiveness in providing the needle movements necessary for Doppler imaging. Combining the optimal needle steering algorithms with ultrasound imaging in a real-time closed-loop controller will pave the way for autonomous percutaneous interventions.

We will collaborate with practicing surgeons and interventional radiologists who will act in an advisory capacity for our initial work. Although it is not a component of this proposal, our overall goal is to transition to patient use as quickly as possible. This makes regular input from clinicians crucial.

C. Approach

A clinician's role in manual needle-insertion procedures can be divided into two subtasks: processing medical images to localize their tool, and controlling tool motion while inserting. These subtasks are combined by the clinician to place the needle with respect to target anatomy. We will develop methods to allow robotic systems to perform both subtasks. Computer algorithms will process ultrasound image data to reliably and accurately localize the needle. A robotic manipulator will insert and steer a flexible needle. The two subtasks will be combined to allow closed-loop control of needle position in 3D.

C.1. Specific Aim 1

The goal of Specific Aim 1 is a method for automatic localization of robotically-steered needles in 3D ultrasound. This method will build upon existing techniques for ultrasound Doppler imaging. In Doppler imaging, the raw acoustic echoes received by the ultrasound transducer are processed to determine the change in frequency from the original transmitted echo. This change in frequency, called the Doppler shift, is proportional to the velocity of the object reflecting the echo. Doppler imaging mode is available on most modern ultrasound machines, and is primarily intended for imaging blood flowing through vessels. Previous studies have used Doppler imaging mode to detect the motion of needles or instruments that are externally vibrated [5]. We will use a similar concept, but rather than apply unwanted vibration, we will characterize and recognize the motion generated by the robotic needle steering system.

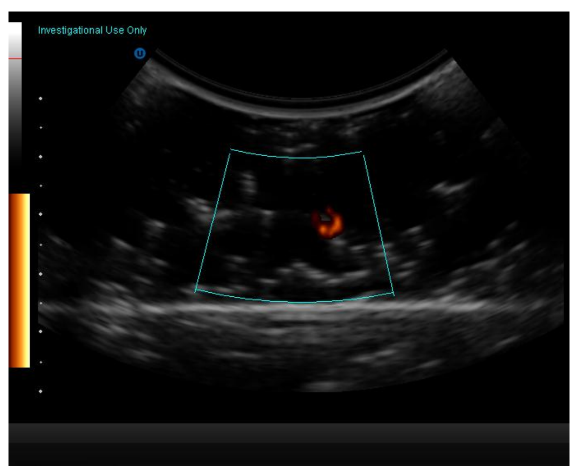

Figure 1: Doppler signals can be used to highlight needles in noisy ultrasound images, reducing the complexity of the image analysis problem.

Task 1.1: We will develop a simplified mechanical model of the needle and tissue that applies to robotic needle steering. This will allow us to characterize to a first-order approximation what motion of the needle and tissue results from insertion and rotation of the needle base. We will also relate the expected velocities to the variable position of the ultrasound transducer, since orientation of target velocity has a significant impact on the measured Doppler signal.

Task 1.2: Based on a model of the resulting needle and tissue motion, we will design algorithms for detecting and segmenting the needle in 3D ultrasound data. We will experimentally measure the magnitude and variance of Doppler shift around a steered needle, as well as the power of the shifted wave (power Doppler), and attempt to determine recognizable characteristics. Through the novel application of high and low pass filters to the raw radiofrequency echoes, along with intensity-based filters on the processed Doppler images, we will highlight the needle relative to surrounding tissue (as shown in Figure 1) and reduce the complexity of the segmentation task.

If it is not possible to segment the needle precisely enough using only Doppler signals, we will alternatively localize the needles using both Doppler and standard B-mode data. For example, we will use Doppler information to mask B-mode images, and identify the centroid of the resulting intensity image as the needle profile.

Task 1.3: Following completion of the previous two tasks, we will determine the overall accuracy of segmentation using our algorithm. We will test the accuracy of identifying the needle path, as well as the localization of the needle tip along the path. We will perform imaging tests in artificial tissue and ex-vivo animal tissue such as bovine and porcine liver. In these tests, needles will be inserted using a robotic needle steering system while being imaged using 3D ultrasound. Afterwards, the needles will also be imaged with a second modality, likely CT imaging, and segmented to create a gold-standard for comparison. We will evaluate the accuracy of our algorithm by comparison with clinical requirements that are discussed in the literature for specific procedures such as biopsy, ablation and brachytherapy.

C.2. Specific Aim 2

The goal of Specific Aim 2 is to develop, test, and compare multiple methods for open-loop control of steerable needles along complex trajectories within tissues. We will start with simulation of each method based upon nonholonomic kinematic models of steerable needles and later evaluate the most promising methods experimentally on our needle steering robot.

Task 2.1: To simulate the dynamics of a flexible bevel tip or bent tip needle moving through tissue, we will utilize the nonholonomic kinematic models proposed in [11]. These generalizations of the unicycle and bicycle models use experimental data to fit a set of parameters to a given needle that allow six degree-of-freedom analysis of its motion based upon the two input degrees of freedom: insertion speed and rotation speed. Most importantly for path planning, these parameters of the needle define the radius of curvature that its circular path will trace out for an insertion with no rotation. A simple target trajectory for the needle tip in three dimensions can thus be constructed as a series of arcs of this specific radius in varying directions, where the control inputs consist of a rotation to the target plane followed separately by an insertion without rotation, repeated for each arc in the path.

Many procedures would benefit from the ability to follow more complex target trajectories that include arcs with different radii of curvature than the natural curvature of the needle path [3]. This has motivated the development of a technique called “duty-cycling,” in which the insertion speed is held constant while the needle alternates at fixed intervals between rotating at a fixed speed and not rotating [6]. The percentage of time spent rotating, or duty cycle, defines how much the curvature of the needle path is reduced, with 100 percent corresponding to a perfectly straight path and 0 percent corresponding to the natural radius of curvature of the needle. This method assumes that the needle rotation speed is much greater than the insertion velocity, and

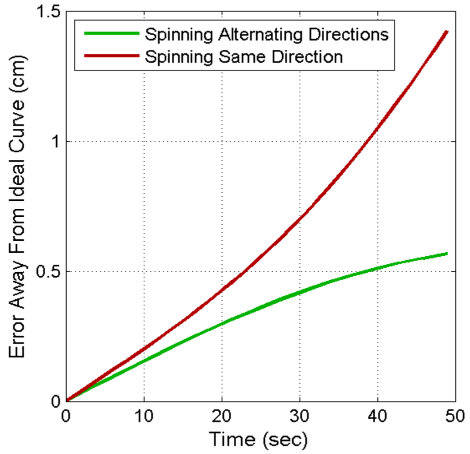

Figure 3: Theoretically, alternating the direction of rotation between duty cycles will prevent the error created by the helical path from propagating over many cycles.

that the needle is oriented the same way at the end of each cycle.

One of our proposed needle control algorithms expands upon the principles of this duty cycling approach with the goal of reducing tracking error, particularly in situations where the rotation speed may be limited. Based upon the nonholonomic models, a needle that rotates while inserting will follow a helical path. This does not result in the same three-dimensional orientation at the end of the rotation as at the start, an error that can propagate over multiple rotations. To limit this error propagation, our proposed algorithm splits each cycle into exactly one rotation of the needle at a constant speed, with alternating cycles turning the needle in opposite directions. Essentially, as the needle inserts at a constant speed the needle will rotate one rotation clockwise, stop rotating for the duration of the cycle, rotate one rotation counterclockwise, stop for the duration of the cycle, and repeat. The same definition of duty cycle percentage applies. Figure 2 shows how the error would theoretically either level off or propagate differently between the two strategies for an arbitrary set of needle parameters.

An additional proposed algorithm would combine the stringing together of multiple arcs at the radius of curvature of the needle with the duty cycling technique of breaking the trajectory into many short two-phase cycles to effectively straighten the needle path. Each cycle consists of one arc in the direction of the desired path and a shorter arc opposite the direction of the desired path, where equal arc lengths correspond to an overall straight path. **Error! Reference source not found.** depicts a version of such a trajectory where the cycle length and needle curvature have been exaggerated to demonstrate the algorithm. The advantage of this algorithm is that the average error theoretically would not propagate over the course of a long trajectory, though the maximum error could be large if the cycle time were not short enough. We will also consider additional control algorithms that may include, for example, continuous adjustment of rotation or insertion speed, in order to verify whether these additional factors further decrease tracking error.

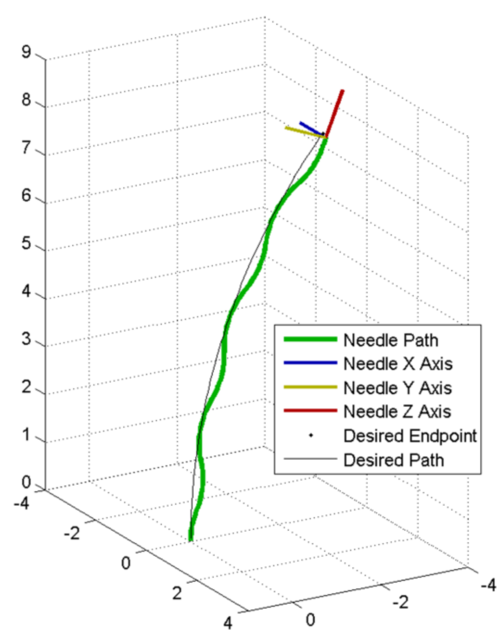

Figure 2: A sample trajectory of the needle with exaggerated cycle length demonstrates the functionality of the flipping algorithm.

Task 2.2: After completing the theoretical simulation and analysis of potential control algorithms for needle insertion along complex trajectories, we will experimentally validate the results on an actual needle steering robot. The robot, shown in Figure 4, has two DOF: one motor rotates the needle base and another rotates a lead screw to insert the needle. For each algorithm, we will send the robot the control inputs necessary to guide the needle along a set of paths inside a tissue phantom. The paths, which will remain constant across all algorithms, will range in complexity from straight lines to slight arcs to long trajectories consisting of multiple arcs of different radii. We will compute the RMS error and maximum error for each algorithm and each trajectory to quantitatively compare the tracking accuracies. For each algorithm, we will run these experiments at a variety of insertion and rotation velocities to validate our models of how these velocity adjustments affect tracking error over the course of a trajectory.

The potential problems we foresee arising in this specific aim relate to the complexities of needle-tissue interactions during insertions. The rotation of the needle base does not necessarily correspond perfectly to the rotation of the needle tip, particularly when the tip is deep inside the tissue. An alternative strategy would be to compensate for the anticipated torsional dynamics of the needle-tissue interaction in the controller algorithms using the models presented in [9]. Artificial tissue also does not perfectly emulate real human tissue, particularly at stiffer boundaries to organs or surfaces. An alternate experimental approach using ex-vivo tissue may thus prove necessary to accurately evaluate the tracking capabilities of the control algorithms we develop.

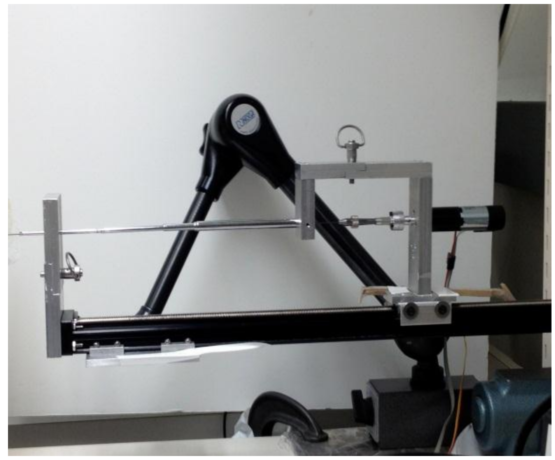

Figure 4: The needle steering robot that will be used to quantitatively evaluate the control algorithms.

C.3. Specific Aim 3

Specific Aim 3 will combine the results of SA1 and SA2 into a closed loop controller for needle insertion and tracking in real tissue.

Task 3.1: From SA1 we will have experimentally determined how needle tip motion affects the ability of Doppler imaging to localize the needle. These experiments will provide a set of ideal rotation speed and insertion speed parameters that will maximize the ability to localize the needle in ultrasound, as well as an estimate of how variation away from these optimal speeds will affect the visibility. From SA2 we will have experimentally determined which open loop controller algorithms result in the smallest errors as well as how adjusting the rotation and insertion speeds for each of these algorithms will affect tracking. We will develop and implement an optimization method for selecting the control algorithm and insertion velocities that maximize the ability to localize the needle, while minimizing the open loop tracking error.

Task 3.2: We will combine our open loop controller with the Doppler imaging results to provide closed loop feedback control. A block diagram for our proposed controller is shown in Figure 5. A primary task in tuning this closed loop controller will involve weighting the estimates of needle position provided by the open loop simulator of the needle dynamics and the estimates provided by imaging feedback from the ultrasound. The experimental results of SA1 and SA2 will help determine these Kalman filter weightings. We will expand upon the two dimensional needle insertion planning work of [2] to develop our algorithms for three dimensional path planning of the steerable needle.

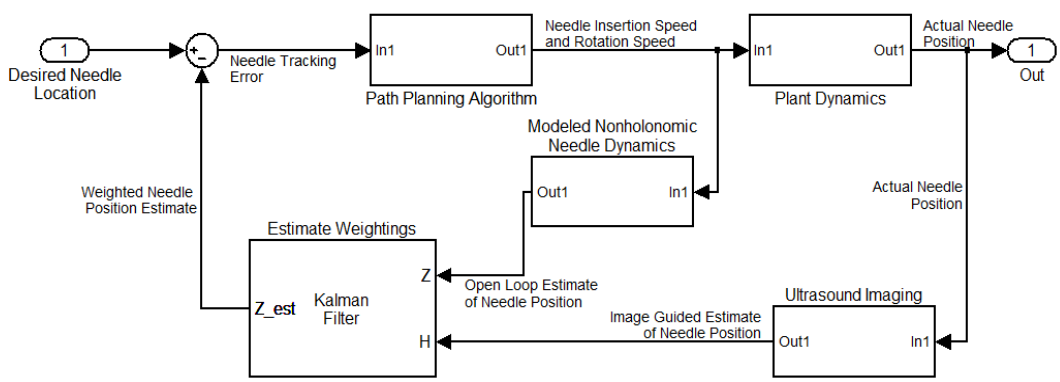

Figure 5: The proposed block diagram for the closed loop controller relies on a Kalman filter to weight the estimates of needle position.

Task 3.3: Closed loop control of a steerable needle in human tissue requires accurate, on-line registration of the needle in the controller frame to the segmented needle in the ultrasound image frame. In a practical system, the ultrasound transducer would be likely to move throughout a procedure. We will use the curved needle path itself as a registration feature, although this may introduce ambiguity in the early stages of insertion. Alternatively, we will use magnetic or optical tracking systems to provide real-time updates on the relative position of the ultrasound transducer and the needle insertion robot.

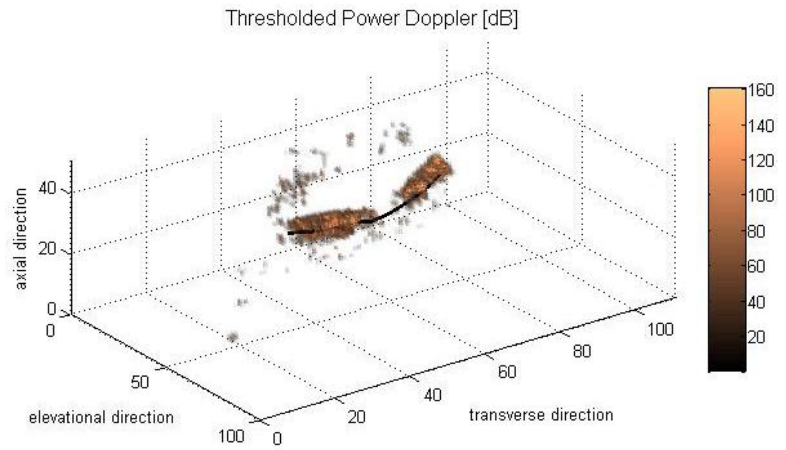

Figure 6: Power Doppler ultrasound data showing the outline of a rotating needle in a tissue phantom. The manually segmented needle is also shown (black).

C.4. Preliminary Data

Doppler

As discussed above, prior studies have demonstrated that applied mechanical vibration combined with Doppler imaging mode can increase the visibility of surgical tools, such as needles, in ultrasound images. We aim to use only needle rotation and insertion to generate a useable Doppler signal. To demonstrate the feasibility of this, we rotated a 0.9-mm stainless-steel needle in artificial tissue at 5.86 rad/s using a robotic needle steering system, and captured 3D RF data using a mechanical convex 3D probe. The RF data was processed into volumetric B-mode and power Doppler data offline. Figure 6 shows the power Doppler data after applying a threshold. The figure reveals a strong Doppler response along the axis of the rotating needle. The needle axis was manually segmented and is shown in the figure.

Duty-Cycle control

We have simulated the dynamics of a needle tracking a path of an arbitrary radius for the two control algorithms we have described above. The first algorithm, which spins the needle at a constant velocity to straighten its path, is limited in its tracking accuracy by the ratio of the rotation speed to the insertion speed of the needle. The second algorithm, which involves flipping the needle back and forth at 180-degree increments, improves its tracking accuracy as the cycle time between flips shortens. As shown in the right subplots, changing between algorithms or adjusting parameters within an algorithm results in different velocity profiles for both insertion and rotation. We can use this fact to select a needle control algorithm to maximize visibility in Doppler imaging and minimize tracking error.

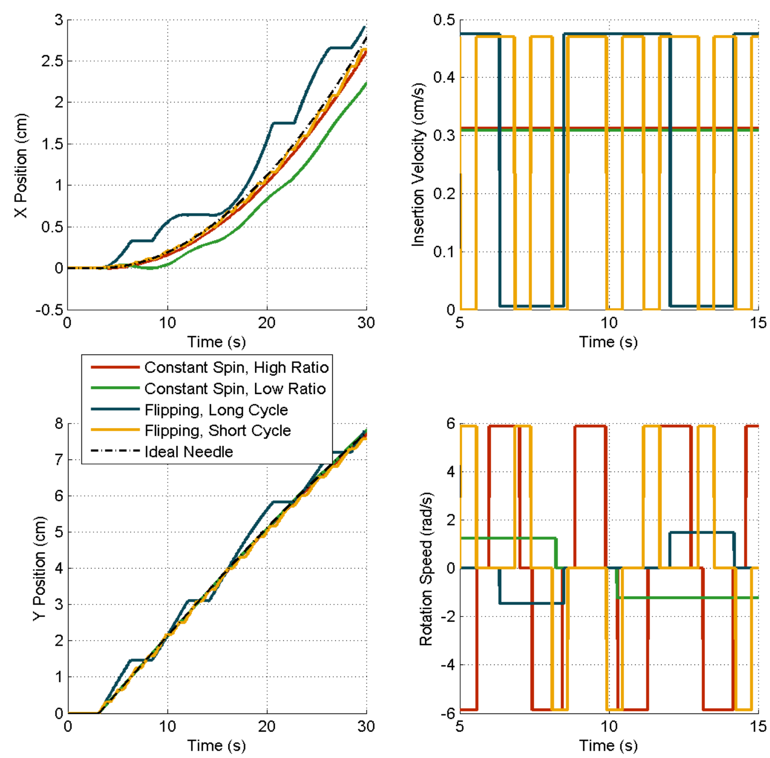

Figure 7: Simulated needle tracking of arbitrary arc with various control strategies.

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