Telemanipulation and Telestration for Microsurgery

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Constrained Cartesian Motion Control for Teleoperated Surgical Robots

Janes Funda, Russel H. Taylor, *Fellow, IEEE*, Benjamin Eldridge, Stephen Gomory, and Kreg G. Gruben, *Member , IEEE*

J. 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.

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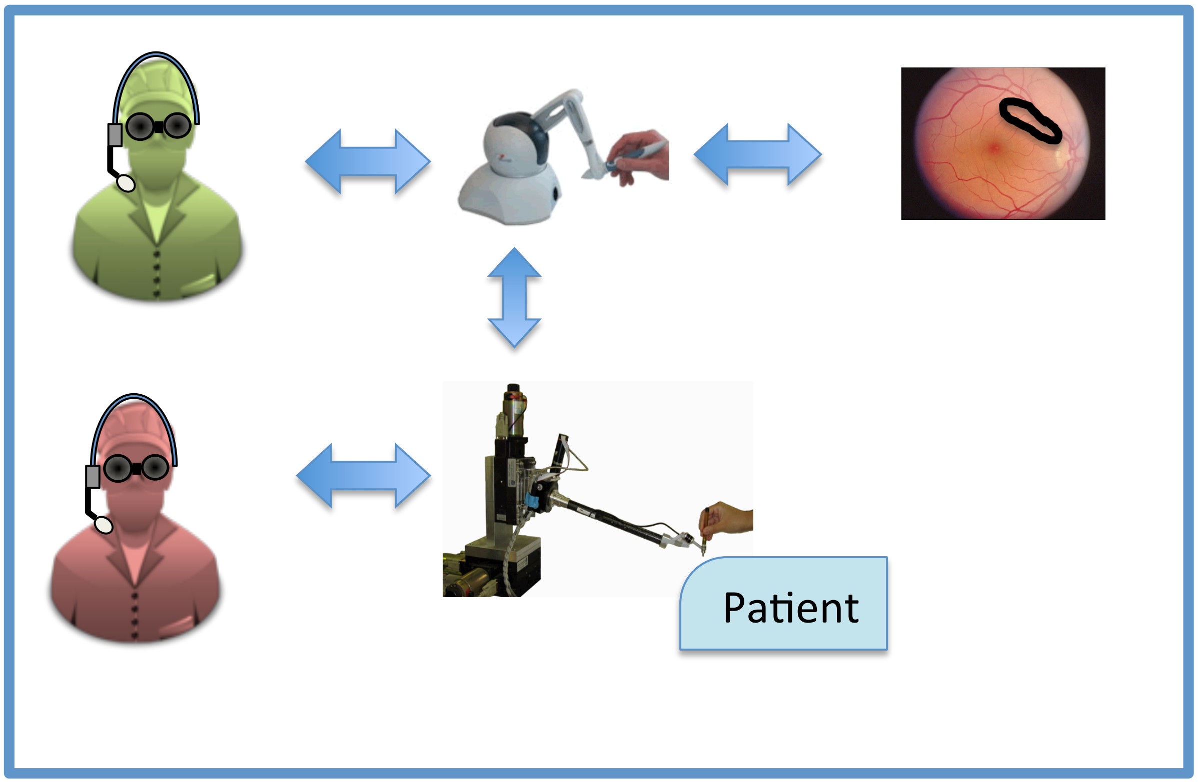
Project Overview

Telestration

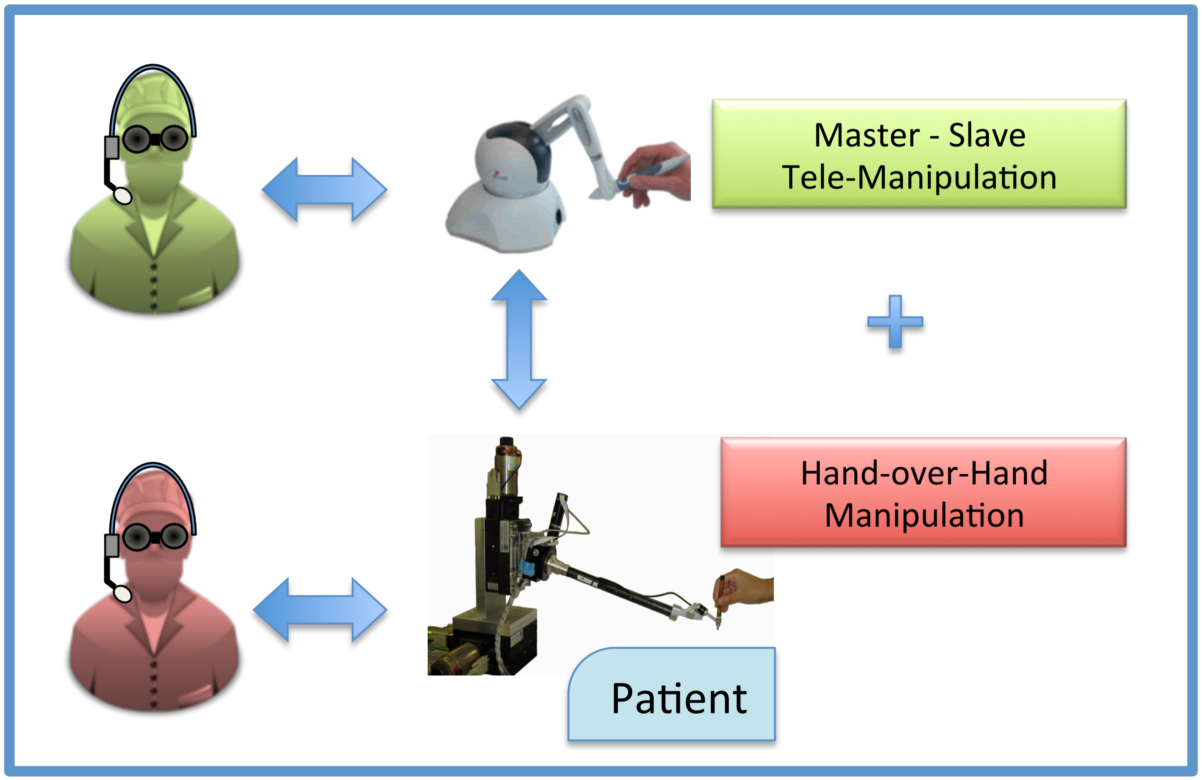


microSurgical workstation

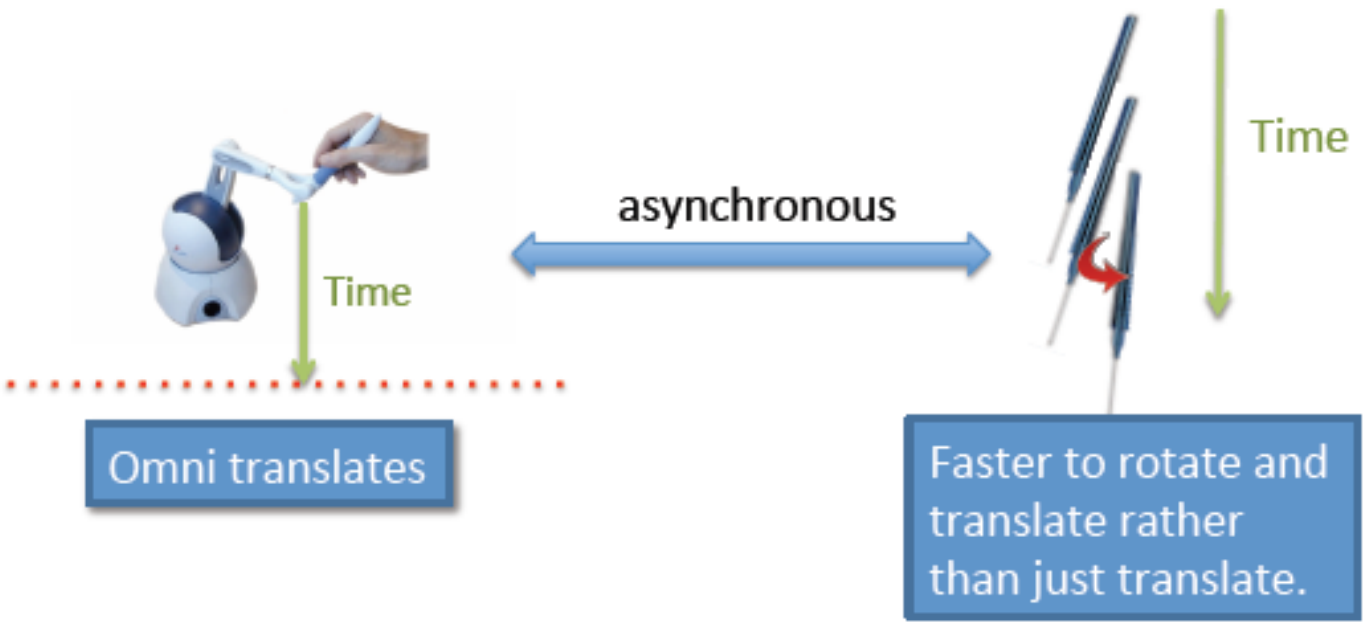
LABORATORY FOR
Computational Sensing + Robotics
THE JOHNS HOPKINS UNIVERSITY

Project Overview

Telemanipulation



Project Overview



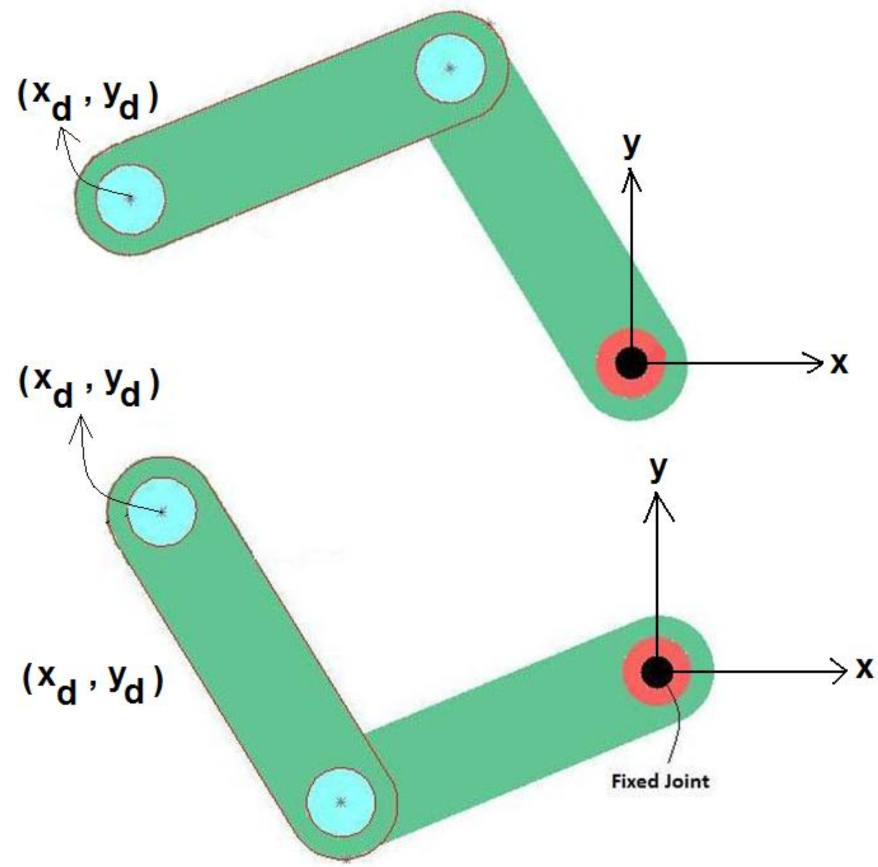
Paper Overview

Constraint Cartesian Motion Control for Teleoperated Surgical Robots

- Purpose: Optimal motion control for teleoperated surgical robots to maneuver in limited workspace.
- Problem: Determine how best to use the available robot degree of freedom to perform a surgical task.
- How: Experimental results of the application of this control methodology.

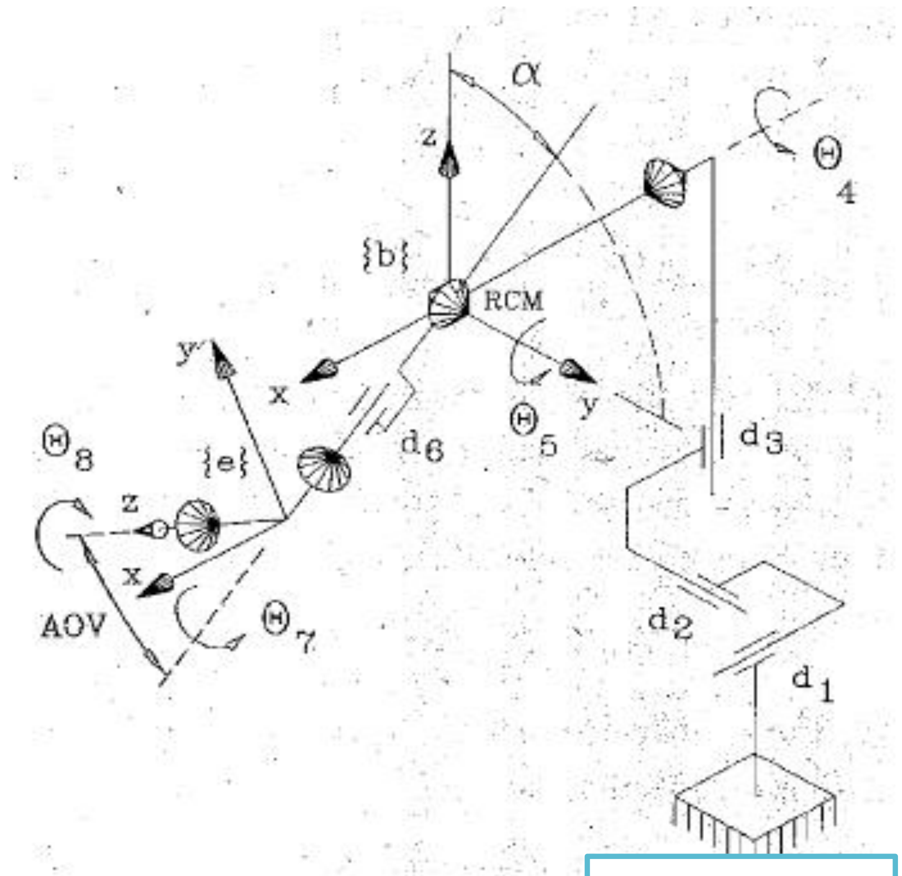
Motivation and Significance of Optimization

- For a 2 link mechanism in order to reach the desired point (xd, yd), there are two possible configurations.



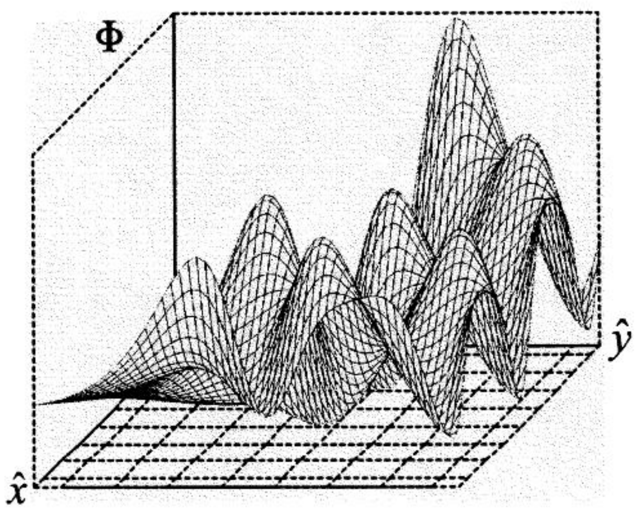
Motivation and Significance of Optimization

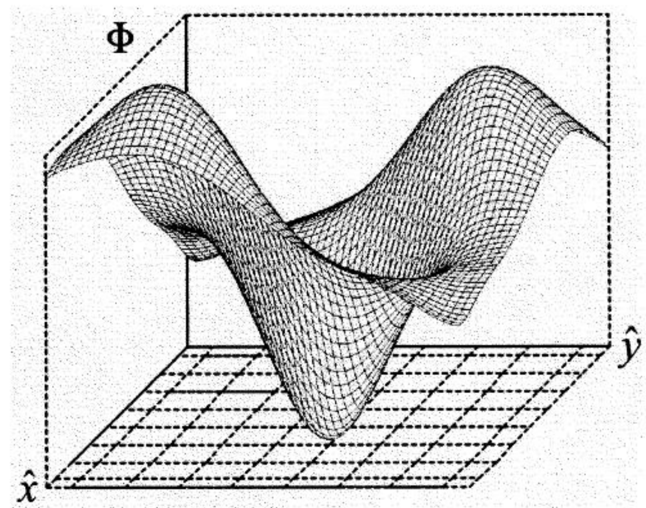
- What if we have a system that has 8 degree of freedom(DOF)
- How many different configurations satisfy the desired final destination?
- Which solution is the best?



Funda et al.

Motivation and Significance of Optimization





- There are many satisfying solutions.
- This is where optimization (constrained or not) plays an important role in choosing the most suitable configuration.

- Steady-hand Eye Robot has 5 dof, so there are many options in reaching to a desired point.

Current Techniques

1st Tech.: Inverse Jacobian Method: $\overrightarrow{q_{des}} = \vec{q} + J^{-1}(\vec{q})\Delta\vec{x}_{des}$

- Depending on the task deficiency or task redundancy , pseudo inverse can be used in taking the inverse of the Jacobian.

2nd Tech.: Gradient protection techniques: $\Delta\mathbf{q} = \mathbf{J}^{+}\Delta\mathbf{x} + (\mathbf{I} - \mathbf{J}^{+}\mathbf{J})\mathbf{z}$

- where 'z' is an arbitrary vector in the null-space of the Jacobian.
- Setting $z = \alpha\nabla\varphi(q)$ allows specification of couple of secondary performance criteria like obstacle avoidance.

- And many others..

<u>Task deficiency:</u> Available robot dof is less than task dof

<u>Task redundancy:</u> Available robot dof is more than task dof

Constraint Cartesian Motion Control

- In this method desired motion is formulated as sets of task goals in different task frames, optionally subject to additional linear constraints in each of the task frames.

- Then, using the quadratic optimization solution technique, the kinematic control problem is solved using a Real Time PC.

Definitions and Nomenclature

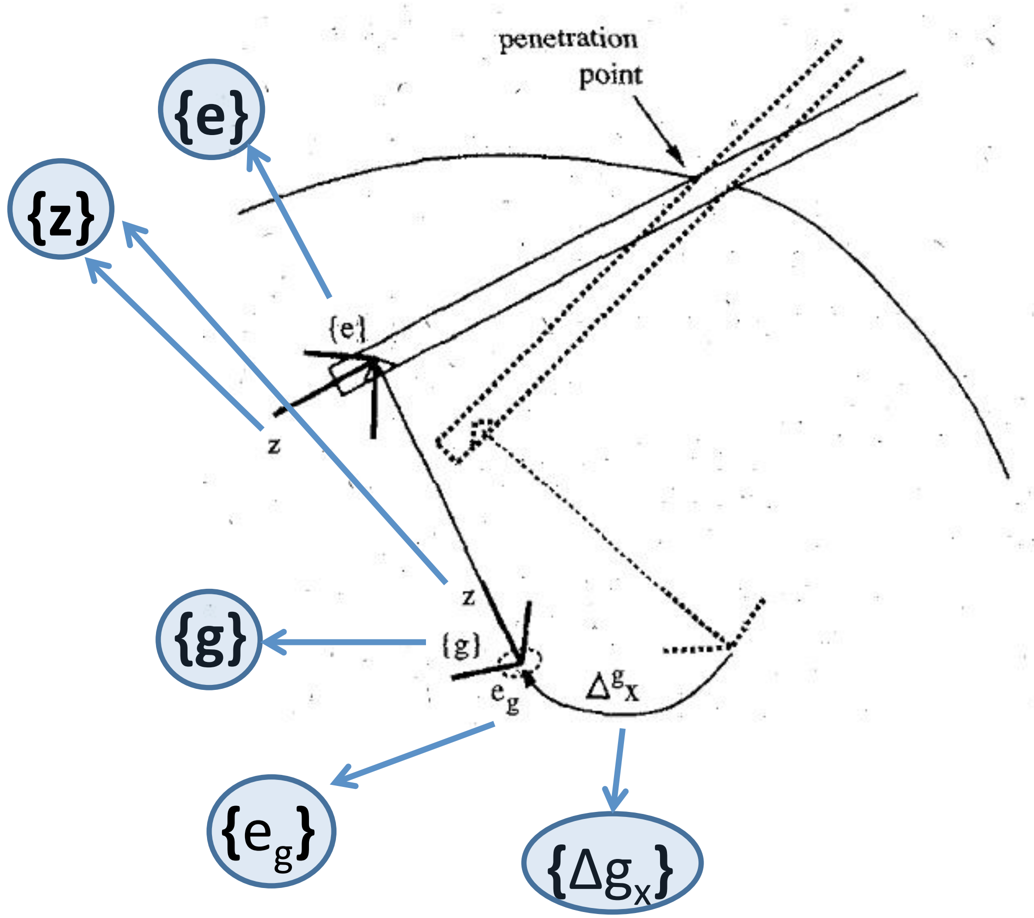
- {e} : end- effector frame
- {c} : camera frame (whose origin is at the optical center of projection of the laparoscopes optics)
- {g} : gaze frame (whose origin is coincident with the 3D point on the patient’s anatomy appearing in the center of 2D camera image)
- { j } : manipulator’s joint space
- *gaze distance* : separation between gaze frame and the camera
- *task space* : 3D operating volume of the robot

Theory Implementation Example

- Changing the position of a laser beam with Cartesian displacement of the gaze frame by an amount of $\Delta^{g}x$.

- 'q' denotes the joint variables and 'x' denotes the state variables under concern such that:

$$\Delta^{g}x_d = [x, y, z, 0,0,0]^T$$



Theory Implementation Example: Specifying Constraints and Frame Objective Functions

$$\left\| \begin{bmatrix} \Delta^g \mathbf{x}[1] \\ \Delta^g \mathbf{x}[2] \end{bmatrix} - \begin{bmatrix} \Delta^g \mathbf{x}_d[1] \\ \Delta^g \mathbf{x}_d[2] \end{bmatrix} \right\| \leq \epsilon_g$$

Laser beam hitting the target location within desired tolerance ‘ε’.

$$[\cos(\theta_k), \sin(\theta_k), 0, 0, 0, 0]^T \cdot (\Delta^g \mathbf{x} - \Delta^g \mathbf{x}_d) \leq \epsilon_g, \quad k = 1, \cdots, n$$

Above equation can be approximated into this form.

$$\mathbf{H}_g \Delta^g \mathbf{x} \geq \mathbf{h}_g$$

We can simplify it into this form.

$$\|\mathbf{W}_g (\Delta^g \mathbf{x} - \Delta^g \mathbf{x}_d)\|$$

Minimizing the rotational error about the viewing ‘z’ axis, which is the same as minimizing Δx[6] - Δxd [6]

$$\mathbf{H}_e \Delta^e \mathbf{x} \geq \mathbf{h}_e$$

Putting linear constraints on the motion of the end effector where ‘He’ and ‘he’ can be defined as below.

$$\mathbf{H}_e = \begin{bmatrix} \mathbf{I} \\ -\mathbf{I} \end{bmatrix} \quad \text{and} \quad \mathbf{h}_e = \begin{bmatrix} \underline{\Delta^e \mathbf{x}} \\ -\overline{\Delta^e \mathbf{x}} \end{bmatrix}$$

Theory Implementation Example: Specifying Constraints and Frame Objective Functions

Minimizing extraneous motion of the instrument $\|\mathbf{W}_e \Delta^e \mathbf{x}\|$

$$\underline{\mathbf{q}} - \mathbf{q} \leq \Delta\mathbf{q} \leq \overline{\mathbf{q}} - \mathbf{q}$$

Putting joint limits on actuators

$$\mathbf{H}_j \Delta\mathbf{q} \geq \mathbf{h}_j$$

Above relation can be rewritten in this form such that 'Hj' and 'hj' can be defined below.

$$\mathbf{H}_j = \begin{bmatrix} \mathbf{I} \\ -\mathbf{I} \end{bmatrix} \quad \text{and} \quad \mathbf{h}_j = \begin{bmatrix} \underline{\mathbf{q}} - \mathbf{q} \\ -(\overline{\mathbf{q}} - \mathbf{q}) \end{bmatrix}.$$

$\|\mathbf{W}_j \Delta\mathbf{q}\|$ Minimizing the total motion of the joints of the surgical manipulator.

Theory Implementation Example:
Specifying Constraints and Frame Objective Functions

$$^{f}\mathbf{J} = {}^{*}\mathbf{J} \cdot {}^{e}\mathbf{J}$$

To travel between different frames, this relation can be used.

where

$$^{*}\mathbf{J} = \begin{bmatrix} \mathbf{R}^T & \mathbf{R}^T[\mathbf{p}] \\ \mathbf{0}_{3\times 3} & \mathbf{R}^T \end{bmatrix}$$

$$\|\mathbf{W}_g({}^{g}\mathbf{J}(\mathbf{q})\Delta\mathbf{q} - \Delta^{g}\mathbf{x}_d)\|$$

The rotation minimization $\|\mathbf{W}_g(\Delta^{g}\mathbf{x} - \Delta^{g}\mathbf{x}_d)\|$ can be represented in terms of joint variables.

$$\mathbf{H}_g\,{}^{g}\mathbf{J}(\mathbf{q})\Delta\mathbf{q} \geq \mathbf{h}_g$$

The above relation can be represented in this general form.

Theory Implementation Example: Combining all

gaze: $\mathbf{W}_g$

End effector: $\mathbf{W}_e$

joint: $\mathbf{W}_j$

$$\left\| \begin{bmatrix} \mathbf{W}_g & & \\ & \mathbf{W}_e & \\ & & \mathbf{W}_j \end{bmatrix} \left(\begin{bmatrix} {}^g\mathbf{J}(\mathbf{q}) \\ {}^e\mathbf{J}(\mathbf{q}) \\ \mathbf{I} \end{bmatrix} \Delta \mathbf{q} - \begin{bmatrix} \Delta^g \mathbf{x}_d \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} \right) \right\|$$

Subject to the constraint:

$$\begin{bmatrix} \mathbf{H}_g & & \\ & \mathbf{H}_e & \\ & & \mathbf{H}_j \end{bmatrix} \begin{bmatrix} {}^g\mathbf{J}(\mathbf{q}) \\ {}^e\mathbf{J}(\mathbf{q}) \\ \mathbf{I} \end{bmatrix} \Delta \mathbf{q} \geq \begin{bmatrix} \mathbf{h}_g \\ \mathbf{h}_e \\ \mathbf{h}_j \end{bmatrix}.$$

The final form:

$$\text{minimize } \|\mathbf{A}\,\Delta \mathbf{q} - \mathbf{b}\|, \text{ subject to } \mathbf{C}\,\Delta \mathbf{q} \geq \mathbf{d}$$

Theory Implementation Example: Optimization weights

- In order to minimize rotation $\|\mathbf{W}_j \Delta \mathbf{q}\|$ in the total motion of the joints of the surgical manipulator the choice of the weighting factors is very important.

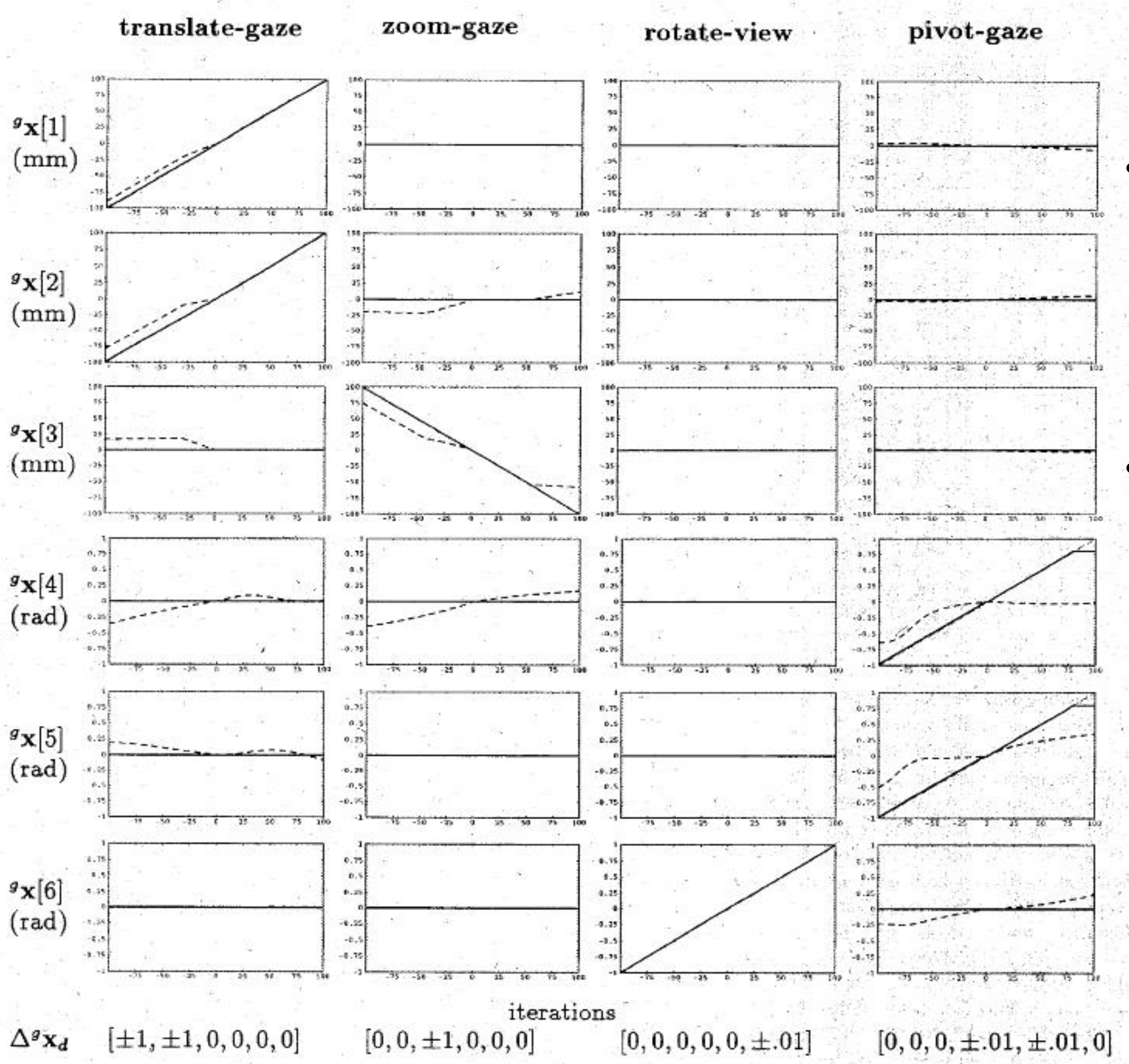
- If not, undesired dynamics may dominate the optimization process.

- The weighting constants compose of two terms:

$$\mathbf{w}_f[i] = \mathbf{u}_f[i] \cdot \mathbf{v}_f[i]$$

- u[i] is the relative importance of that particular joint, and v[f] takes care of unit conversion between linear and rotational axis movements.
- Also we can adjust the weights dynamically

Experimental Evaluation and Results



- Results for 4 different motion types listed at the top of the table.
- Dashed lines are for task-deficient system whereas the solid lines are for task-redundant system and dotted lines for desired motion.

Conclusions

- It is good to show that algorithm worked for both task redundant and task deficient dof systems.

- But it needs a good initial guess. (homing the robot can work)

- User must be careful in task-deficient operations as in the case of RCM mode operations because the required position may not be achievable with such constraints.

Applying to our Project…

- Translation only mode:

Task: robot only moves on x , y , z coordinates

In order to do that, we implemented the Constrained Cartesian Motion Control Algorithm and define rotational weights bigger than translational weights. This case algorithm tend to use x , y , z motions to achieved the desired goal.

Thoughts

- Positive
  - Simple and clear result
  - Experimental set up in the form of "correct" or "incorrect" constitutes easy analysis
  - Clear difference between LARS and SHR
- Room for improvement
  - More details about the experiment (e.g. how many tries did each subject have?)
  - Illustration of the metallic plate sandwich
  - Missing the purpose and details of the autonomous series
  - "Several other factors such as mistakes made in positioning the needle, spacing between sutures, etc…"

Questions?