“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
    \[ M : \mathbb{R}^3 \to S^2; \quad p \mapsto \frac{p}{|p|} \quad q := M(p) \]
    \[ \lambda(q) : S^2 \to \mathbb{R} \quad \lambda = \text{distance from } p \text{ to camera optical center} \]
  - Find rotational velocity
    \[ \theta(q) := -\hat{\Omega} \times q + \frac{-1}{\lambda(q)} \left( I - qq^T \right) V \]
    \[ \theta_R(q) \quad \theta_T(q) \]
    \[ \theta(q) = \text{optical flow}, \quad \theta_R(q) = \text{rotational part}, \quad \theta_T(q) = \text{rotational part} \]
    \[ V = \text{translational velocity}, \quad \hat{\Omega} = \text{rotational velocity around optical center} \]
  - Use central region of image, C, as a reference
    \[ (I - qq^T)V \quad \text{and} \quad 1/\lambda(q) \]
    \[ \text{become small} \]
    \[ \text{in } C, \quad \theta_T(q) \approx 0 \quad \theta(q) \approx \theta_R(q) = -\hat{\Omega} \times q. \]
    So \( \theta(q) \) can be used to estimate \( \hat{\Omega} \). \( \hat{\Omega} \) can then be used to find \( \theta_T(q) \).
Optical Flow Continued

• Implementation
  – Lucas-Kanade optical flow algorithm

\[ \text{n flow vectors represented as vector pair } (u_i, v_i) \in S^2 \times S^2 \]

• Compute rotation matrix, \( R \), for points in \( C \)
• Find translational flow vector

\[ \theta_{Ti} := \frac{1}{\Delta t} (R^{-1}v_i - u_i) \]
\( \Delta t = \text{time frame, } R^{-1}v_i = v_i \text{ compensated for rotation} \)

• Find rotational velocity, \( \omega \), for pan (x) and tilt (y)

\[ \phi_L := \text{mean}(\|\theta_{Ti}\|_2 \mid v_i \in L) \]
\[ \phi_R := \text{mean}(\|\theta_{Ti}\|_2 \mid v_i \in R) \]
\[ \omega_x = K(\phi_R - \phi_L) \quad \text{K = constant gain} \]
Intensity-Based Image Processing

• Create binary image using thresholding and use histogram equalization

\[ I(x, y) = \text{grayscale image, } x \text{ and } y \text{ are horizontal and vertical pixel positions} \]

• Calculation center of dark region, \( c \)

\[ I''(x, y) := 255 - I'(x, y) \quad I'(x, y) = \text{inverted image} \]

\[
\begin{bmatrix}
  c_x \\
  c_y
\end{bmatrix} = \frac{\sum_A \begin{bmatrix} x \\ y \end{bmatrix} \cdot I''(x, y)}{\sum_A I''(x, y)}
\]

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

Target
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

\[ c_a = \text{output of vision algorithm} \]
\[ c_r = \text{reference center found manually} \]

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

R. Eckl, J.D.J. Gumprechct, 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

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