Design and analysis of a soft continuum robot prototype for colonoscopy

Author 1, Author 2

Abstract

The abstract goes here.

Index Terms

IEEEtran, journal, LaTeX, paper, template.

I. Introduction

- 1st paragraph: To introduce the advantages of using soft robots in endoscopy
  - Clinical data of endoscopy, showing the increasing need of robotic endoscope
  - Review of some state-of-the-art robot-assisted endoscopy with rigid structure
    - tendon-driven
  - Current applications of soft robots in medical applications
  - Advantages of using soft robots in endoscopy
    - low-cost
      - disposable
    - easy to fabricate
    - particularly fluidically-driven soft continuum robots
- 2nd paragraph: To introduce the technical challenges of using soft robots in endoscopy
  - State-of-the-art soft robotic technologies
    - achievements in literature
  - requirements for endoscopy
    - safe
    - fast response
    - small size
    - with working channel *
    - (with embedded camera)
  - the technical challenges in design:
    - choice of material
    - structural and geometrical design
    - how stiff should be enough?
    - simulation of hyper-elastic materials and interaction with internal instrument
- 3rd paragraph: How do we solve these challenges
  - state-of-the-art FEA for hyperelastic material
    - achievement in literature
  - what are the contributions of our FEA?
    - any literature have done simulation of interaction with internal instrument?
    -
  - what are our approach/tricks that can approximate the hyperelastic behaviour?
    - new FEM formulations?
    - new combination of element?
    - optimized for fast computation?
    - etc…
  - how the FEA results be incorporate in the design optimization
    - description of role of FEA in the design optimization cycle
  - Fig. 1. The endoscope prototype.

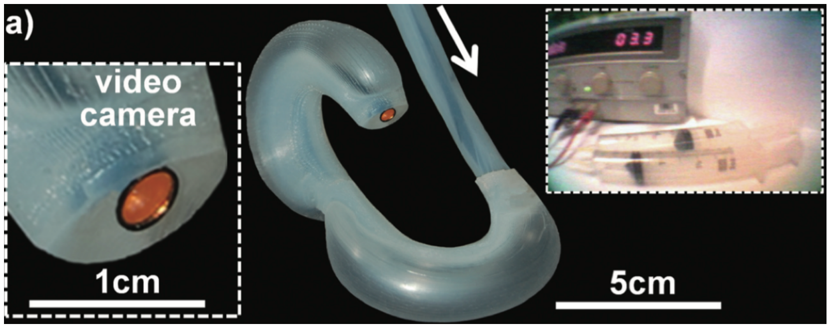

Fig. 1. The endoscope prototype.

- 4rd paragraph: Clearly list out the contributions using the proposed FEM-based design
  1) Novel structural design to improve the stiffness and durability (section II-B)
     * dump-bell-shaped actuation chamber
  2) FEM methods for simulating the effects of including working channel (section II-C)
     * e.g. buckling
  3) The smallest soft continuum robot with working channel (xmm) for endoscopic interventions (section III)
     * how much output force?
     * smallest too aggressive?

II. Materials and methods

A. Design and performance requirements

- specify the target application – colonoscopy
- a working channel is preserved
  - for biopsy, suction, irrigation, and other instruments
  - give common dimension of clinically-used instruments (e.g. biopsy forceps)
    * dimensions in specific applications: e.g. colonoscopy
  - requirement for the diameter: the larger the better
    * specify a dimension for the prototype in this paper
- target dimension: Outer diameter and length
  - why such dimension?
    * clinical reason
- The requirement of bending behavior
  - curvature ratio
  -
- constrained elongation
  - i.e. only bending without much elongation
  - why?
    * camera is mount at the tip. bending with large elongation will cause loss of tracked vision target in the endoscopic view
- How stiff should the scope be? - the key problem of this paper
  - sufficient to be stable during instrument manipulation
  - sufficient to withstand high input pressure
  - we use FEM simulations to characterize the stiffness properties
- Durability
  - long life cycle
- actuation method - fluidic actuation
  - advantages of fluidically driven - can be only Hydraulic/pneumatic
    * safe without internal electric component or some toxic component
    * hydraulic: incompressible transmission media gives fast response, ...
    * pneumatic: ease of assembly, ...

    * MRI-compatible
    * a sentence about the control method
    * why not tendon-driven? (move to discussion section)?
      · here we may need to mention also the advantages of tendon-driven soft continuum robot
- discuss difficulties of miniaturization - the inclusion of working channel
  - mention the state-of-the-art (smallest) soft robot dimension (for colonoscopy)
  - difficulties of including a central working channel
    * weaken structure
    * reduced volume of material –¿ less elongation and thus smaller bending curvature
  - are we the first soft robot with working channel of that small dimension?
- Assume that the camera and LED are not considered during simulation, but they are included in the real prototype.

B. Structural design

- the actuation response depends on the structural design
  - the geometric design of the actuation chambers and internal tubings
  - materials
  - fabrication process
- we use FEA to simulate the kinematic and dynamics behaviour in the design optimization process, regarding to the first two factors
- we can first give the design using fan-shaped actuation chambers
- then use FEM to demonstrate the weak points at the chamber corners
- then provide the dump-bell-shaped design

1) Geometrical design of actuation chambers:

- Fig. 2. 2D FEM model

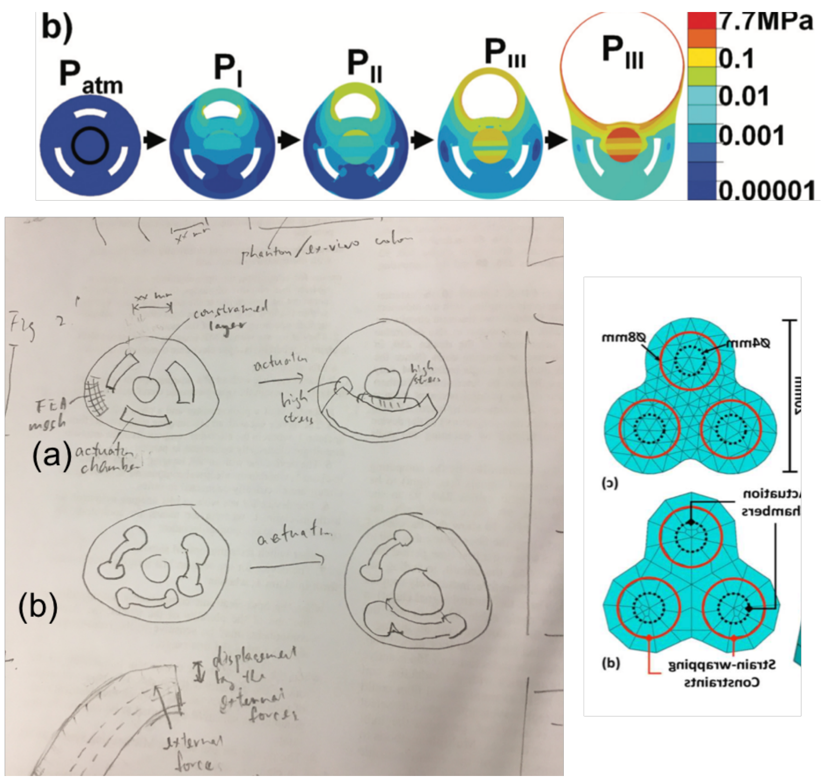

Fig. 2. Internal stress during actuation. (a) Fan-shaped actuation chamber design has higher stress. (b) Dump-bell shaped chamber design has lower stress.

- actuation chamber design - 1st version: the fan-shaped
  - number of chambers
    * 3-chambers are commonly used in the literature
  - chamber geometry

    * why do we use the fan-shaped chamber?
    * done in [1].
  - mention about chamber arrangement/location
    * why this offset from the center?
- constraint layers
  - where are the constraint layers
  - what are the benefits of the constraint layers?
  - why they are necessary?
- dimension of the working channel
  - to match requirement mention in II-A
- actuation chamber design - 2nd version: the dump-bell shaped
  - thicker walls between the chambers and the central channel
  - no-corner chambers
  - why?
    * during actuation, high stress are found in the fan-shaped chambers
      · in the walls between the chambers and the central channel
      · at the corners

2) The choice of materials:

- Fig. 3. Stress-strain characteristics of the materials in used

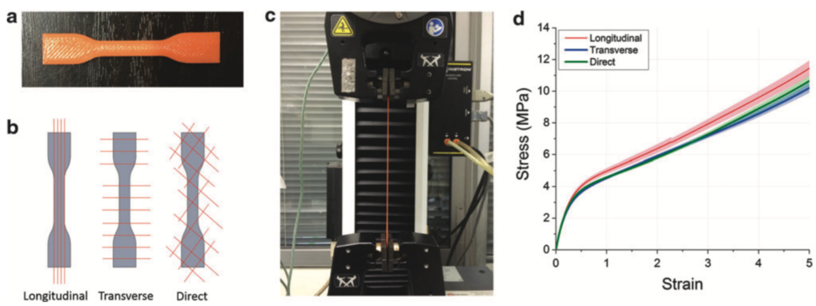

Fig. 3. Stress-strain curves of the materials in used. These measurement data are used for identification of hyperelastic model in Table I.

- show the stress-strain properties of the material (Fig. 3)
  - the body
    * the constraint layer
    * the central channel
    * both longitudinal and axial stress-strain
    * show failure limit
- reasons for the choice
  - for the body
    * large longitudinal strain
    * can withstand high stress
  - for the constraint layer
    * insignificant axial strain
    * can withstand high stress
  - for the central channel
    * insignificant axial strain
    * can withstand high stress

C. FEM-based modeling and response characterization

1) Identification of hyperelastic model:

- Table I. Table of hyperelastic models
- Table II. FEM simulation parameters

TABLE I
HYPERELASTIC MODEL CANDIDATES FOR FEM SIMULATION.

TABLE 3. HYPERELASTIC STRAIN ENERGY FUNCTIONS

Hyperelastic model	*Strain energy function*
Ogden	$W = \sum_{i=1}^{3} \frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3)$ μ_i and α_i are empirical parameters, and λ_1, λ_2, λ_3 are deviatoric principal stretches
Yeoh	$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$ I_1 is the first deviatoric strain invariant, and C_{10}, C_{20}, C_{30} are material specific parameters
Mooney–Rivlin	$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$ I_1, I_2 are the first and second deviatoric strain invariant, and C_{10}, C_{01} are material-specific parameters
Arruda–Boyce	$W = \mu \sum_{i=1}^{5} \frac{c_i}{\lambda_m^{2i-2}}(I_1^{\,i} + 3^i)$ $C_1 = \frac{1}{2}, C_2 = \frac{1}{20}, C_3 = \frac{11}{1050}, C_4 = \frac{19}{7000}, C_5 = \frac{519}{673750}$ μ and λ_m are empirical parameters

TABLE II
FEM SIMULATION PARAMETERS.

TABLE 4. PARAMETER VALUES FOR DIFFERENT HYPERELASTIC MODELS

Hyperelastic model	*Parameter*	*value*
Ogden	μ_1	–30.921
	α_1	0.508
	μ_2	10.342
	α_2	1.375
	μ_3	26.791
	α_2	–0.482
	sse	0.644
Yeoh	C_{10}	1.653
	C_{20}	0.0324
	C_{30}	0.000486
	sse	159.481
Mooney–Rivlin	C_{10}	0.677
	C_{01}	1.621
	sse	45.280
Arruda–Boyce	μ	2.272
	λ_m	11757.615
	sse	460.901

- the identifying hyperelastic materials for FEA
  - how to choose the strain energy functions?
    * list several candidates, and then discuss how to choose among them.
  - what software you are using?
- how to choose the finite element? and why?
  - hexahedral element for the hyperelastic material, truss for the constraint layer?
    * with the element number in that software (e.g. Abaqus element type C3D10H)
- Simulation parameters
  - what is the number of elements?
  - what are the types of elements?
  - simulation time
  - list in a table

2) Characterization of bending behavior and stiffness:

- Fig. 4. 3D FEM model for stiffness simulation

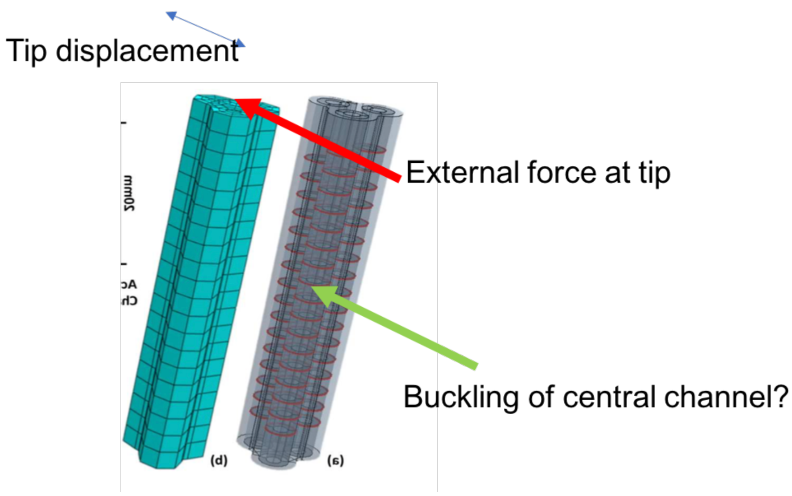

Fig. 4. FEM simulation to estimate the robot stiffness. An external force is exerted at the tip perpendicular to the pointing direction. Stiffer robot requires larger force to move the tip.

- simulate bending performance: ratio = curvature/length
- bending force
  - what is bending force? the force at the tip ?
  - the force with the same direction with the tip movement
- how to estimate stiffness?
  - applying a force to the inner wall of the working channel
  - stiffness = force / displacement
- we need to simulate the stress acting on the embedded tubings?
  - can we simulate the buckling of the tubing? when and how the buckling occurs?
  - as including a central channel is also the key difference from the literature, such simulation will be the novelty of the method
  - buckling causes collapse and thus malfunction of the central channel.

D. (Fabrication process) - optional

- Fig. 5. Fabrication procedure – optional
- Fabrication process
  - low-cost
  - basic procedure (of course some basic tricks that can be disclosed)
    * e.g. sequence of molding and filling material, temperature
    * reference: e.g. Fig.1 in [1].
  - what should be paid attention to? why?

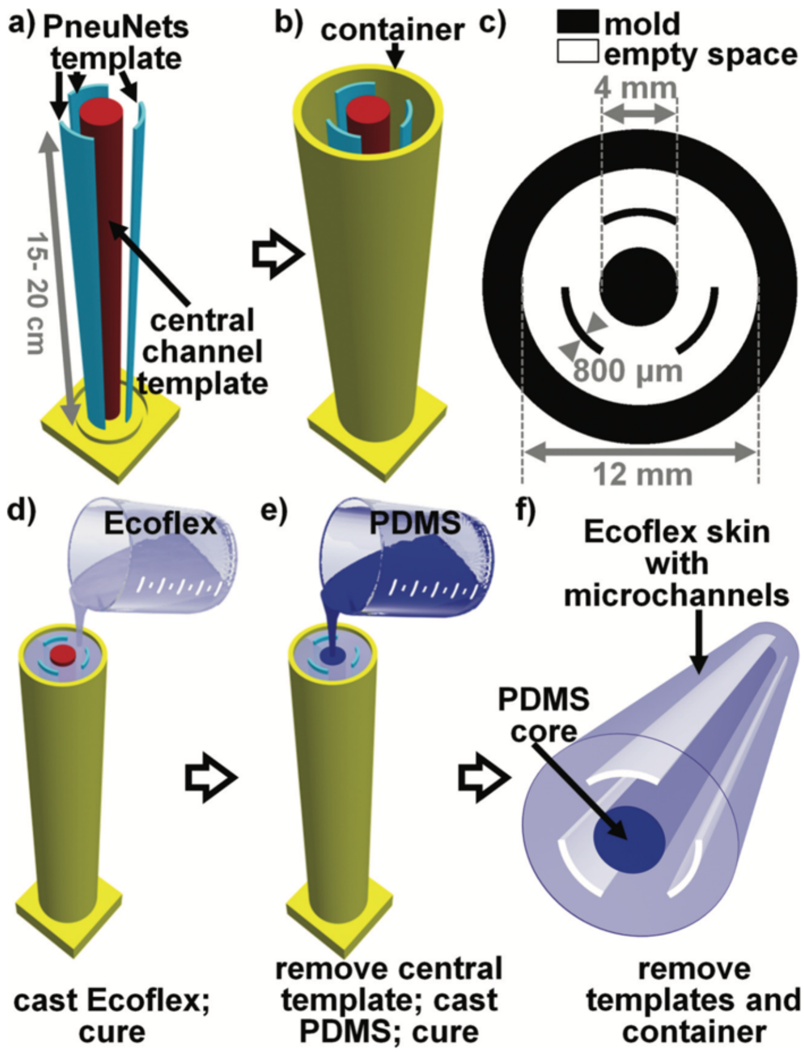

Figure 1. Fabrication of 3D tentacles. a) Mold with the templates for the PneuNet and the central channel templates. b) The mold is placed into a container having the final outer diameter of the tentacle. The channel templates and container are parallel. c) Top view of the mold with the dimensions of the cross section of the tentacle. d) The mold is filled with Ecoflex and cured at 60 °C for 15 min. e) Removing the central channel allows PDMS to be poured into that space. PDMS and Ecoflex bond together after curing for 2 h at 60 °C. f) The tentacle is removed from the mold.

Fig. 5. Fabrication procedure of the endoscope prototype. - optional

        * e.g. temperature control, material filling speed, assembly cautions
        * …

III. Results and discussion

- Comparison of the results between FEA and the real robot
- workspace analysis
    - using random pressure inputs
- how to measure the bending force
- how to measure the internal force
    - fatigue test
        * no. of cycle until failure
    - can take reference from yap2016highforce

A. *Quasi-static bending behavior*

- Fig 6. Bending behaviour

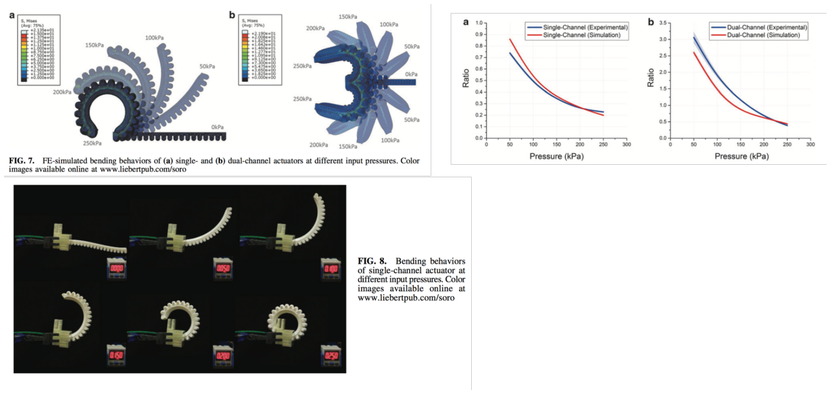

Fig. 6. Bending behavior of the endoscope. (a) FEA results with different chamber pressure. (b) Snapshots of the real robot. (c) The relationship between chamber pressure and the bending curvature, for different preloaded pressure. (d) Bending coplanarity of the prototype. (e) Workspace of the prototype.

- experiment settings
  - the prototype based is fixed
    - what were measured?
      - bending radius
      - length of the prototype
      - position of the tip
    - what instruments were used?
      - e.g. EM tracker to measure the 3D position of the tip
      - e.g. analyzed from captured images to measure the radius and the length
  - actuation condition?
    - bending when actuating 1 chamber
    - bending when actuating 2 chambers
    - different preloaded pressure
    -
  - refer a figure that can illustrate the setting
- Assessment of the bending degree
  - ratio = bending radius/length
  - lower ratio means better bending degree
  - both FEA and real robot results
  - real robot data of different preloaded pressure
  - 2 figures:
    1) ratio vs chamber pressure
    2) length vs chamber pressure
  - expected results
    -
- workspace analysis
  - real robot data is enough
  - actuation of 1 and 2 chamber
    - using random chamber pressure
    - uniform distribution
  - 1 result figure
    - a 3D surface plot of the tip position
    - with some vectors showing the tip directions when adding more pressure at the 3 chambers
  - to show if the resulting cloud points are evenly distributed
    - if the relationship of bending vs pressure is linear, the cloud points should be evenly distributed
  - expected results

*

- (Assessment of motion coplanarity - optional)
  - to examine if the bending is in a fixed plane
  - FEA may not reveal the coplanarity, because this might be due to some technical problems in the fabrication process, such as uneven material density
  - how to quantitatively measure the coplanarity?
    - for each bending from 0 to max degree
    - obtain instantaneous velocities $\{\boldsymbol{v}^{tip}\}_k$ of the tip at time step k.
      - $k = 0, ..., N$ indicates the time step
      - let $\boldsymbol{n}$ be the normal vector of the bending plane
      - $0 \geq \theta \geq 2\pi$
      - kinematics of the tip can be obtained using EM tracker
    - a scalar performance index evaluates if two consecutive velocities $\boldsymbol{v}_i^{tip}$ and $\boldsymbol{v}_{i+1}^{tip}$ stay on the bending plane
      - $J = (\boldsymbol{v}_i^{tip} \times \boldsymbol{v}_{(i+1)}^{tip}) \cdot \boldsymbol{n}_\theta$
    - index closer to 0 means more coplanar bending
  - figures
    - a 3D plot of the velocity vectors of a bending movement
    - showing the mean and the range of the coplanarity performance index of all recorded bending movements

B. *Stiffness analysis*

- Fig. 7. Stiffness measurement setting.

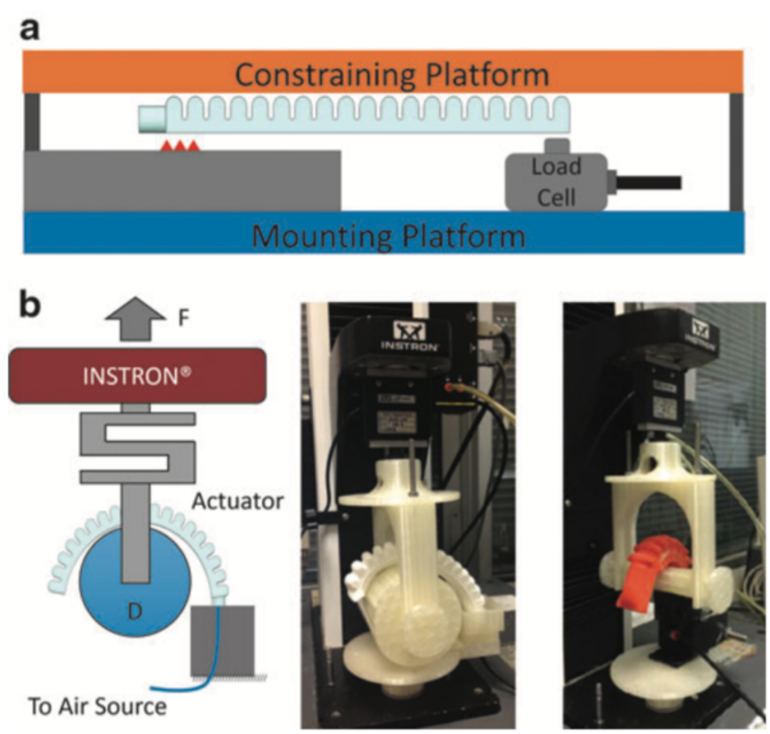

FIG. 11. (a) Schematic of the customized system for blocked force measurement. **(b)** Schematic and real setup for grip force measurement. Color images available online at www.liebertpub.com/soro

Fig. 7. Stiffness measurement setting. The tip of the robot is connected to a pulling device with a force sensor. The robot is fixed to a platform. The platform is tilted to ensure the force is exerted perpendicular to the pointing direction.

- Fig. 8. Stiffness results

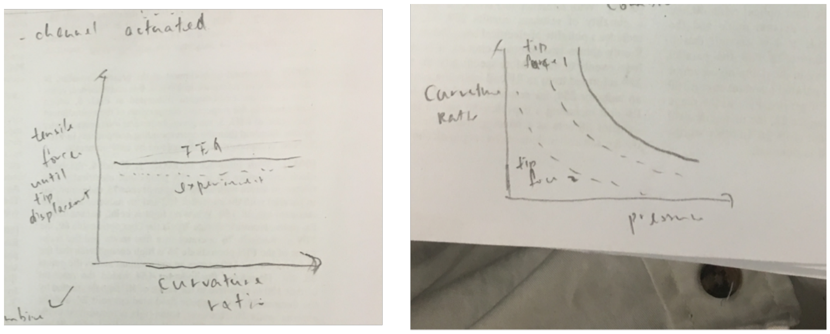

Fig. 8. Stiffness of the protoype. (a) The min. force required to move the tip for Xmm vs curvature ratio, for different preloaded pressure. This force indicates the stiffness of the prototype. (b) The maximum displacement of the tip when accelerating a biopsy forceps inserted in the central channel.

- experiment settings
  - fig of the setting
    - the robot base is fixed on a robotic platform
    - the tip of the robot is pulled by an external force
      - pull until the tip is displaced (e.g. several mm)
    - the platform is tilted to ensure the pulling force acts perpendicularly to the robot pointing direction
    - the test is repeated with different robot bending angle
  - how to measure the force?
    - type and name of the sensors
  - how to measure the displacement?
    - EM tracking system?
    - Image analysis system?
  - conditions
    - actuation of 1 chamber
    - actuation of 2 chambers
    - different preloaded pressure
    -
- stiffer robot requires larger forces to displace the tip
- Assessment of the stiffness - ratio: $\frac{\text{pulling force}}{\text{tip displacement}}$
  1) min. force required to move the tip
  2) displacement of the tip when accelerating a biopsy forceps (or a catheter) inserted in the central channel
- 2 result figures
  1) force vs preloaded pressure
     - several curves for different chamber pressure
  2) displacement of the tip vs acceleration of the inserted instrument
- expected results
  - for 1)
    - larger force will be required when larger pressure is preloaded
    - at the same prelaoded pressure but with different chamber pressure, the values of the force required would be similar. Since a chamber pressure = a curvature ratio, we will similar stiffness for various curvature ratio.
  - for 2)
    - Two increasing slopes will be observed.
    - more gentle slope before a certain value of the acceleration, the tip displacement will be insignificant.
    - A steeper slope after the value of acceleration.

C. Dynamic response

- Fig. 9. Dynamic responses
- experiment settings
  1) for step response and frequency response:

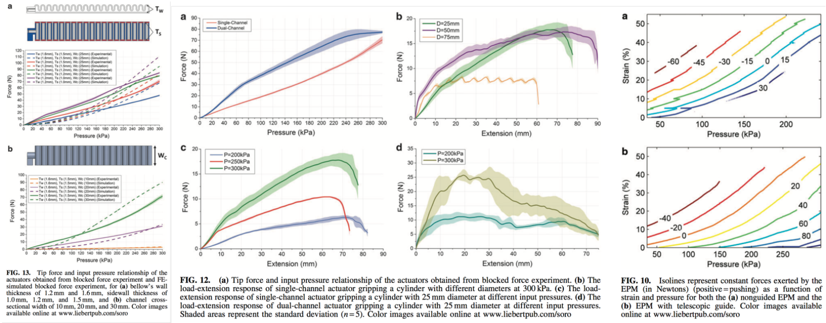

Fig. 9. Dynamic response analysis. (a) The relationship of the tip force output and chamber pressure, for different preloaded pressure . (The tip force is measured while constraining the robot at 0 bending angle) Kinematics histories of the (b) step responses and (c) frequency responses of the robot.

        - the same setting as the bending test in section III-A
        - giving step input and sine input for the chamber pressure instead
    2) for tip force output
        - the same setting as the stiffness test in section III-B
        - not pull the tip, but giving pressure to the robot instead
        - measure the force at the tip
        - the force is perpendicular to the tip's pointing direction
- actuation condition
    - 1 chamber actuation
    - 2 chambers actuation
    - different preloaded pressure
    -
- assessment of the dynamic response
    1) tip force output
    2) step response - typical performance indexes
        - e.g. rise time
        - e.g. transient response
        - e.g. overshoot
    3) frequency response - typical performance indexes
        - frequency response plots
- result figures
    1) tip force vs preloaded pressure
        - several curves for different chamber pressure (i.e. curvature ratio)
    2) time history of the tip displacement
        - several curves for different preloaded pressure (i.e. curvature ratio)
    3) frequency response plots
        - amplitude vs frequency
        - phase vs frequency
- expected results
    -

D. Performance Limits

- Fig. 10. Prototype limits
- experiment settings
    - increase the chamber pressure up to the maximum bending angle
    - measure the boundary curvature ratio
    - measure the tip force output
    - measure the life cycle
- condition
    - actuation of 1 chamber

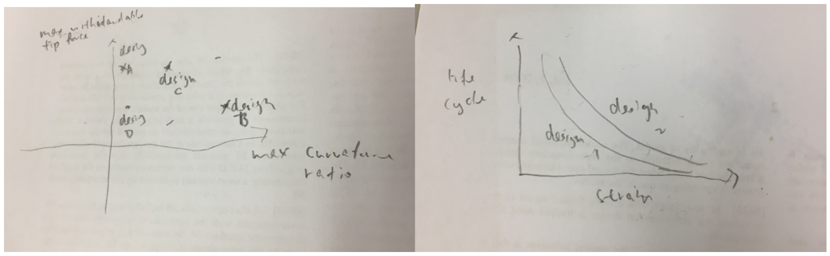

Fig. 10. Performance limits of the prototype for different preloaded pressure . (a) Stiffness vs max. curvature ratio. (b) Life cycle.

- actuation of 2 chambers
- different preloaded pressure
-
- run until failure

- Assessment of the performance limits
  1) The maximum curvature achieved
     - curvature ratio of different preloaded pressure
     - can reuse/interpret the data obtained in the bending experiment in section III-A
     -
  2) The maximum stiffness achieved
     - define stiffness index = ratio: $\frac{\text{pulling force}}{\text{tip displacement}}$
     - stiffness of different preloaded pressure
     - can reuse/interpret the data obtained in the bending experiment in section III-B
     -
  3) life cycle
     - life cycle for different preloaded pressure
       * 2 chamber actuated
- result figures
  1) max. curvature ratio vs max. stiffness
     - each point represents the value of a specific preloaded pressure
  2) life cycle
     - life cycle vs curvature ratio (˜strain)
       * several curves for different preloaded pressure
- expected results
  - for 1) lower preloaded pressure will have lower stiffness and curvature ratio
  - for 2) using lower pressure will have longer life

E. Discussion

- Fig. 11. Demonstration of basic endoscopic procedure

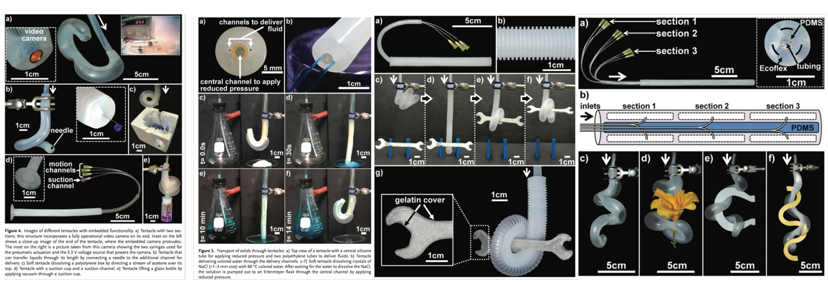

Fig. 11. Basic functions of the prototype. (a) Endoscopic view when performing a biopsy task inside a phantom model. (b) Suction and (c) Irrigation of colored liquid. The demonstrations can also be found in the provided videos.

- Demonstrate the robot can perform basic functions for endoscopy
  - endoscopic view

  - the use of working channel
    * instruments such as biopsy forceps
    * suction and irrigation
  - the first soft continuum robot that demonstrates such basic functions
    * [1] demonstrated the use of camera through the working channel
  - Fig. 11
- Discuss about the proposed FEM methods for design optimization
  - can approximate the bending behavior and dynamic response
  - simulate the effects of the internal tubings
    * buckling
- Discuss about the high stiffness and output force
  - advantages of having such high stiffness and output force
  - potential applications, not limited to endoscopic interventions
- Discuss about the performance limits

$$\mathbf{v}\boldsymbol{\alpha}\frac{1}{2} \tag{1}$$

IV. Conclusion

- summary
- future work

References

[1] R. V. Martinez, J. L. Branch, C. R. Fish, L. Jin, R. F. Shepherd, R. M. D. Nunes, Z. Suo, and G. M. Whitesides, "Robotic tentacles with three-dimensional mobility based on flexible elastomers," *Advanced Materials*, vol. 25, no. 2, p. 205212, Sep 2012. [Online]. Available: http://dx.doi.org/10.1002/adma.201203002

[2] H. K. Yap, H. Y. Ng, and C.-H. Yeow, "High-force soft printable pneumatics for soft robotic applications," *Soft Robotics*, vol. 3, no. 3, p. 144158, Sep 2016. [Online]. Available: http://dx.doi.org/10.1089/soro.2016.0030