“Image-Based Flexible Endoscope Steering”

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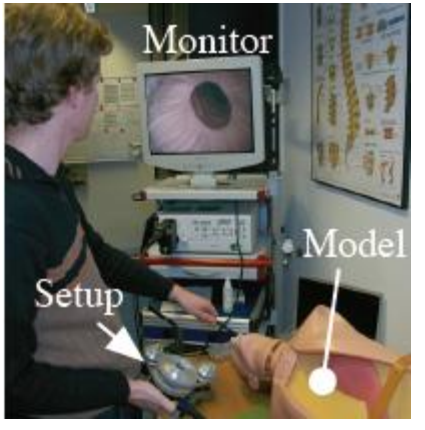
Project Goals

- Design, build, and test a clinical quality prototype robotic system to control a flexible endoscope with three degrees of motion.

Significance

- Creates a robotic system for control of a flexible endoscope
- Can be used with commercial endoscopes with 2 degrees of freedom for tip
- Uses computer vision algorithms to navigate endoscope

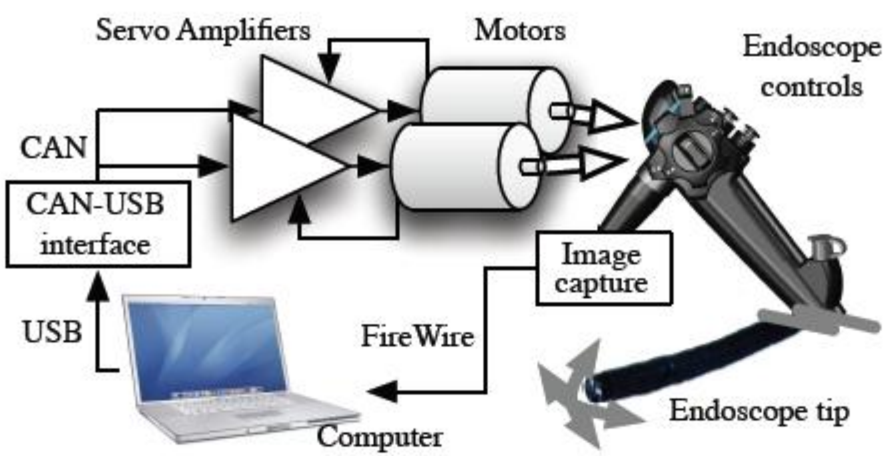


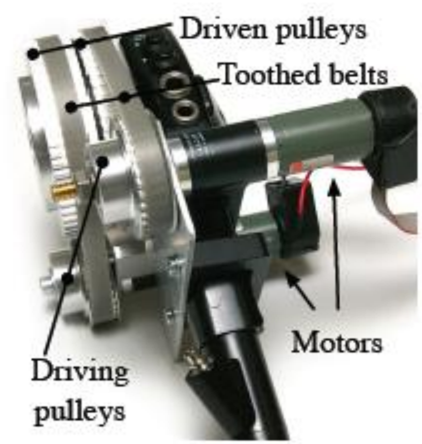
Summary of the Problem

- Insertion and navigation of endoscope requires dexterity and skill
- Control is not intuitive for the two degrees of tip freedom (two concentric circles)
- **Steering is difficult and time consuming for surgeons, increasing time of procedure and complications**

Design

- Pentax EG-2930K gastroscope
- Laptop computes set points for motor positions based on image
- Servo amplifiers control motors with external encoders





Control

- Dynamic image-based look-and-move structure
  - Control feature is center of lumen
  - Simple integral controller ($C_f = K/s$) with constant gain, K
  - Manually tuned gain on setup

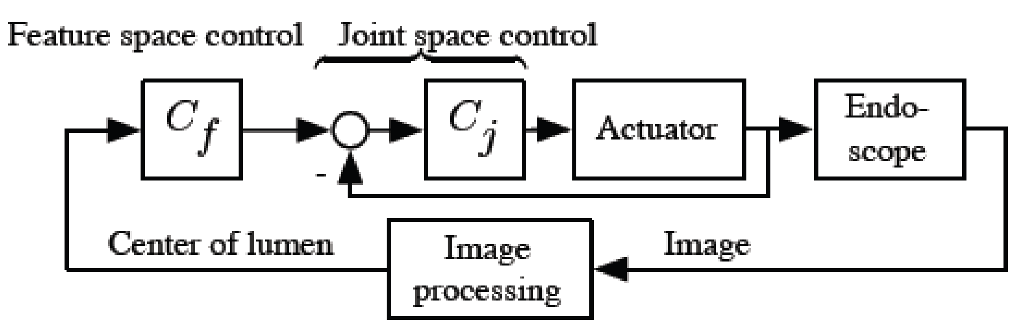


Image Algorithms

- Required real time processing for use in feedback control loop
- **Goal: Keep furthest part of the lumen centered in the image from the endoscope**
  - Optical flow-based algorithm
  - Image intensity-based algorithm
- Tested each algorithm first in simulation and in an experimental setup using a phantom

Optical Flow-Based Image Processing

- Depth estimation

$$M : \mathbb{R}^3 \to S^2; \quad \mathbf{p} \mapsto \frac{\mathbf{p}}{|\mathbf{p}|}$$

$$\mathbf{q} := M(\mathbf{p})$$

$$\lambda(\mathbf{q}) : S^2 \to \mathbb{R}$$

$$\theta(\mathbf{q}) := \underbrace{-\boldsymbol{\Omega} \times \mathbf{q}}_{\theta_{\mathbf{R}}(\mathbf{q})} + \underbrace{\frac{-1}{\lambda(\mathbf{q})} (\mathbf{I} - \mathbf{q}\mathbf{q}^{\mathrm{T}})\, \mathbf{V}}_{\theta_{\mathbf{T}}(\mathbf{q})}$$

$$(\mathbf{I} - \mathbf{q}\mathbf{q}^{\mathrm{T}})\mathbf{V}$$

$$1/\lambda(\mathbf{q})$$

$$\text{in } C,\ \theta_{\mathbf{T}}(\mathbf{q}) \approx 0$$

$$\theta(\mathbf{q}) \approx \theta_{\mathbf{R}}(\mathbf{q}) = -\boldsymbol{\Omega} \times \mathbf{q}.$$

- Implementation

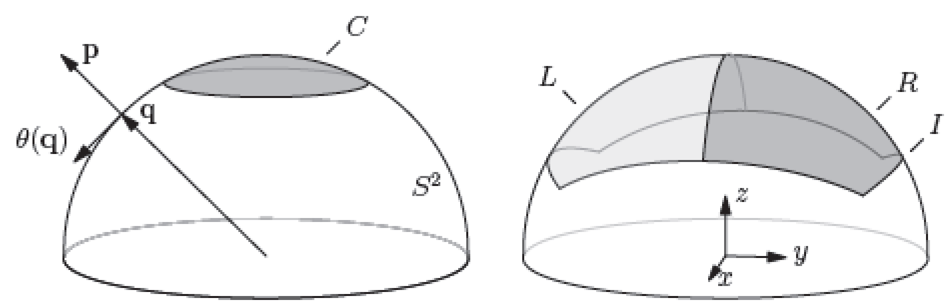
$$(\mathbf{u}_i, \mathbf{v}_i) \in S^2 \times S^2$$

$$\theta_{\mathbf{T}i} := \frac{1}{\Delta t}(\mathbf{R}^{-1}\mathbf{v}_i - \mathbf{u}_i)$$

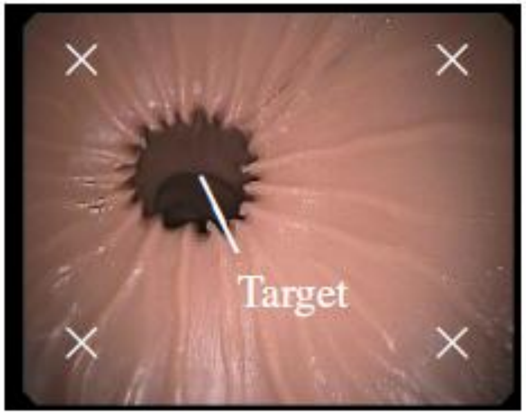
$$\phi_L := \mathrm{mean}(\{||\theta_{\mathbf{T}i}||_2 \quad | \ \mathbf{v}_i \in L\})$$

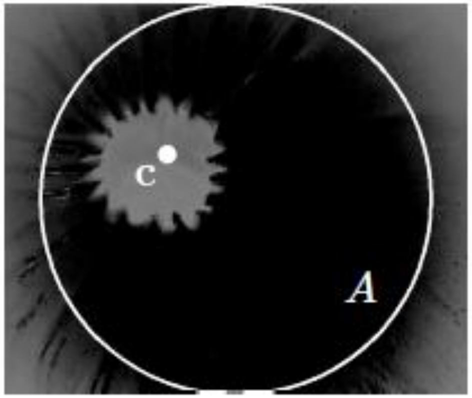
$$\phi_R := \mathrm{mean}(\{||\theta_{\mathbf{T}i}||_2 \quad | \ \mathbf{v}_i \in R\})$$

$$\omega_x = K(\phi_R - \phi_L)$$



Intensity-Based Image Processing





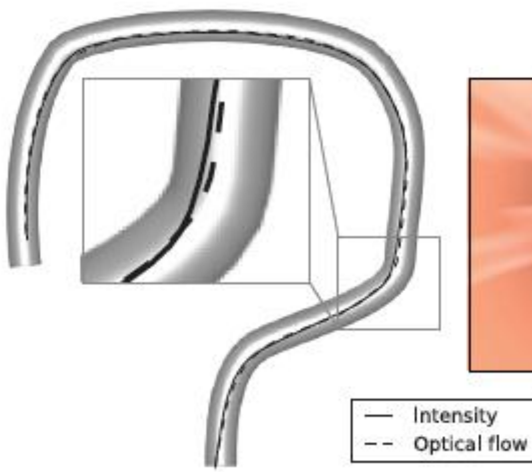
$$I''(x,y) := 255 - I'(x,y)$$

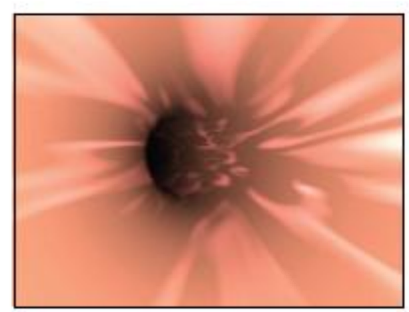
$$\mathbf{c} = \begin{bmatrix} c_x \\ c_y \end{bmatrix} = \frac{\sum_A \begin{bmatrix} x \\ y \end{bmatrix} \cdot I''(x,y)}{\sum_A I''(x,y)}$$

$$\begin{bmatrix} \omega_x \\ \omega_y \end{bmatrix} = -K \begin{bmatrix} c_x \\ c_y \end{bmatrix}$$

Simulation Results

- Found root mean square (RMS) distance between camera position and center line of lumen (% of lumen width)
  - Optical Flow Based Algorithm: 21%
  - Intensity Based Algorithm: 24%
- When light intensity increased to 400% of shown, RMS deviated by less than 5% of lumen width

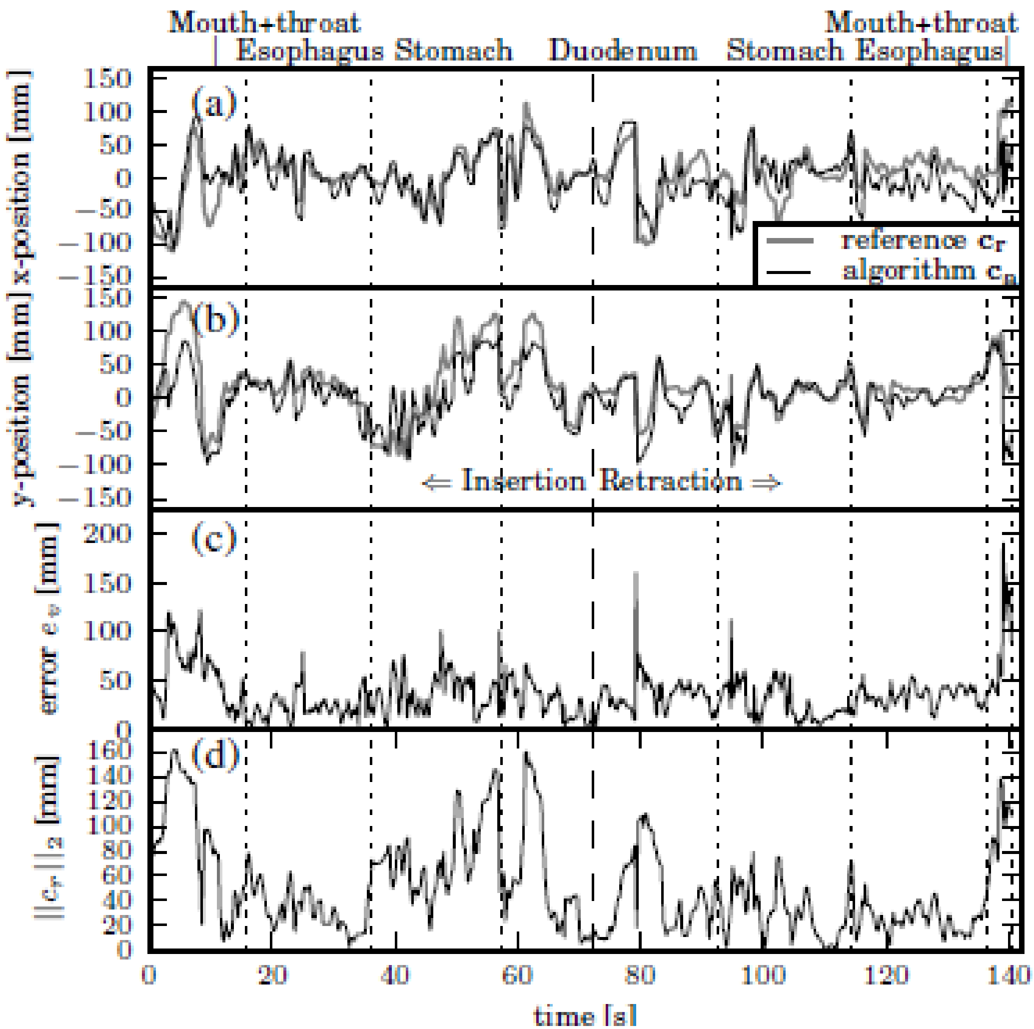




Phantom Experiment

- Could not use optical flow due to lack of texture in GI tract of phantom
- Endoscope manually retracted starting at duodenum with image-based steering keeping lumen centered
- Compared against 10 gastroscopies performed by 5 med students with flexible endoscopy training

Experimental Results



c_a = output of vision algorithm

c_r = reference center found manually

$$e_v := ||\mathbf{c_r} - \mathbf{c_a}||_2$$

RMS of error = 42 mm or **10%** of image

Conclusion

- RMS of position error for overall experiment was **16%** of image width (66 mm)
- Compared to manual steering
  - Average RMS position error for ten experiments was 110 mm (standard deviation= 10 mm) or **27%** of image width
  - **68% higher error than in robotically steered experiments**