“Image-Based Flexible Endoscope Steering”

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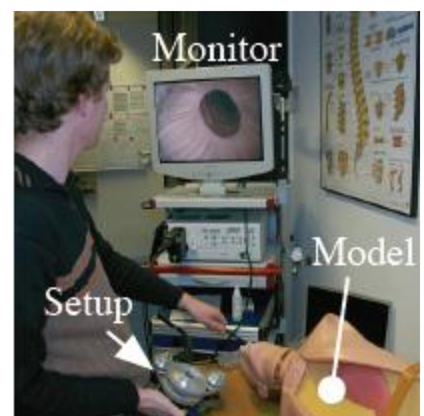
Project Goals

- 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

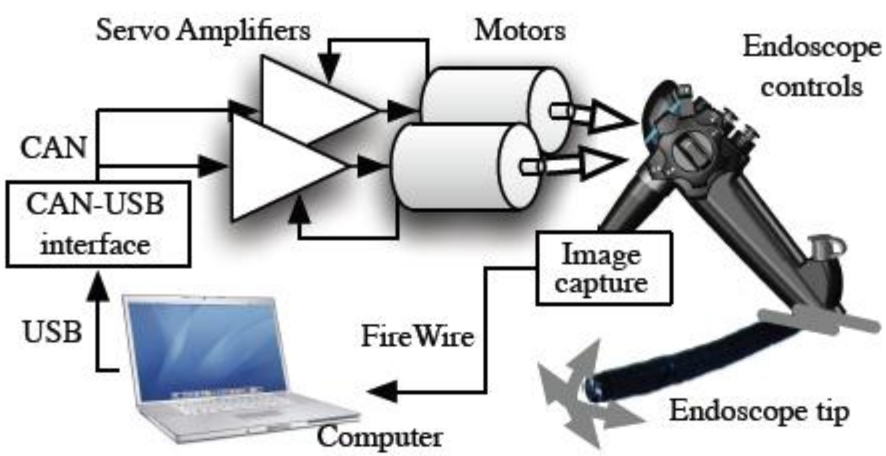


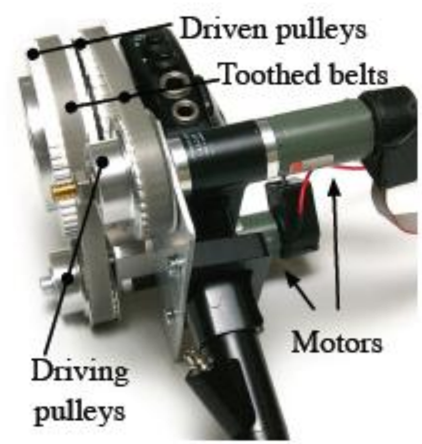
Summary of the Problem

- 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

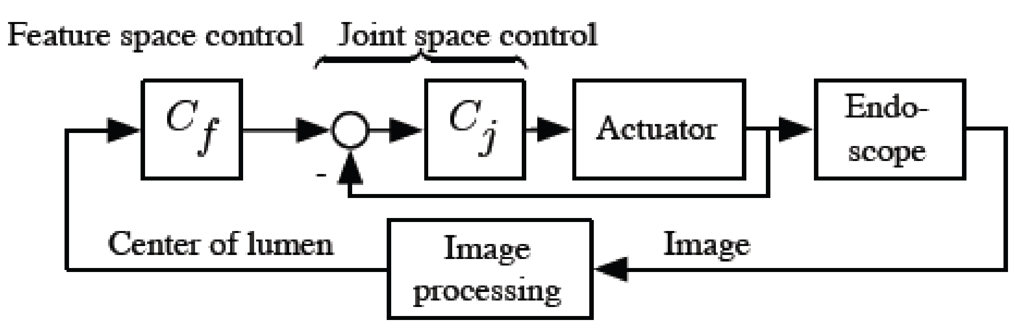
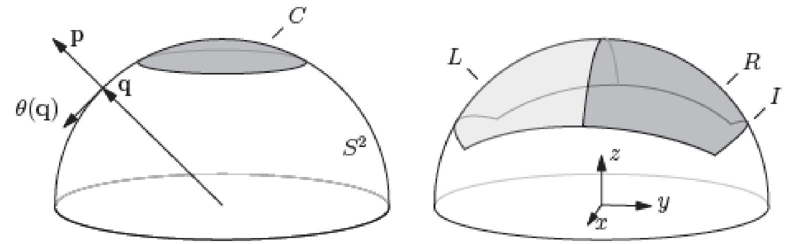


Image Algorithms

- 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
  - Projects points to sphere



$$M : \mathbb{R}^3 \rightarrow S^2; \quad \mathbf{p} \mapsto \frac{\mathbf{p}}{|\mathbf{p}|} \qquad \mathbf{q} := M(\mathbf{p})$$

$$\lambda(\mathbf{q}) : S^2 \rightarrow \mathbb{R} \quad \lambda = \text{distance from p to camera optical center}$$

  - Find rotational velocity

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

$\theta(q)$ = optical flow, $\theta_R(q)$ = rotational part, $\theta_T(q)$ = rotational part

V = translational velocity, Ω = rotational velocity around optical center

  - Use central region of image, C, as a reference

$(\mathbf{I} - \mathbf{q}\mathbf{q}^{\mathrm{T}})\mathbf{V}$ and $1/\lambda(\mathbf{q})$ become small

$$\text{in } C,\ \theta_{\mathbf{T}}(\mathbf{q}) \approx 0 \qquad \theta(\mathbf{q}) \approx \theta_{\mathbf{R}}(\mathbf{q}) = -\mathbf{\Omega} \times \mathbf{q}.$$

So $\theta(q)$ can be used to estimate Ω. Ω can then be used to find $\theta_T(q)$.

Optical Flow Continued

- Implementation
  - Lucas-Kanade optical flow algorithm

    n flow vectors represented as vector pair $(\mathbf{u}_i, \mathbf{v}_i) \in S^2 \times S^2$

    - Compute rotation matrix, R, for points in C
    - Find translational flow vector

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

      Δt = time frame, $R^{-1}v_i = v_i$ compensated for rotation

    - Find rotational velocity, ω, for pan (x) and tilt (y)

      $$\begin{aligned}\phi_L &:= \mathrm{mean}(\{\|\theta_{\mathbf{T}i}\|_2 \mid \mathbf{v}_i \in L\})\\ \phi_R &:= \mathrm{mean}(\{\|\theta_{\mathbf{T}i}\|_2 \mid \mathbf{v}_i \in R\})\end{aligned}$$

      φ = mean flow (left or right)

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

      K = constant gain

Intensity-Based Image Processing

- Create binary image using thresholding and use histogram equalization

$\mathrm{I}(x, y)$ = grayscale image, x and y are horizontal and vertical pixel positions

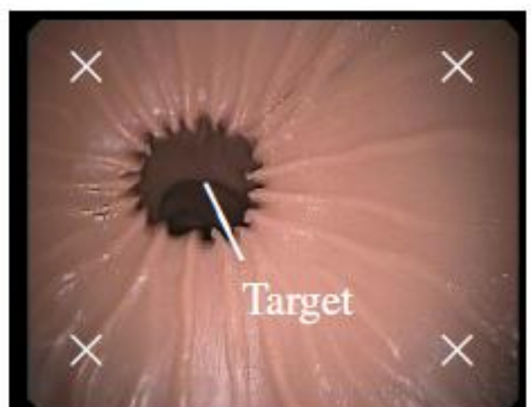
- Calculation center of dark region, **c**

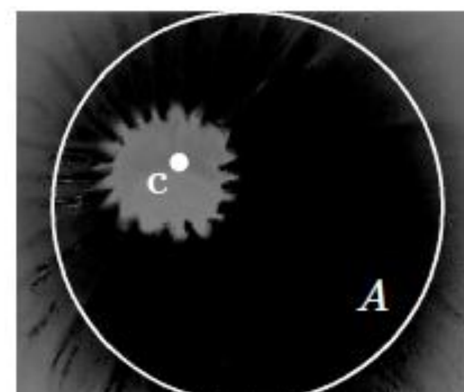
$$I''(x,y) := 255 - I'(x,y)$$

$\mathrm{I}'(x,y)$ = inverted image

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

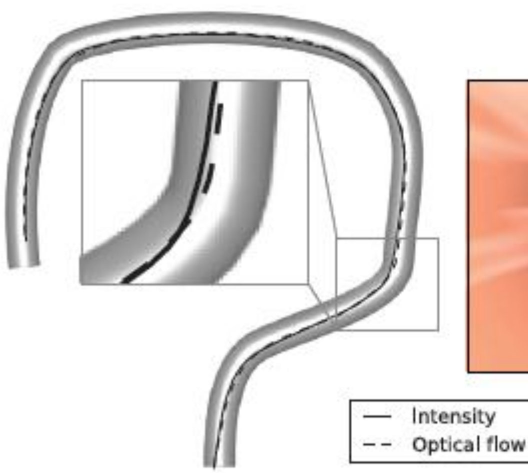
$$\begin{bmatrix} \omega_x \\ \omega_y \end{bmatrix} = -K \begin{bmatrix} c_x \\ c_y \end{bmatrix}$$





Simulation Results

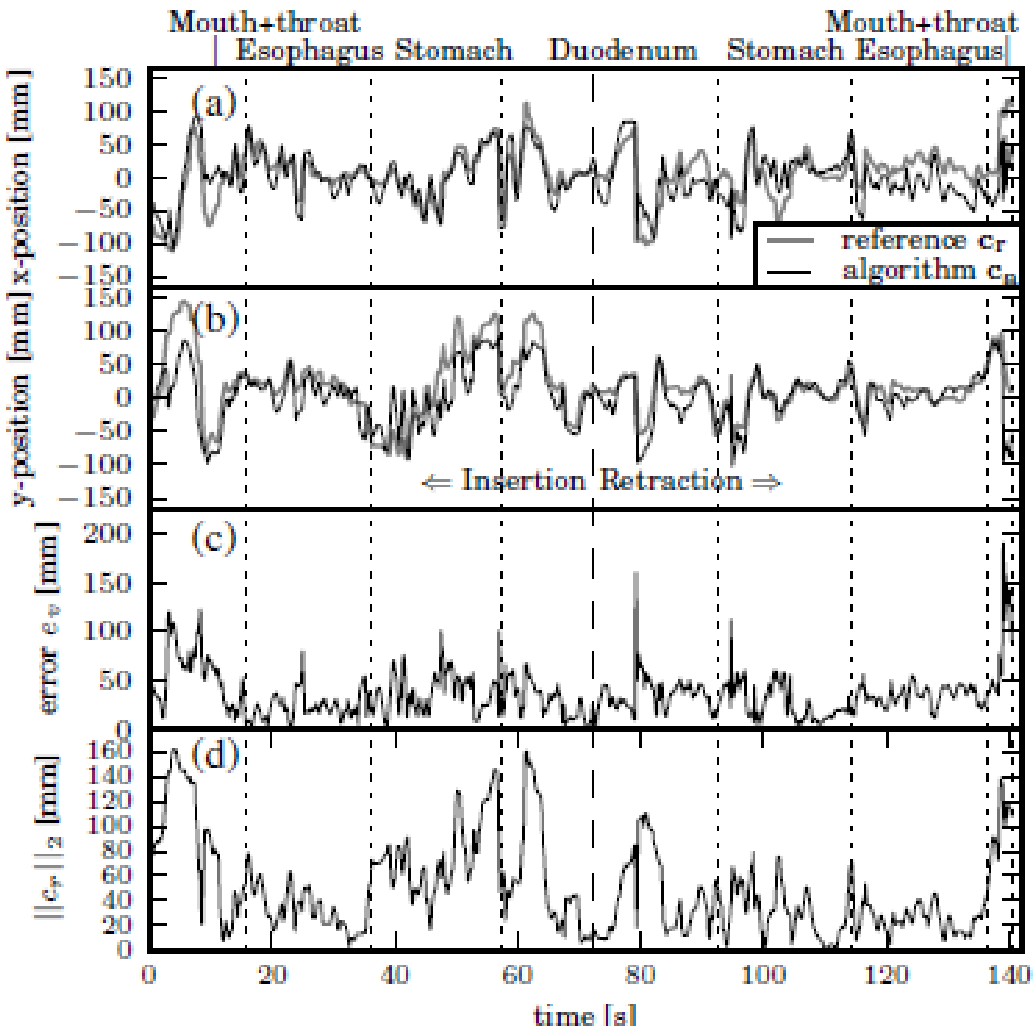
- Found root mean square (RMS) distance between camera position and center line of lumen (% of lumen width)
  - Optical Flow Based Algorithm: 21%
  - Intensity Based Algorithm: 24%
- When light intensity increased to 400% of shown, RMS deviated by less than 5% of lumen width



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
c_r = reference

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

RMS of error =

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**

Comparison of manual Steering and Steering via Joystick of a flexible Rhino Endoscope

R. Eckl, J.D.J. Gumprecht, G. Strauss, M. Hofer, A. Dietz and T.C. Lueth, *Member, IEEE*

32nd Annual International Conference of the IEEE EMBS (Buenos Aires, Argentina, 08/31/10- 09/04/10)

Summary

- Uses a simple robotic manipulator system to steer rhino endoscope
- System had no additional functionality for easing steering
- Compared steering times for hand versus joystick for manipulating robotic system
- Cannot conclude if one method leads to shorter performance times
- Future work: add steering functionality

Results

- A Flexible Endoscopic Surgical System: First Report on a
- Conceptual Design of the System Validated by Experiments
- Toshiaki Kobayashi1, Sean Lemoine1,2, Akihiko Sugawara1,2, Takaaki Tsuchida1, Takuji Gotoda1,
- Ichiro Oda1, Hirohisa Ueda3 and Tadao Kakizoe1
- 1National Cancer Center, 2Japan Association
- Jpn J Clin Oncol 2005;35(11)667–671
- doi:10.1093/jjco/hyi177