Visual-based Model-free Control of Soft Continuum Robot for Effective Endoscopic Navigation

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Abstract

The abstract goes here.

Index Terms

IEEEtran, journal, LaTeX, paper, template.

I. Introduction

- Why do we use soft robot for endoscopy
  - Endoscope is an tubular instrument for intra-cavitary or intra-luminal inspection in minimal invasive surgical procedure.
  - In conventional design, an endoscope comprises of a long and flexible body and a cable-driven steerable tip mounted with a camera.
  - This slender body is pliant to the surrounding objects, which facilitates versatile operations within the confined surgical environments.
  - The orientation of the tip can be manipulated by antagonistically adjusting the tensions and positions of the embedded cables.
  - This allows directing the camera and delivering interventional instruments such as biopsy forceps at particular regions of interest.
  - However, the cable tensions are difficult to control [ref] for stable interventional procedures.
  - The rigidity of tip may also cause damage to the soft tissue or even perforation [ref] when the endoscope is forced to pass through narrow corners against interior luminal surfaces.
  - These drawbacks motivate the development of totally soft, fluid-driven continuum robotic systems for endoscopic interventions.
  - Soft continuum structure can be readily fabricated from hyperelastic materials such as silicone (e.g. Ecoflex) using advanced 3D-printed technologies [ref: pnet].
  - This enables production of low-cost and disposable soft endoscopes to facilitate sterilization process, where the risk of cross infection would be minimized [ref].
  - Briefly introduce achievements of soft continuum robots for surgical applications
    - Endotics [ref]
      - for colonoscopy
    - Aer-O-space [ref]
      - for colonoscopy
    - STIFFLOP [ref]
      - controllable stiffness
    - other examples [ref]
  - Yet the kinematic and dynamic behavior of the deformable structure is usually highly nonlinear and is easily complicated by external disturbances.
  - Consequently the responses upon actuation can be dramatically unalike at different robot configurations.
  - This pose difficulties in deriving control methods for precise manipulation of such soft continuum structure.
- Various close-loop control methods have been proposed for soft continuum robots.
  - Model-based approaches relies on obtaining close-formed solutions [ref] from analytical models of the robot's kinematics or dynamics [ref].
    - Several modeling methods have been proposed to approximate the hyperelastic behavior
    - piecewise contant curvature models [refs],
      - infintie degree-of-freedom systems [ref],
      - interconnected spring-mass systems [refs],
      - geometrically exact formulations based on Cosserat theory [ref].

    * Model-based controllers could be applied to regulate either cable-driven [ref] or fluid-driven continuum robots [ref], and even generate bio-mimicking sterotyped motions [ref].
    * However, the assumptions made could be invalid in the presence of disturbances such as payload and external interactions.
    * Complicated procedures are also required to determine proper analytical models and system parameters beforehand [ref].
    * Such system identification process inevitably have to be started from scratch, if the structural properties that govern the robot's mechanical behavior have been significantly modified.
    * These drawbacks hinder model-based methods from applications to robot manipulation the confined surgical environments involving substantial contacts.
  - Model-free approaches
    * NN
    * Yips
    * advantages of model-free approach
  - However, most of the literature assume feedback of absolute robot position is avaliable
- The visual servoing camera-in-hand problem and control in constrained environment
  - Endoscopic images are the primary source to provide positional feedback of robot in real time
  - provide immediate positional displacement in the image domain caused by the robot motion.
  - The minautrized camera at the distal tip can offer high resolutions images, which can be streamed to computing units for pattern recognition [ref]
  - because installation of additional positional sensors may be infeasible due to limited size or clinical constraints.
  - explain briefly the camera-in-hand problem visual-servoing
  - this problem have been extensively studied in the case of rigid-link manipulators [refs]
  - only one example could be found in the case of continuum robots and its methods
    * wang's model-based cable-driven visual servo [ref]
  - no existing example of visual-based control for soft fluid-driven continuum robot
- propose our model-free visual servo approach
  - why nonparametric methods?
  - Contributions:
    * first attempt the camera-in-hand visual servoing for fluid-driven continuum robots for intra-luminal endoscopy
    * Novel model-free visual servoing control method (section II)
    * demonstrated enhanced manipulation in tele-mainpulation tasks (section III)

II. Materials and methods

A. *Overall control architecture for tele-manipulation*

- Explanation of the tele-manipulation in endoscopic navigation
  - Fig.1 : Schematic diagram of the overall control architecture
  - Components: the user input, the controller, the robot, the endoscopic camera
- Definition of the control problem
  - redundantly actuated soft robot
    * Fig. 2: sketch of the soft robot
  - we consider operational space control
    *

B. *Real-time image processing*

- what is the output of the image processing
  - the displacement in the endoscopic view
  - use filter technique to smooth the output
  - is the smoothing technique specific for the endoscopic environment?

C. Model-free Kinematic control

1) Kinematic transition of soft continuum robot:

- general nonlinear function to describe the kinematic relation
  - why quasi-static?
    * robot tip motion should be gentle for smooth output in the endoscopic view
    * large pressure change must be prohibited
  - quasi-static transition model [ref]
    * the robot is in stationary condition at time step k with static chamber pressure $\boldsymbol{u}_k$
    * the robot state is represented $\boldsymbol{x}_k$
  - when the chamber pressure is changed by $\Delta\boldsymbol{u}_k$, the state at the next time step is:
  - $\boldsymbol{x}_{k+1} = f(\boldsymbol{x}_k, \Delta\boldsymbol{u}_k, \boldsymbol{\eta}_k)$ or $\boldsymbol{x}_{k+1} = f(\boldsymbol{x}_k, \Delta\boldsymbol{u}_k) + \boldsymbol{\eta}_k$
  - where $bm\eta_k$ is unknown external disturbance
    * e.g. ???
  - kinematics relative to a base frame
    * indicate in Fig. 2
  - In endoscopic procedure, image feedback is the only available feedback to close the robotic control loop
  - The tip orientation $\boldsymbol{y}_k$, and the corresponding image output $\boldsymbol{z}$ are
    * $\boldsymbol{y}_k = g_e(\boldsymbol{x}_k)$
    * $\boldsymbol{z}_k = g_c(\boldsymbol{y}_k) + \tilde{\boldsymbol{\epsilon}}_k$
    * where $\boldsymbol{\epsilon}_{\mathrm{k}}$ is the measurement noise
- During the tele-manipulation process, the desired target $\boldsymbol{z}^*_{k+1}$ is given by the operator via the user input.
- Therefore, the controller needs to compute the required change of chamber pressure $\Delta\boldsymbol{u}_k$, which can be represented as the inverse kinematic model below:
  - $\Delta\boldsymbol{u} = \tilde{\pi}(\boldsymbol{x}, \boldsymbol{\eta}, \boldsymbol{z}_k, \boldsymbol{z}^*_{k+1}) + \boldsymbol{\epsilon}$
  - $\boldsymbol{\epsilon}$ is the noise resulting from the measurement inaccuracy
- however, $\boldsymbol{x}$ and $\boldsymbol{\eta}$ are unknown.
- Under the quasi-static transition behavior, we hypothesize that the pressure $\boldsymbol{u}_k$ can provide information of the state $\boldsymbol{x}_k$.
- Besides, the controller have to adapt the external disturbance $\boldsymbol{\eta}_k$, which inherently affects the robot transition.
- Therefore, we propose to adopt online learning technique to acquire the following approximated inverse model from measurement data:
- $\Delta\boldsymbol{u} = \pi(\boldsymbol{u}, \boldsymbol{z}_k, \boldsymbol{z}^*_{k+1}) + \boldsymbol{\epsilon}$

2) Estimation of the absolute position from real-time visual feedback:

- use image displacement and the chamber pressure at the last time step to estimate the absolute orientation
- $\hat{\boldsymbol{s}}_k = h(\Delta\boldsymbol{z}_k, \boldsymbol{u}_{k-1})$
- this estimation will be employed in the model-free controller described below.

3) Learning the inverse model for operational space control:

- brief introduction of online nonparametric method
  - advantages of directly learning the inverse
    * low gain feedback controller
  - difficulty in directly learning the inverse
    * redundancy problem in the control space
- proposed our method
  - how to resolve the redundancy problem
- discuss the difference from related works regarding the learning/control methods

III. Results and Discussion

- (Validation by simulation)
  -
- experimental setup
  - Description of the endoscope prototype
    * dimension, bending angle, basic endoscopic functions: e.g. insulflation, irrigation, ...
    * Fig. 3

- Description of the experimental platform
  - The base of the robot is fixed
  - to simulate the colonoscopy procedure, in which the operator searches for specific features such as polyps.
  - Fig. 4a, b
    - a: overall setting, with EM tracker at the tip
    - b: endoscopic view with feature markers
- To quantitatively evaluate the benefits to the navigation procedure, we measures the performance of the tele-manipulation task in terms of
  - completion time
  - the discrepancy between the desired and the actual image displacement
- #xx subjects were divided into 3 groups, in each of which the subjects performed the task using
  - open-loop control
  - EM-based feedback
  - Visual-based feedback

- Results
  - Table I. performance indexes of the 3 cases
  - Fig. 3D trajectories of the 3 cases
  - overlayed on a virtual colon model

IV. Conclusion