Auto-calibration and Hybrid Force/Position Control for the Cerberus Cardiac Robot

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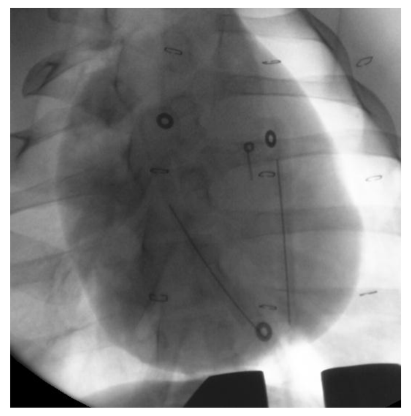
Background

Cerberus

- Planar parallel wire robot for **minimally invasive heart surgery**
- Adheres to **beating heart** via suction on three bases
- Rapidly preform multiple injections for **gene therapy research**

Problems

- Actuation redundancy
- Wires can only pull, not push
- Coupled, nonlinear state equations
- Unknown deployed geometry



Goal

- Add **force control** to existing position control to maintain wire tension and increase position accuracy to make device **safer** for surgery
- Auto-calibration

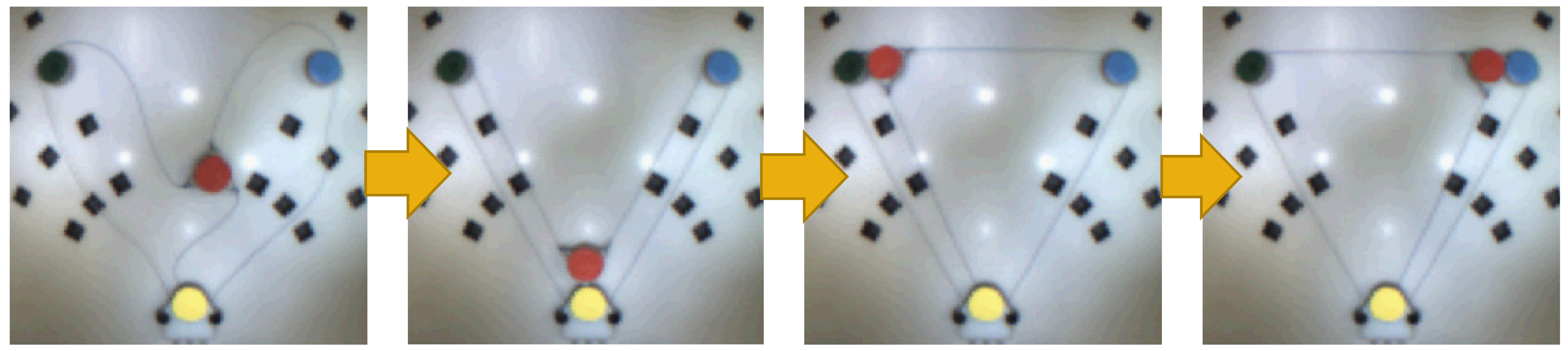
Auto-calibration

- Kinematics and statics depend on accurate knowledge of geometry
  → Geometry is unknown after deployment onto heart
- <u>Auto-calibration</u>
  1. Start in any configuration
  2. Uses forces to move to each base
  3. Estimates geometry using encoder values
  4. Updates to current geometry

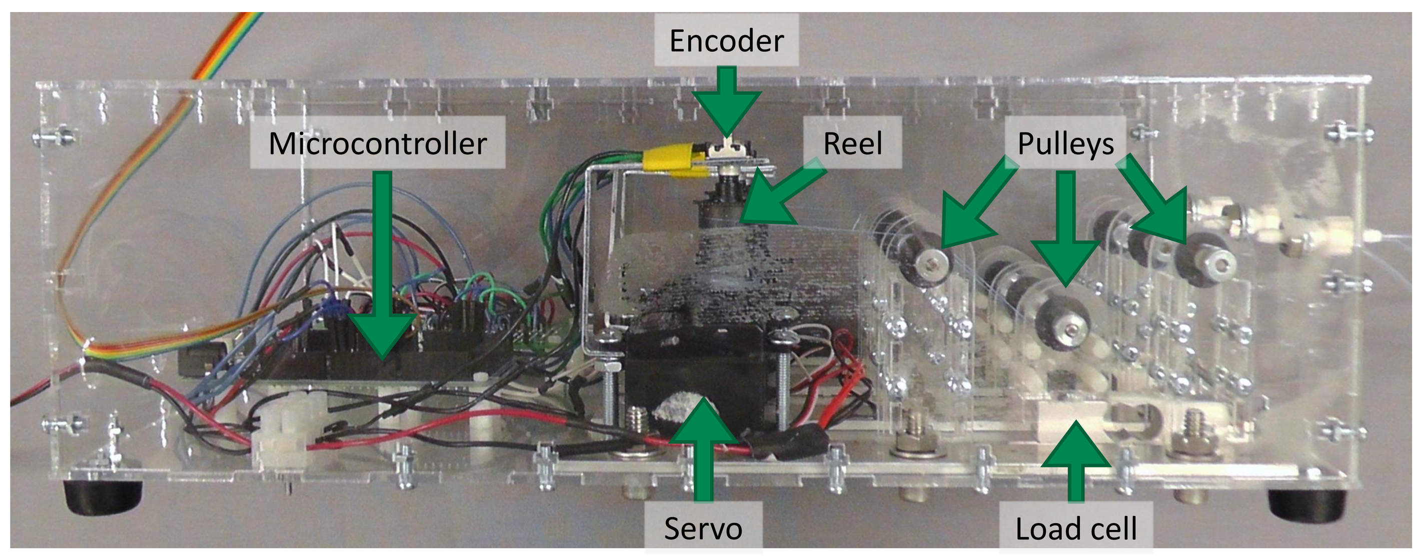
		Error Mean	Standard Deviation
L_l	100 mm	0.469	0.373
L_r	100 mm	0.587	0.304
Angle	30°	-0.897	0.143

Algorithm

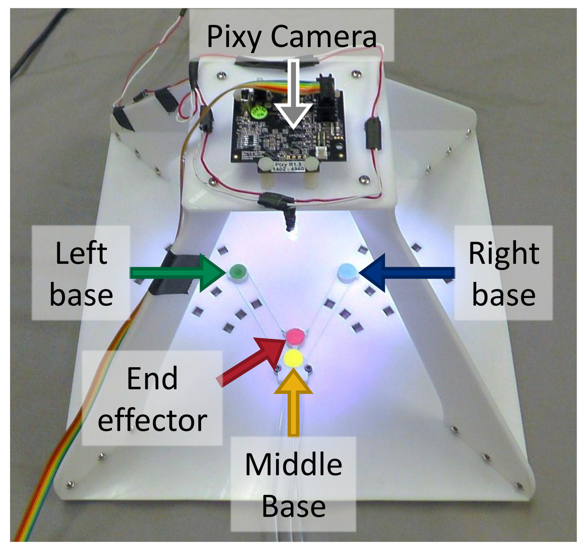
Data: Wire tensions and encoder values
Result: Geometry of robot
for each base
  while target base wire $< T_{max}$
    pull target base wire and keep other wire $\approx T_{min}$
  end
  Record encoder values
end
Convert encoder values to lengths
Use law of cosine to find angle



Hardware



Load cells with pulleys measure tension



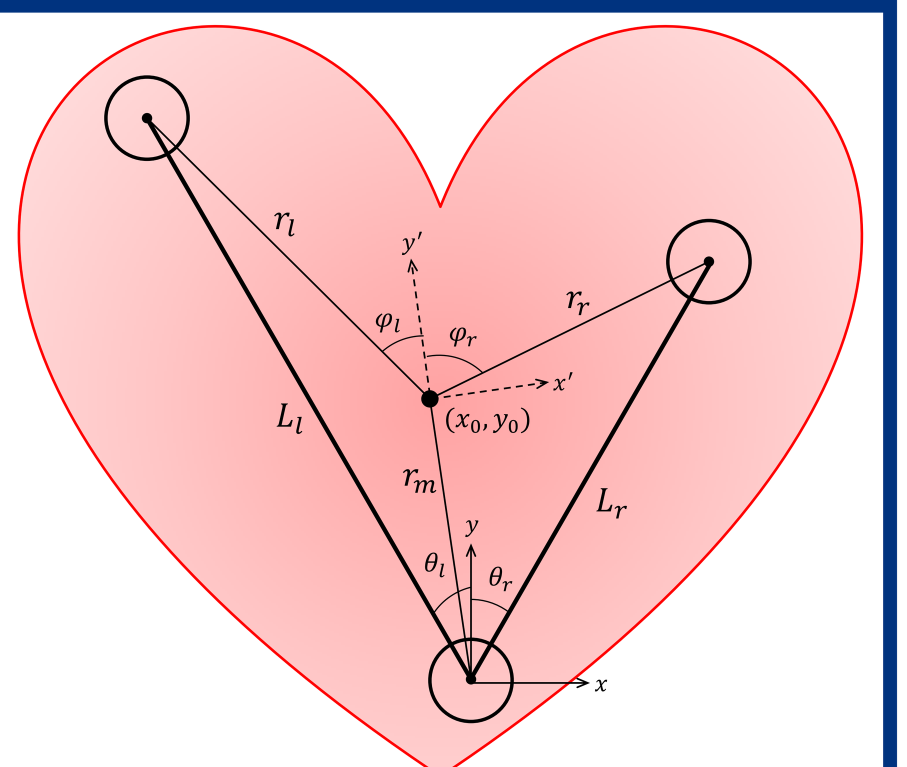
Pixy camera measures locations via color tracking

Kinematics and Statics

Inverse Kinematics [1]

- Wire lengths

$$\begin{bmatrix} r_l \\ r_m \\ r_r \end{bmatrix}^2 = \begin{bmatrix} (x_0 + L_l\cos\theta_l)^2 + (y_0 - L_l\sin\theta_l))^2 \\ {x_0}^2 + {y_0}^2 \\ (x_0 - L_r\cos\theta_r)^2 + (y_0 - L_r\sin\theta_r)^2 \end{bmatrix}$$



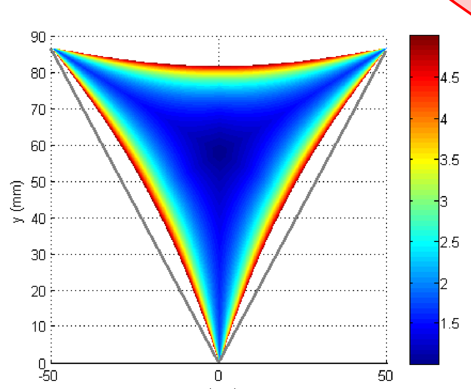
Optimal Tension Distribution [2, 3]

- Maximize workspace
- $T_{min} \leq \mathbf{f} \leq T_{max}$
  $\mathbf{f} \gg T_{max}$ → Break wires or restrict heart movement
  $\mathbf{f} \ll T_{min}$ → Lose control of wire

$$\mathbf{f} = \alpha\mathbf{N}$$

$$\alpha = \frac{T_{min}}{\mathbf{N}_{min}}$$

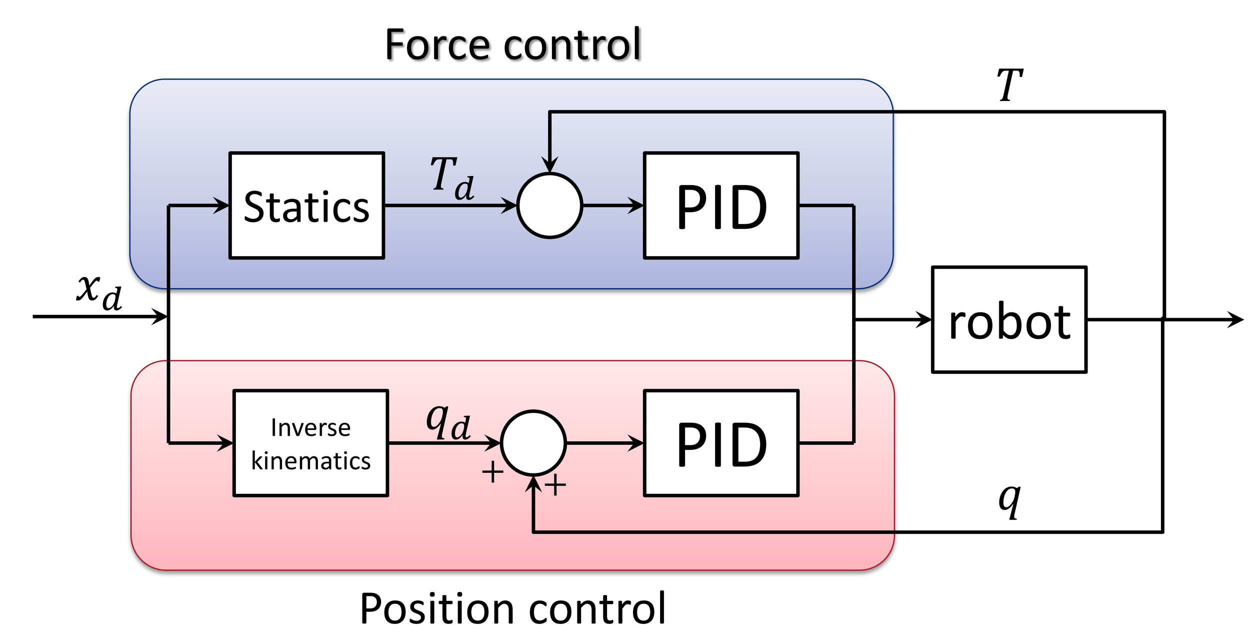
$$\mathbf{N} = \begin{bmatrix} n_l \\ n_m \\ n_r \end{bmatrix} = \begin{bmatrix} \sin\varphi_r \\ \sin(\varphi_r - \varphi_l) \\ -\sin\varphi_l \end{bmatrix}$$

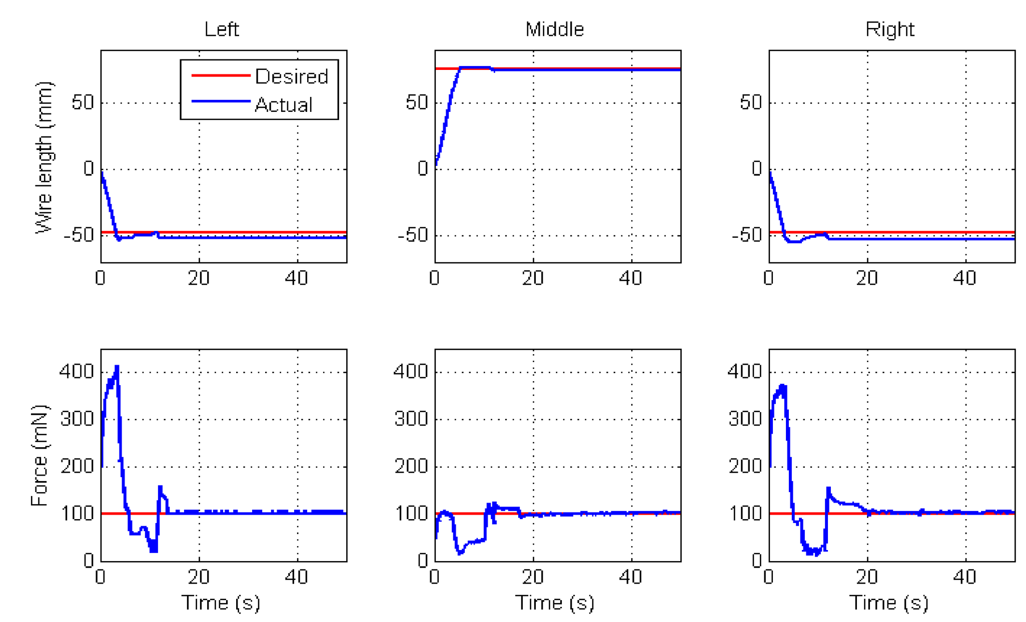


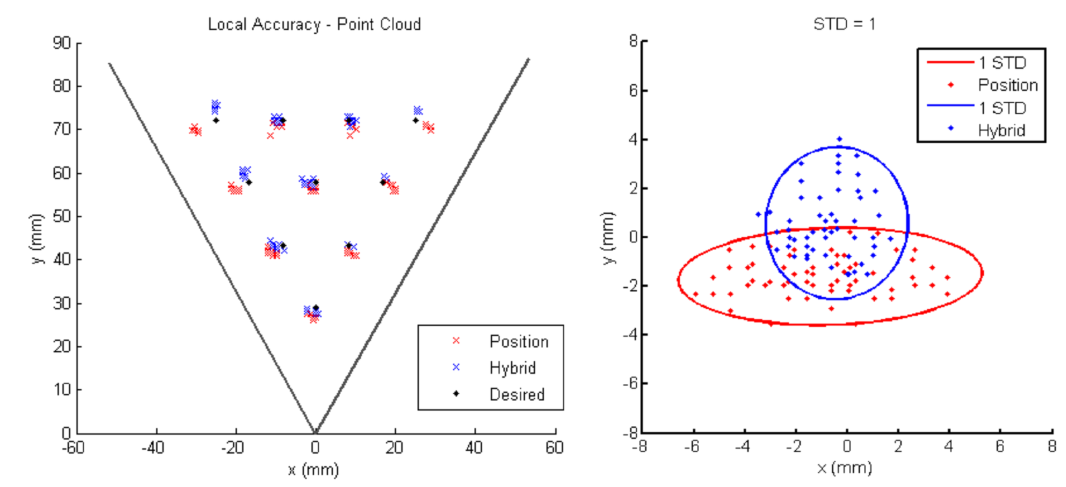
Contour graph of tension optimization where:
$L_l = 100\ mm$
$L_r = 100\ mm$
Angle = 30°
$T_{min} = 100\ mN$
$T_{max} = 500\ mN$

Hybrid Force/Position Control

- Redundant actuation
  – Servos control wires separately
- Position only
  ✗ Position error due to geometric error
  ✗ Wire tensions too low/high
  ✗ Poor control of injection placement
- Hybrid
  ✓ Accurately position device while wire tensions are maintained in proper range







(Top) Hybrid time graphs, (Bottom left) Point cloud of position and hybrid, (Bottom right) Covariance ellipse of position and hybrid
$L_l = 100\ mm, L_r = 100\ mm$, Angle $= 30°$
$T_{min} = 100\ mN, T_{max} = 500\ mN$

Future work

- Improve geometric assumptions
- Translate algorithm to curved surface for more realistic heart conditions

References

[1] A. D. Costanzo, N. A. Wood, M. J. Passineau, R. J. Moraca, S. H. Bailey, T. Yoshizumi, C. N. Riviere, "A Parallel Wire Robot for Epicardial Interventions," *IEEE Engineering in Medicine & Biology Conf. (EMBC)*, to appear August 2014
[2] R. L. Williams and P. Gallina, "Planar Cable-Direct-Driven Robots, Part I: Kinematics and Statics," *presented at the ASME Des. Tech. Conf.*, Pittsburgh, PA, Sep. 2001.
[3] P. H. Borgstrom , B. L. Jordan, B. J. Borgstrom, M. J. Stealey, G. Sukhatme, M. A. Batalin, & W. J. Kaiser (2009). NIMS-PL: a cable-driven robot with self-calibration capabilities. *Robotics, IEEE Transactions on*, *25*(5), 1005-1015