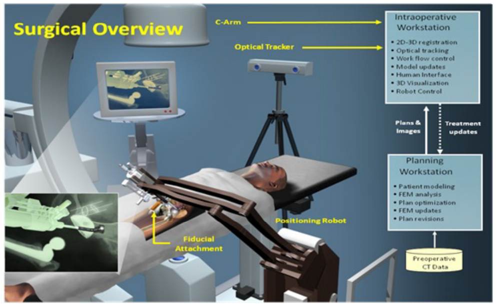
Seminar Presentation

Position Control of BIGSS Lab Snake for Revision Total Hip Arthroplasty (THA) Surgery



Project 6: Farshid Alambeigi

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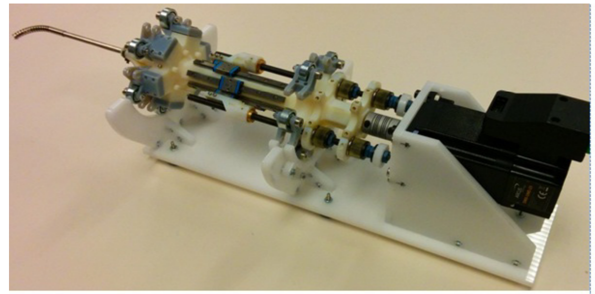
Overview of Goals

- The BIGSS lab is developing a minimally-invasive surgical workstation to treat the osteolytic lesions using using a snake like dexterous manipulator (SDM).
- The SDM will be positioned in the workspace by a robotic arm.
- The focus of this project is integrating the SDM with the robotic arm- which is a 6 DOF Universal Robot (UR5) - and position control of the tip of the SDM inside the lesion area.



Figures are property of BIGSS Lab.

Overview

I briefly describe three main papers I used in my work and explain its correspondence to my project:

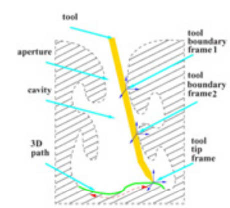
1. A. Kapoor, Mi Li and R. H. Taylor, "*Constrained Control for Surgical Assistant Robots*", Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Florida - May 2006

2. A. Kapoor , N. Simaan , R. H. Taylor, "*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*" , Proceedings of the 12th International Conference on Advanced Robotics, 2005

3. R. J. Murphy, Y. Otake, R. H. Taylor, and M. Armand, "*Predicting Kinematic Configuration from String Length for a Snake-like Manipulator Not Exhibiting Constant Curvature Bending*", submitted in Intelligent Robots and Systems (IROS), 2014.

Paper I: A. Kapoor, et al."*Constrained Control for Surgical Assistant Robots*"

- **Motivation**
  - ❖ Restriction on the robot motions in surgical tasks such as:
    - ✓ prevent the tooltip from entering some undesired region
    - ✓ confine the tool shaft to pass through some fixed point in space such as (incision point etc.).
  - ❖ Considered goal for the robot is:
    - ✓ To obey the constraints
    - ✓ To follow the motions of the surgeon or master robot at the same time



- **Abstract**
  - ❖ This problem has been defined as a constrained optimization problem.
  - ❖ A library of "virtual fixtures" has been defined for different constraints of surgical robots.
  - ❖ Linearizing nonlinear constraints has been investigated.
  - ❖ The concept of "soft" virtual fixture has been defined.

Ming Li, Masaru Ishii, and Russell H. Taylor, "Spatial Motion Constraints Using Virtual Fixtures Generated by Anatomy"

Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

➢ **Method:**

❖This paper divides optimization algorithm to these steps:

$$1)\ Actual\ Position = \underline{forward\ kinematics}(\theta_{Old})$$

$$2)\ \Delta_{pos} = Actual\ Position - Desired\ Position$$

$$3)\ V = J \cdot \dot{\theta} \rightarrow \frac{\Delta x}{\Delta t} = J \cdot \frac{\Delta \theta}{\Delta t} \rightarrow \Delta x = J \cdot \Delta \theta$$

$$4)\ \Delta \theta = \arg\min_{\Delta\theta}(\|\underline{J}.\Delta\theta - \Delta_{pos}\|_2^2 + \|w.\Delta\theta\|_2^2)$$

$$A.\Delta x \le b$$

$$5)\ \theta_{New} = \theta_{Old} + \Delta\theta$$

Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

➢ **Method (cont.):**

❖ Some points regarding this method:

➢ This optimization problem tries to minimize the two-norm of **error between desired and actual incremental motions(**first term**)** with **minimum joint motions** (second term)

➢ For solving this problem we need:
- ✓Forward Kinematics of robot
- ✓Jacobian matrix of robot
- ✓To Find the **A and b** Matrices which are defining our constraints

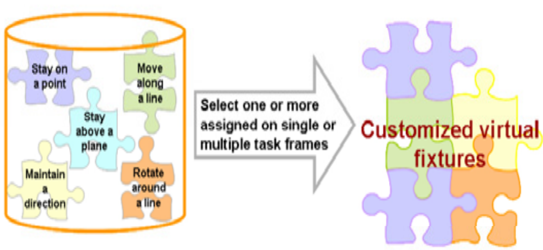
➢We can linearize this nonlinear optimization problem

Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

➢ **Method (cont.): Virtual Fixture Library**

❖ For determining matrix A and b this paper defines a virtual fixture library for 5 basic geometric constraints

❖ Using the proposed library each customized virtual fixtures can be created.



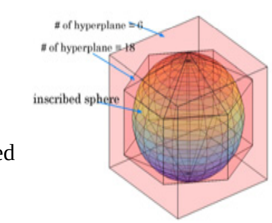
Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

➢ **Method (cont.): Linearizing constraints**

❖ The constraints for the task primitives are often nonlinear however:
- ✓ Solving linearly constrained least squares problems can take less computation time
- ✓ computation of this problem is efficient and robust.

❖ Therefore This paper uses a polyhedron to approximate a geometric constraint region like spherical error tolerance.

❖ As the number of the hyperplanes increases, the volume of the polyhedron reduces and the polyhedron approaches the inscribed sphere.



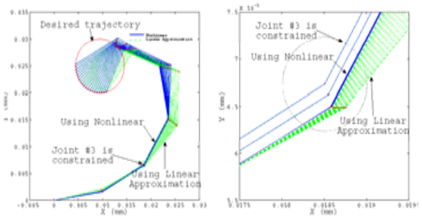
Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

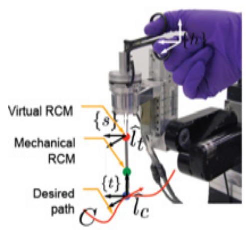
➢ **Simulation and results:**

✓Some experiments have been done to investigate the effect of linearization based on defined optimization problem.

✓ Results show that there is a trade-off between accuracy and speed between linear and nonlinear constraints.

✓Using a linear approximation with fewer numbers of hyperplanes reduces accuracy while has better speed.





Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

➢ **Paper Analysis**

❖**Pros:**

✓ Introducing a useful approach for defining complicated control task as a multi-objective optimization problem

✓Introducing a useful library for virtual fixtures

❖**Cons:**

✓not having pictures for defined geometric constraints

✓The simulated problem has not formulated as the described method (constraints and objective functions)

Paper I: A. Kapoor, et al.“*Constrained Control for Surgical Assistant Robots*”

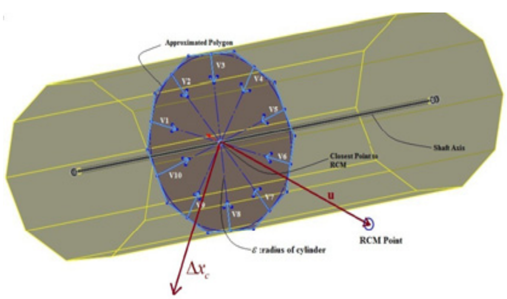
Application in my project:

➢Defining the problem as a described multi-objective optimization

➢Defining RCM constraint using Virtual fixture library:

$$\underbrace{\begin{bmatrix} v_1 \\ \vdots \\ v_m \end{bmatrix}}_{A_1} \cdot \Delta x_c \le \underbrace{\begin{bmatrix} \varepsilon + v_1 \cdot u \\ \vdots \\ \varepsilon + v_m \cdot u \end{bmatrix}}_{b_1}$$

$$\Delta x_c = J_{closest\,point} \cdot \Delta q$$



Paper II: A. Kapoor, et al.“*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*”

➢ **Abstract and Motivation:**

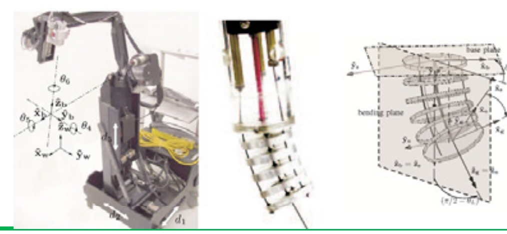
❖This paper presents the kinematic modeling and high level control of a hybrid 8 DoF robots used for suturing in the throat and upper airways.

❖For this work, they have attached a snake-like unit (SLU) to a modified version of the LARS

❖They have used linearized multi-objective constrained optimization method that described in paper 1, therefore they need:

✓Forward kinematics and Jacobian matrix of coupled robots

✓Defining suturing task as matrix A and b.



Paper II: A. Kapoor, et al."*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*"

➢ Kinematic Model

❖ The have used these kinematic relations for determining Jacobian matrix:

$$\dot{x}^{W}_{slu\,base} = J_{Lars} \cdot \dot{q}_{Lars}$$

$$V^{w}_{SLU} = V^{w}_{SLU\,base} + R^{w}_{SLU} . V^{SLUbase}_{SLU\,tip} + \omega^{w}_{SLU\,base} \times R^{w}_{SLU\,base} . p^{SLU\,base}_{SLU\,tip}$$

$$\omega^{w}_{SLUtip} = \omega^{w}_{SLU\,base} + R^{w}_{SLU} . \omega^{SLUbase}_{SLU\,tip}$$

❖ The kinematics of hybrid system consisting of the 6-DoF LARS and 2-DoF SLU can be described using 8 independent variables.

$$J_{combined} = \left[J_{Lars} \quad J_{SLU} \right]; J_{Lars} \in \mathbb{R}^{6\times6}, J_{Snake} \in \mathbb{R}^{6\times2}$$

$$\dot{x}^{W}_{SLU} = J_{combined} \cdot \dot{s}; \;\; J_{combined} \in \mathbb{R}^{6\times8}, \dot{s} \in \mathbb{R}^{8\times1}$$

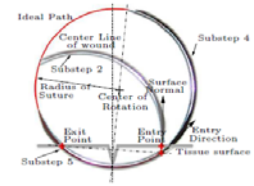
Paper II: A. Kapoor, et al."*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*"

➢ Defining Constraints and Objective Functions:

1. **Minimizing tissue tear:** They rotate the gripper such that its angular velocity vector is perpendicular to the suture plane and the center point of the suture is constrained to lie within a small sphere of radius ε_g :

$$\arg\min_{\dot{x}} (\| W_g (\dot{x}^{w}_{g} - \dot{x}^{w}_{gdesired}) \|_2$$

$$s.t. \; \| p^{w}_{g} - p^{w}_{gstart} \| \le \varepsilon_g \; and \; \dot{x}^{w}_{gdesired} = (0,0,0,0,0,\omega_d)^t$$



2. **Avoiding joint speed limits:** considering limits on the joint velocities of SLU

$$\arg\min_{\dot{x}} (\| W_g (\dot{x}^{w}_{g} - \dot{x}^{w}_{gdesired}) \|_2$$

$$s.t. \; H_t \cdot \dot{q}_{SLU} \ge h_t; H_t = (\mathrm{I}, -\mathrm{I})^t \in \mathbb{R}^{6\times3}$$

$$and \; h_t = (\dot{q}_{SLU\,lo}, -\dot{q}_{SLU\,up})^t \in \mathbb{R}^{6}$$

Fig: A. Kapour. et al., "Spatial Motion Constraints for Robot Assisted Suturing using Virtual Fixtures"

Paper II: A. Kapoor, et al."*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*"

➢ Defining Constraints and Objective Functions (cont.):

3. Avoiding joint limits: To ensure that the motion is within the given workspace of the system with minimum extraneous motion of the system:

$$\arg\min_{\dot{s}} (\| W_s \cdot \dot{s} \|_2$$

$$s.t. \;\; H_s \cdot \dot{s} \ge h_s; H_s = (\mathrm{I}, -\mathrm{I})^t \in \mathbb{R}^{16\times8}$$

$$and \; h_s = (s_L / \Delta\,\mathrm{t}, s_U / \Delta\,\mathrm{t})^t \in \mathbb{R}$$

4. Combining objective functions and constraints:

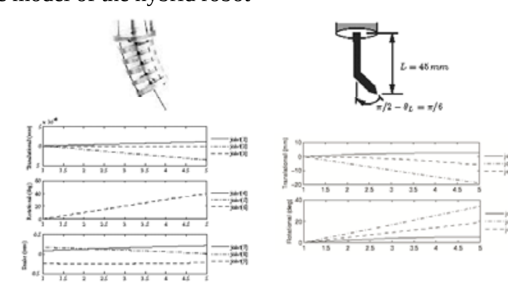
$$\arg\min_{\dot{s}} (\left\| \begin{bmatrix} W_g & 0 \\ 0 & W_s \end{bmatrix}_s \left(\begin{bmatrix} J_{SLU} \\ I \end{bmatrix} \cdot \dot{s} - \begin{bmatrix} \dot{x}^{w}_{gdesired} \\ 0 \end{bmatrix} \right) \right\|_2$$

$$s.t. \begin{bmatrix} H_g & 0 & 0 \\ 0 & H_t & 0 \\ 0 & 0 & H_s \end{bmatrix} \begin{bmatrix} J_{SLU} \\ \begin{bmatrix} 0 & J_{J_{SLU}} \end{bmatrix} \\ I \end{bmatrix} \dot{s} \ge \begin{bmatrix} h_g \\ h_t \\ h_s \end{bmatrix}$$

Paper II: A. Kapoor, et al."*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*"

➢ Simulation and Experimental Results:

✓Simulation has been done to compare suturing using the SLU verses a rigid tool to hold the suture.
✓Results indicate the importance of maintaining tool tip dexterity to avoid large motions in the proximal end of the tools.
✓These simulations have been validated by experiments based on encoder readings and the forward kinematic model of the hybrid robot



Paper II: A. Kapoor, et al.“*Suturing in Confined Spaces: Constrained Motion Control of a Hybrid 8-DoF Robot*”

➢ **Paper Analysis**

❖**Pros:**

- ✓ Introducing a useful approach for coupling a snake-like robot to a robotic arm
- ✓Defining a complicated task such as suturing with some simple geometric constraints problem

❖**Cons:**

- ✓Again, not having pictures for defined geometric constraints

➢ **Application in my project:**

- ✓Using the same procedure for coupling our snake to UR5 robot

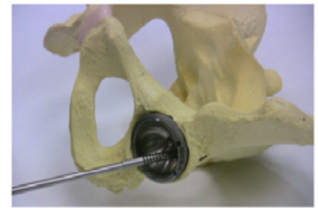
Paper III: Ryan J. Murphy, et al.“*Predicting Kinematic Configuration from String Length for a Snake-like Manipulator Not Exhibiting Constant Curvature Bending*”

➢**Abstract and motivation**

✓This paper uses BIGSS lab snake and tries to find its kinematics model using a series of experiments.

✓General models of continuum robots like piecewise constant curvature model do not work for it.

✓They use a two-step kinematic model to in the **first step** predict the tip position from string length and then in **second step** pin the manipulator tip at the predicted position and run an energy minimization to estimate the kinematic configuration.

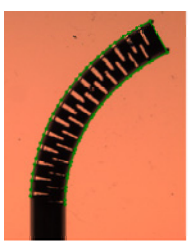
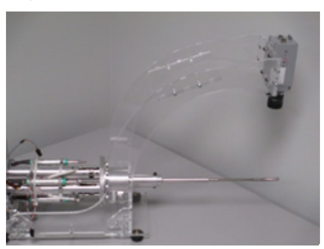



Paper III: Ryan J. Murphy, et al.“*Predicting Kinematic Configuration from String Length for a Snake-like Manipulator Not Exhibiting Constant Curvature Bending*”

EXPERIMENTAL SETUP:

Paper has performed a series of experiments with these considerations:

- ✓ Bending the manipulator freely without obstruction in air
- ✓ Each test limited the tension measured by the load cells to 22.2N
- ✓Calibration procedure for defining the zero cable position prior to each test.
- ✓ Using an acrylic stand with a camera above the manipulator to capture the manipulator
- ✓Using automated, piecewise-rigid 2D/3D registration technique to define the kinematic configuration of the manipulator from each static image

Paper III: Ryan J. Murphy et al.“*Predicting Kinematic Configuration from String Length for a Snake-like Manipulator Not Exhibiting Constant Curvature Bending*”

➢ **Kinematic Prediction:**

First Step : (Predicting end-effector position)

✓**x position:** a nonlinear least-squares optimization fits a combination of Bernstein basis polynomials to the data.

✓**z position:** a nonlinear least-squares optimization fits some of 3 sinusoids to the data.

$$p_x = f_1(l) = B_n(l)$$
$$p_y = 0$$
$$p_z = f_2(p_x) = \sum_{i=1}^{3} a_i \sin(b_i . p_x + c_i)$$
$$p_{eef} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} f_1(l) \\ 0 \\ f_2(f_1(l)) \end{pmatrix}$$

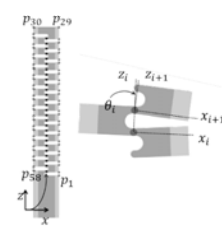
Second Step :(Finding snake configuration)

✓Pins the manipulator tip at the calculated tip position and runs an energy minimization to estimate the kinematic configuration.

✓Each pin joint has been modeled as a torsional spring

✓Assuming least-energy state for a specific tip position they this optimization problem have been solved :

$$\tilde{\theta} = \arg\min \sum_{i=1}^{27} \theta_i^2$$
$$s.t.\ 0 = \left\| \tilde{p}_{eef} - p_{eef} \right\| and \left| \tilde{\theta}_i \right| \le 15^o$$



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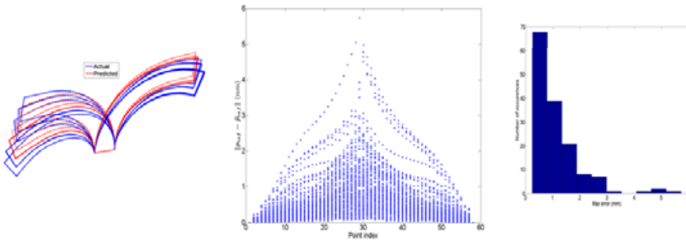
➢ **Simulation and results:**

✓ The magnitude error between the predicted position and configuration were compared to the ground truth derived from the overhead images.

✓Over 68% of the predictions resulted in a maximum error less than 1.25mm .

✓The largest errors occurred at the tip of the manipulator in high-bend configurations where the tip prediction performs poorly.



Paper III: Ryan J. Murphy et al.“*Predicting Kinematic Configuration from String Length for a Snake-like Manipulator Not Exhibiting Constant Curvature Bending*”

➢ **<u>Paper Analysis</u>**

❖**Pros:**

✓ Introducing a useful experimental approach for determining kinematics of non-constant curvature continuum robots

❖**Cons:**

✓Do not showing the relation between tip position and cable length from the real data and predicted one in a graph.

➢ **<u>Application in my project:</u>**

✓Using the kinematic model for predicting tip position
✓Using configuration prediction for demonstration