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

Author 1, Author 2

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# 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)

# Materials and methods

## 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

## 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?

## Model-free Kinematic control

### 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 with static chamber pressure $\bm{u}\_k$
    - the robot state is represented $\bm{x}\_k$
  + when the chamber pressure is changed by $\Delta\bm{u}\_k$, the state at the next time step is:
  + $\bm{x}\_{k+1} = f(\bm{x}\_k,\Delta\bm{u}\_k, \bm{\eta}\_k)$ or $\bm{x}\_{k+1} = f(\bm{x}\_k,\Delta\bm{u}\_k) + \bm{\eta}\_k$
  + where 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 $\bm{y}\_k$, and the corresponding image output $\bm{z}$ are
    - $\bm{y}\_k = g\_e(\bm{x}\_k)$
    - $\bm{z}\_k = g\_c(\bm{y}\_k) + \bm{\tilde \epsilon}\_k$
    - where is the measurement noise
* During the tele-manipulation process, the desired target $\bm{z}\_{k+1}^\*$ is given by the operator via the user input.
* Therefore, the controller needs to compute the required change of chamber pressure $\Delta \bm{u}\_k$, which can be represented as the inverse kinematic model below:
  + $\Delta \bm{u}=\tilde \pi(\bm{x}, \bm{\eta}, \bm{z}\_k, \bm{z}\_{k+1}^{\*}) + \bm{\epsilon}$
  + $\bm{\epsilon}$ is the noise resulting from the measurement inaccuracy
* however, $\bm{x}$ and $\bm{\eta}$ are unknown.
* Under the quasi-static transition behavior, we hypothesize that the pressure $\bm{u}\_k$ can provide information of the state $\bm{x}\_k$.
* Besides, the controller have to adapt the external disturbance $\bm{\eta}\_k$, which inherently affects the robot transition.
* Therefore, we propose to adopt online learning technique to acquire the following approximated inverse model from measurement data:
* $\Delta \bm{u}= \pi(\bm{u}, \bm{z}\_k, \bm{z}\_{k+1}^{\*}) + \bm{\epsilon}$

### 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
* $\bm{\hat s}\_k = h(\Delta \bm{z}\_k,\bm{u}\_{k-1})$
* this estimation will be employed in the model-free controller described below.

### 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

# 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

# Conclusion