Visual Servo Control of Cable-driven Soft Robotic Manipulator

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Outline

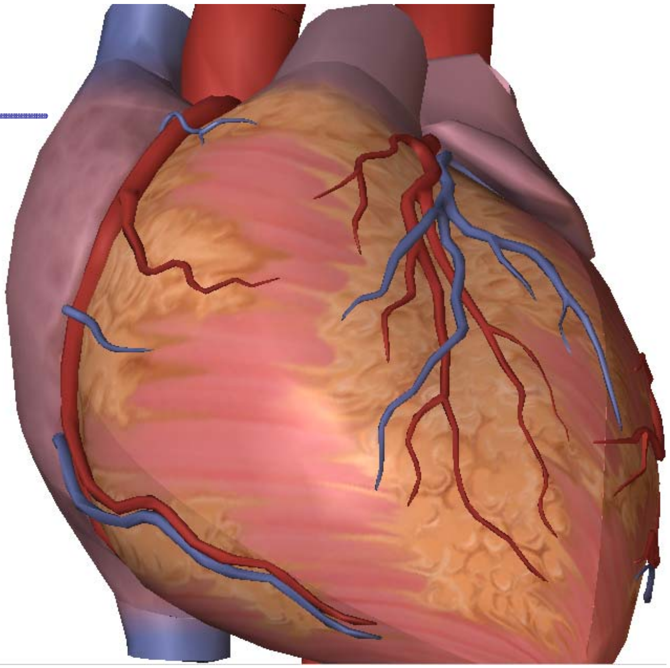
- Introduction
- Background
- System Design
- Kinematics
- Controller Design
- Experimental results
- Conclusion

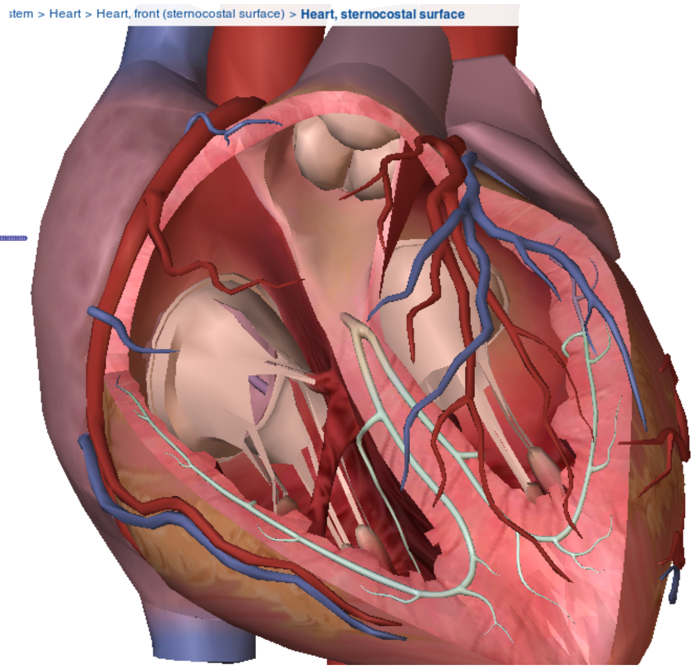
Background

Minimally Invasive Surgery (MIS)

On the surface of the beating heart

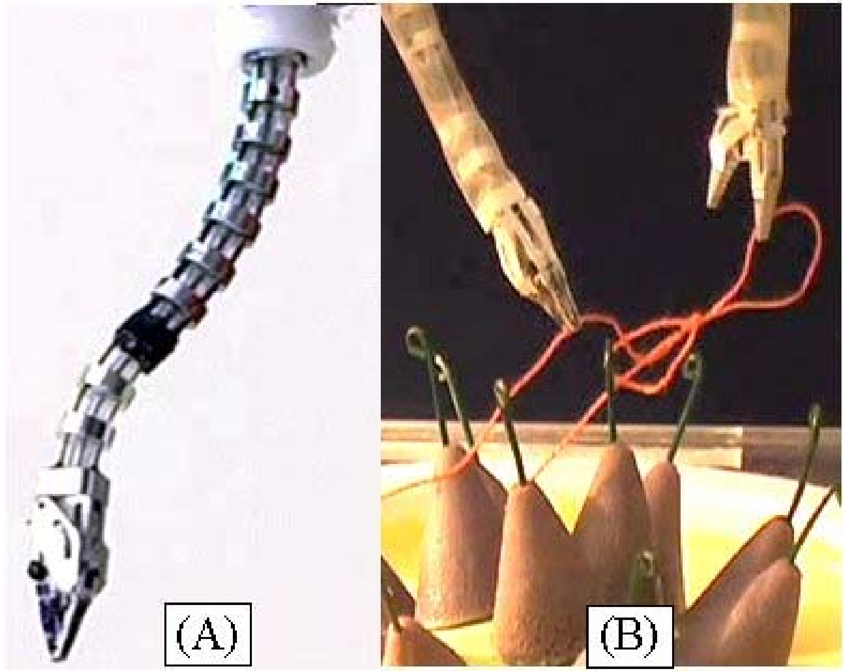
Inside the beating heart



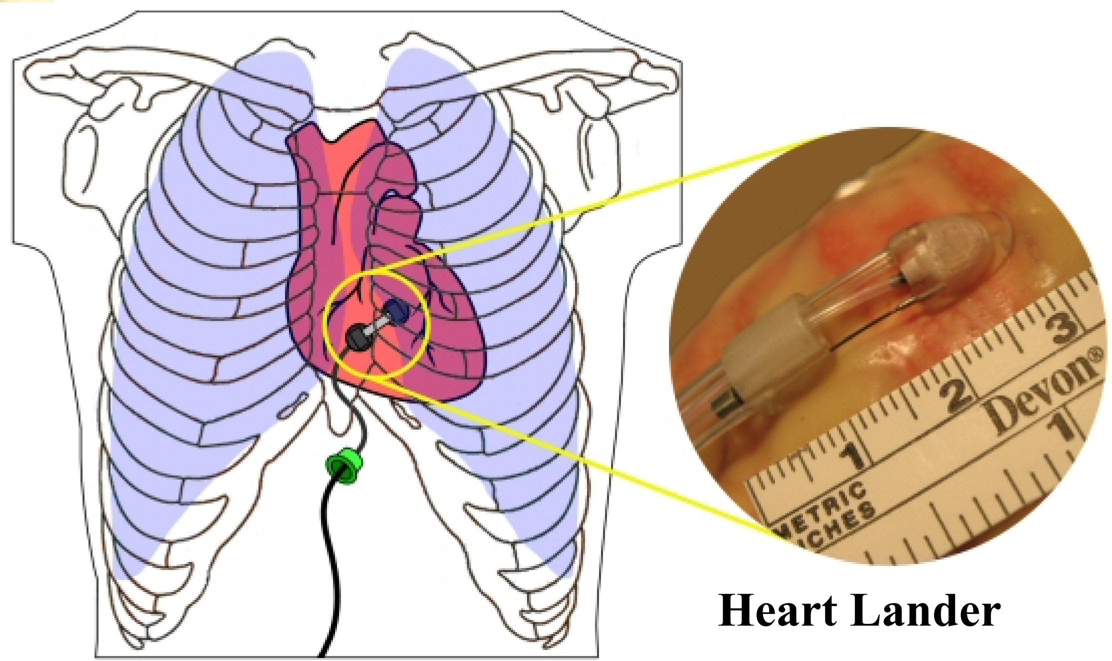


Background

HARP



Concentric Tube Robot



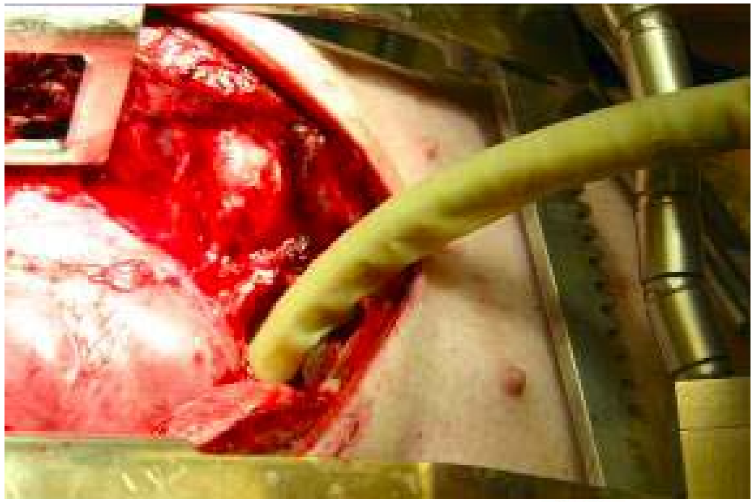
Heart Lander

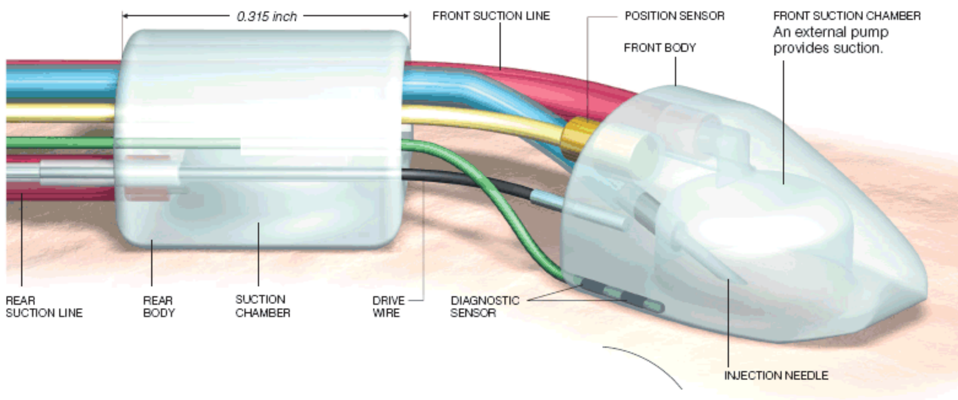
Background

Not Soft Enough

Not Safe Enough

Not Practical Enough





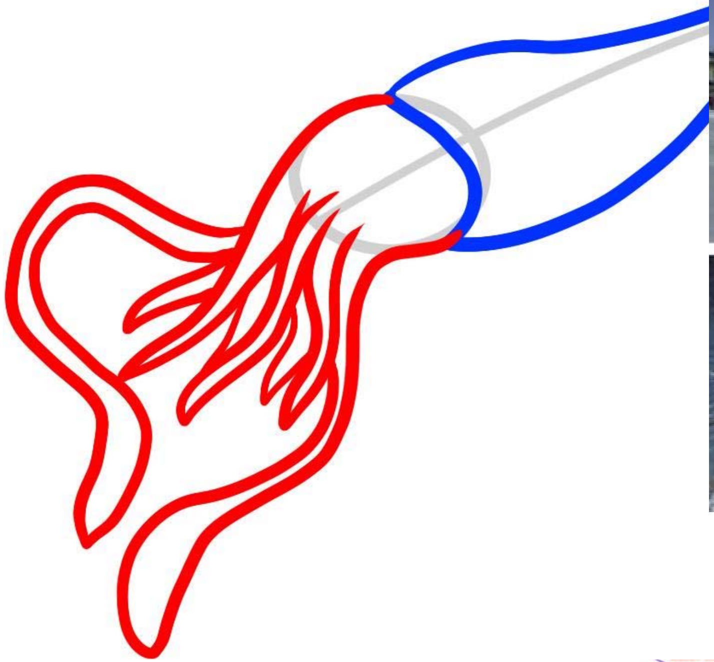
Background

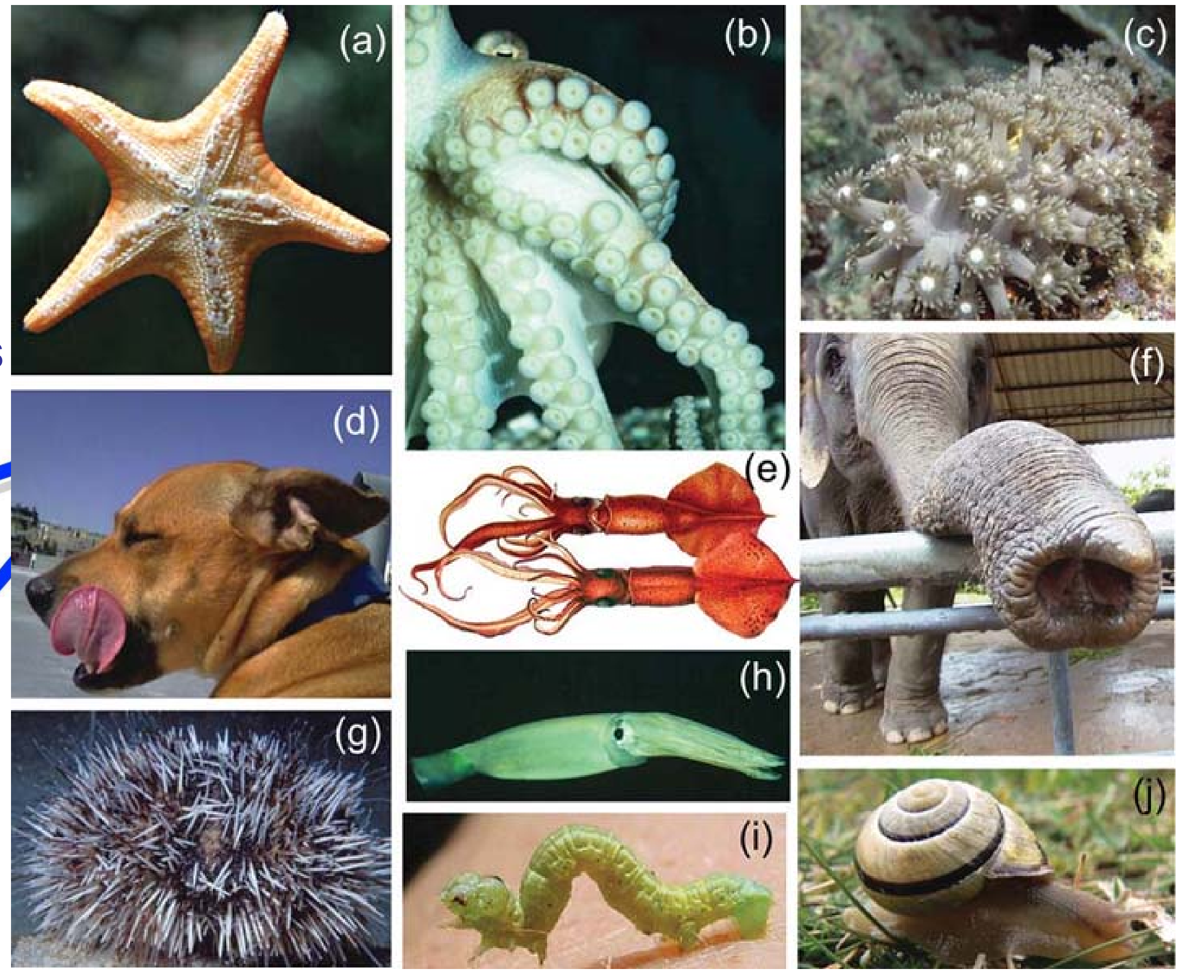
“Soft” robotic systems

-Conform to the surroundings

-Ease of operation

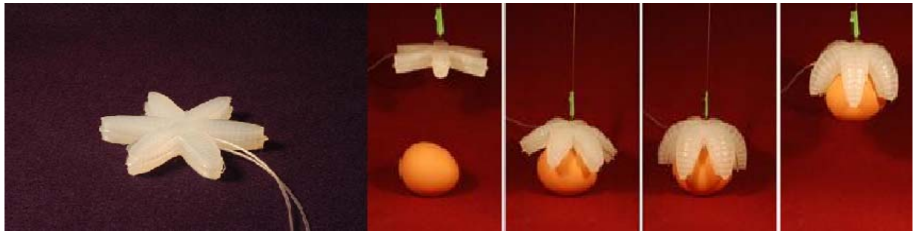
-”Fit” to Dynamic environments





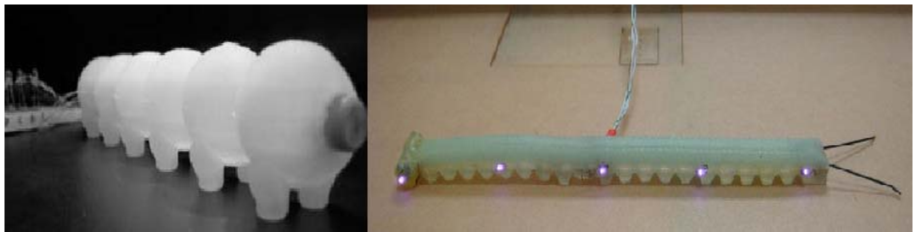
Research Background

- Soft robots: material, manufacturing, Control Theory, computer simulation
- Applications: minimally invasive surgery, military, exploration, rescue...



（1） Starfish robot

（2）Quadruped deformable robot



（3） Caterpillar robot

（4）Mechanical octopus tentacle

Characters of soft robot

Characters	Rigid robots	Redundant robot	Hard continuum robot	Soft robot
DOF	Small	Many	Infinite	**Infinite**
Material strain	None	None	Low	**High**
Accuracy	Very High	High	High	**Low**
Safety	Low	Low	Medium	**High**
Flexibility	Low	High	High	**High**
Compatibility with obstacles	None	Good	Medium	**Very good**
Controllability	Easy	Medium	Hard	**Hard**
Positioning	Easy	Medium	Hard	**Hard**

System Design

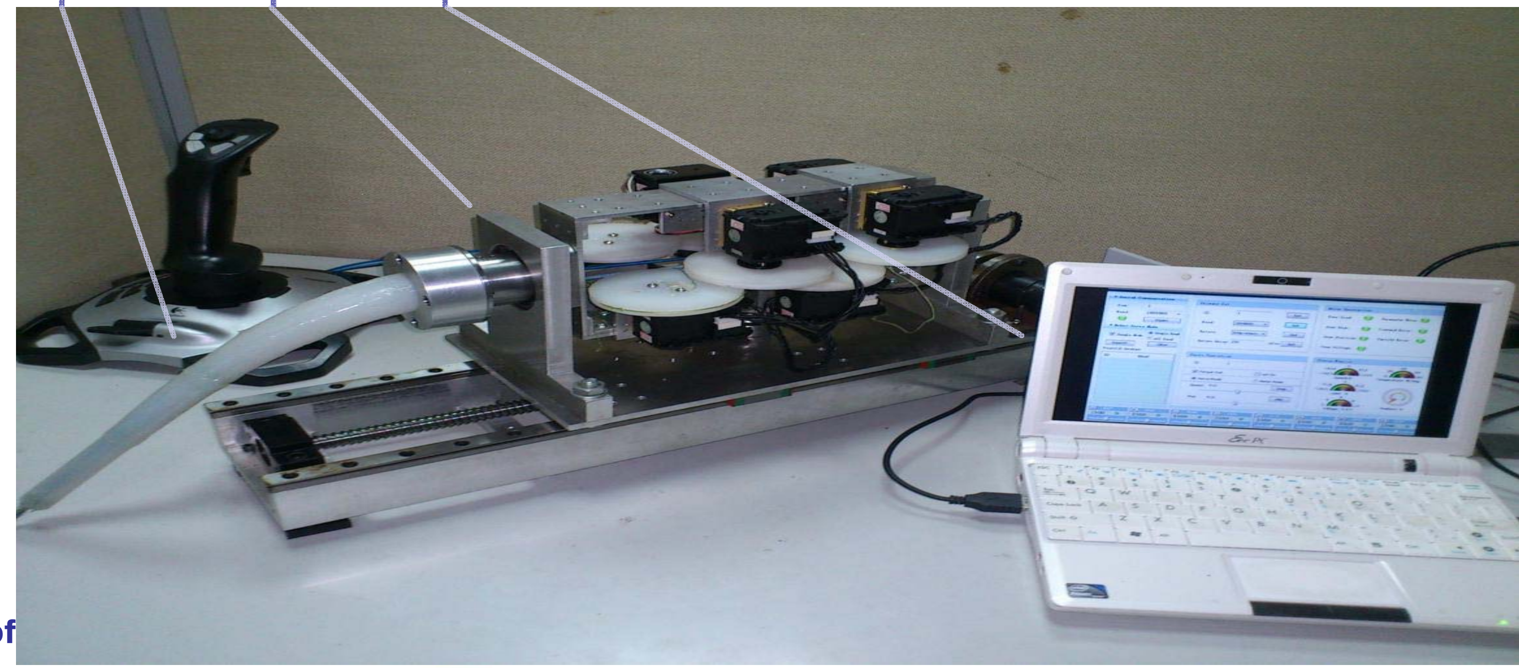
Soft Robotic Manipulator

- Kinematics - hyper-redundancy

System Design

System Composition

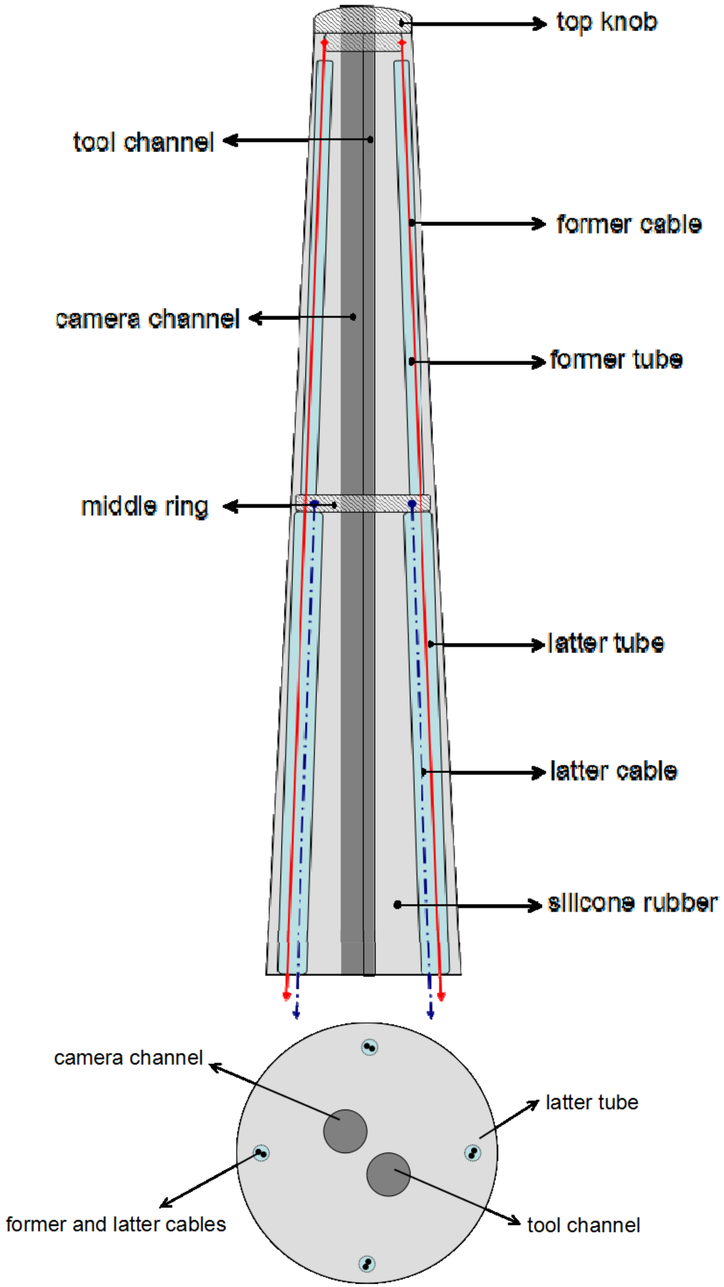
- A soft manipulator
- A drive base frame
- Control and display system



System Design

The Soft Manipulator

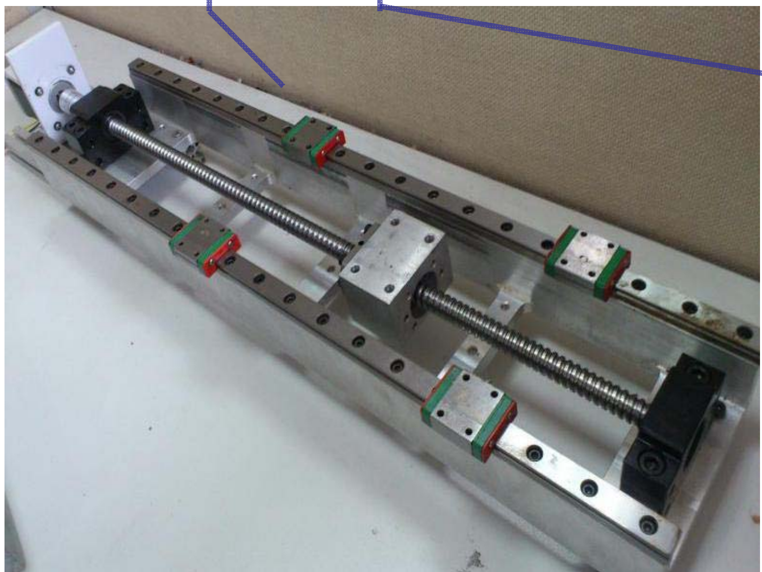
- 30mm
- silicone rubber (ECOFLEX™)
- 8 non-abrasive fiber cables (DyneemaTM)
- plastic caps
- ablation tools and a micro CCD camera

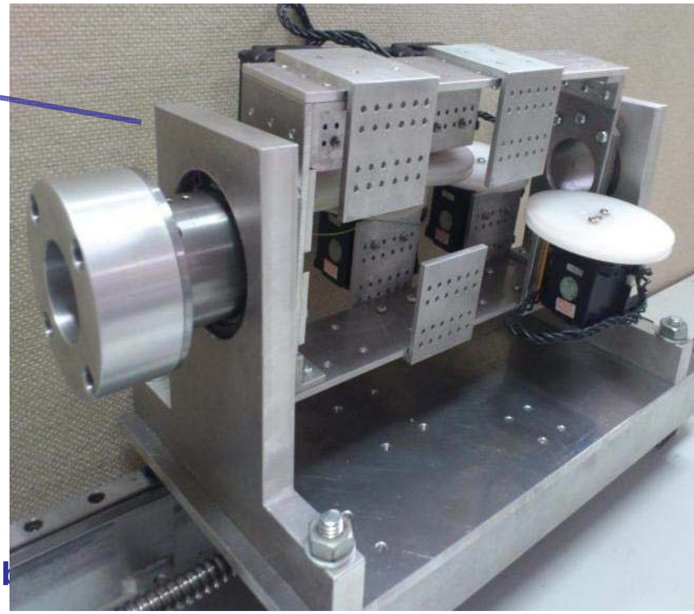


System Design

The Drive Base Frame

- Linear motion system
- Rotational motion system

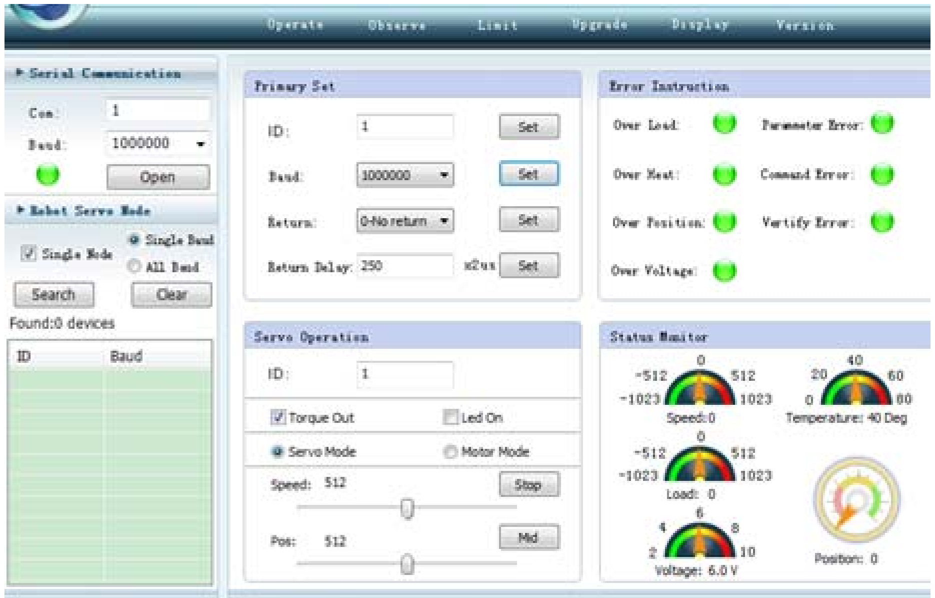




System Design

Control and Display System

- Joystick Control
  - Cameral Display
    - Control Software



System Manipulation

Manipulate method

Manual Mode

- The cable tension can be changed by setting the Head angle
- Adding functional buttons
  - functional buttons for each behavior
  - buttons for selecting which cables are being controlled
  - buttons for emergency

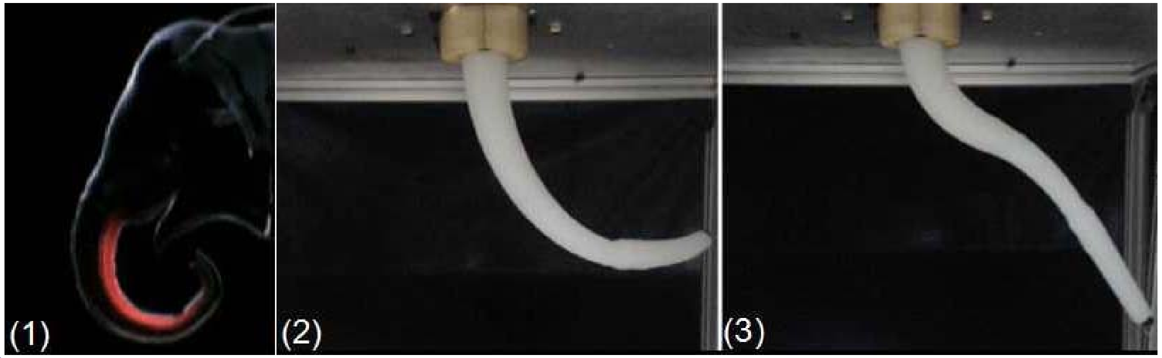
Automatic Mode

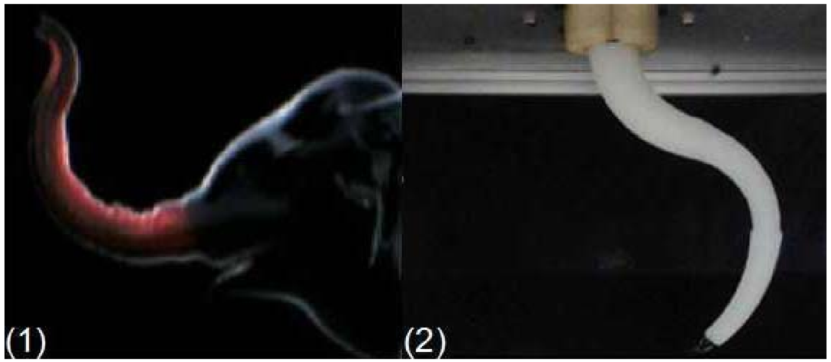
- Path planning & Localization on the surface of the heart

System Manipulation

Behavior Implementation

1. Blending
2. Contracting
3. Advancing/Retreating
4. Wriggling
5. Blending and Wriggling partly
6. S shape





Movie 5

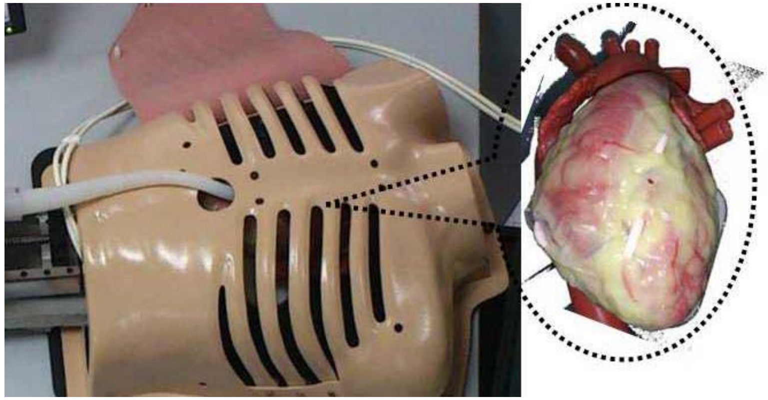
Experiments

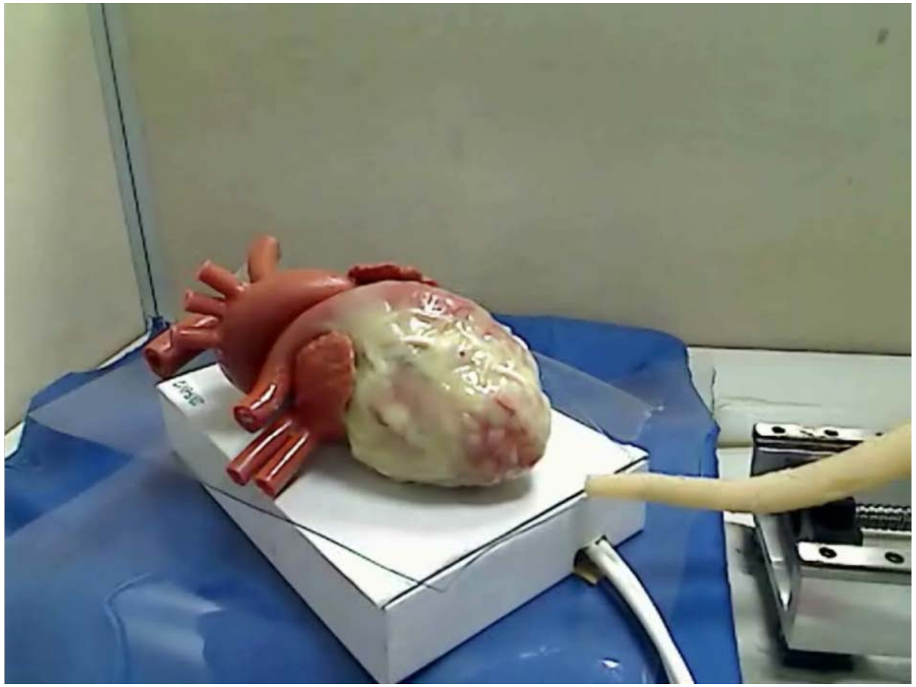
Unconstrained Environment

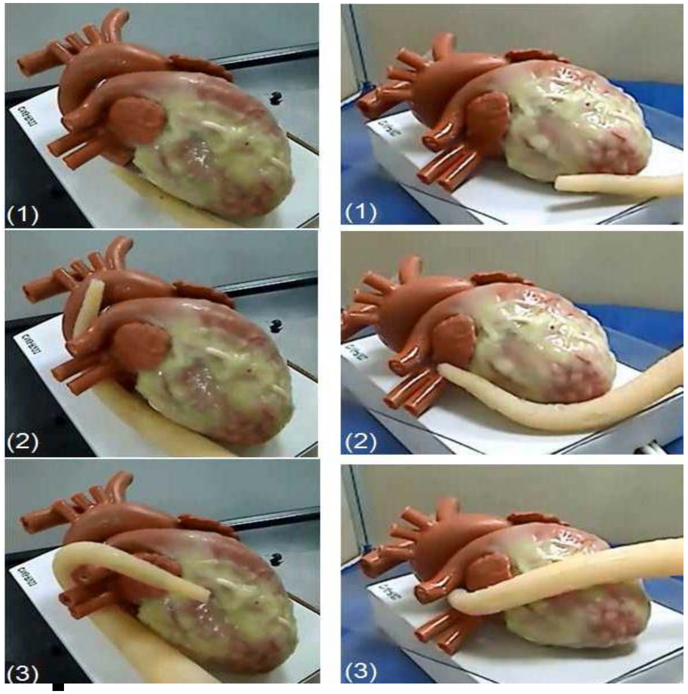
-with a plastic thorax and a silicone heart

-different simulated paths on the surface

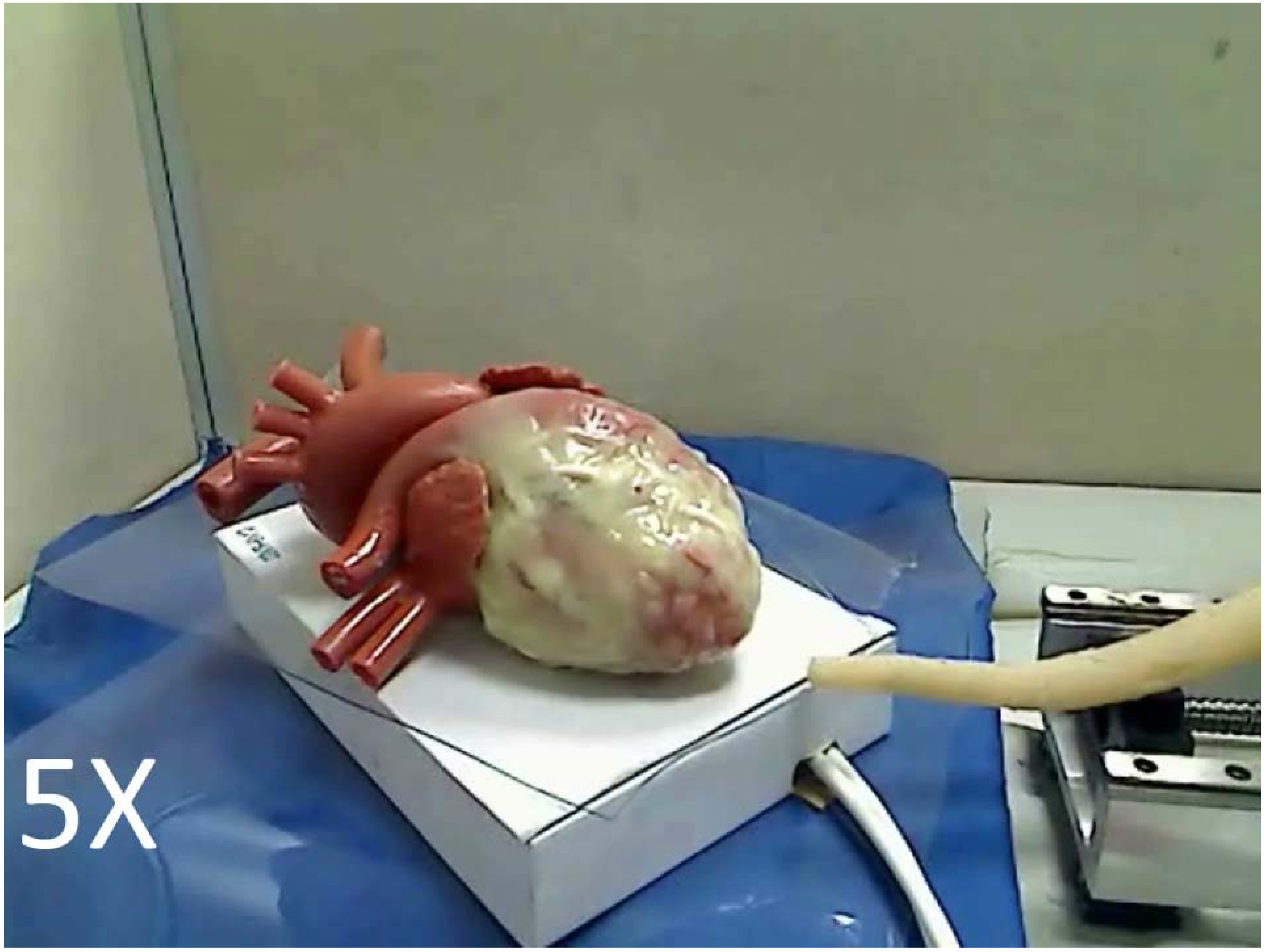
-to identify the geometrical shape and flexibility







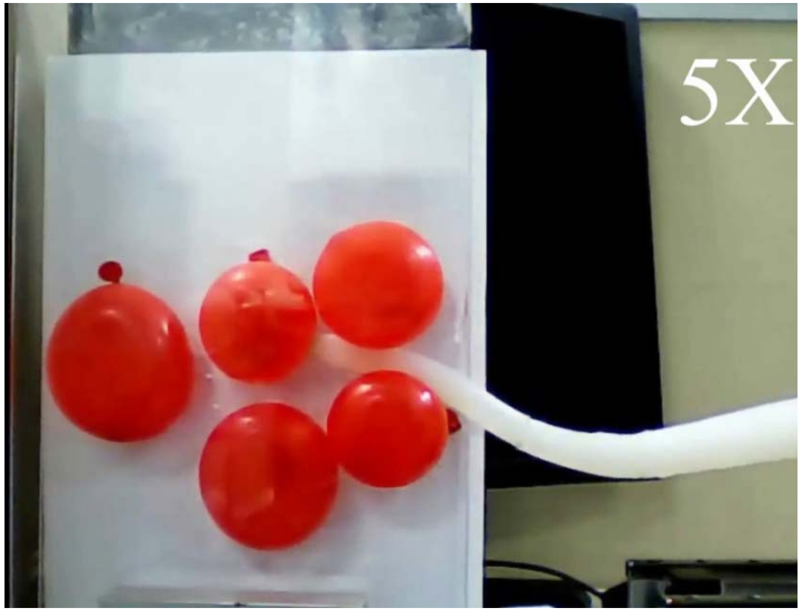
Experiment Video

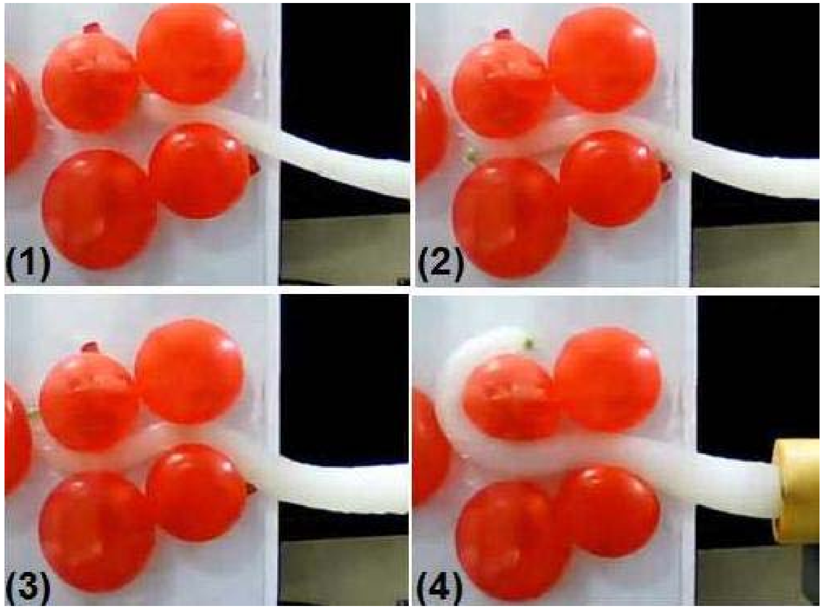


Experiments

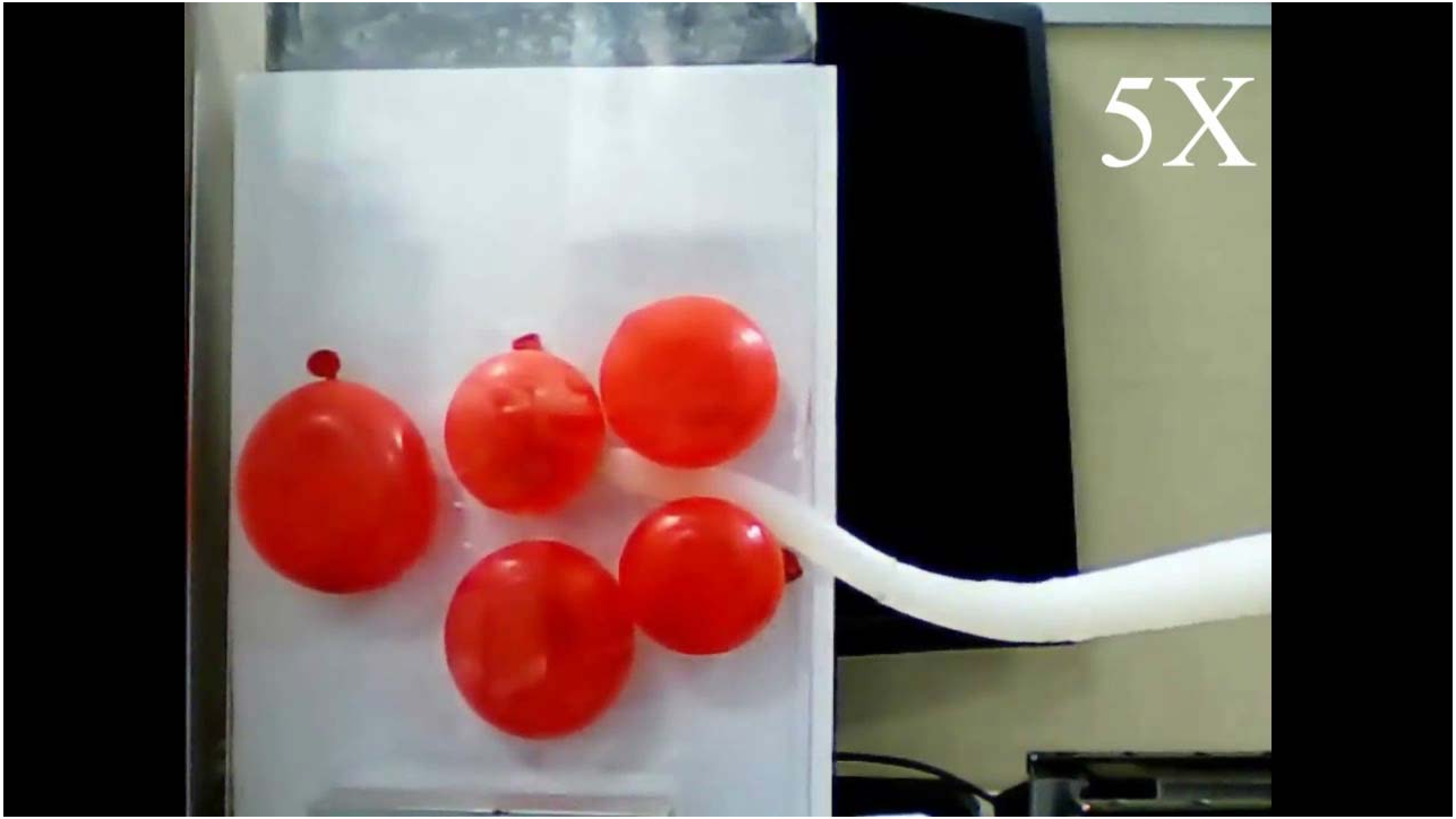
Limited Environment

- made of balloons to imitate the human tissue
- complicated path to guide the soft probe
- effects of the gravity and surroundings



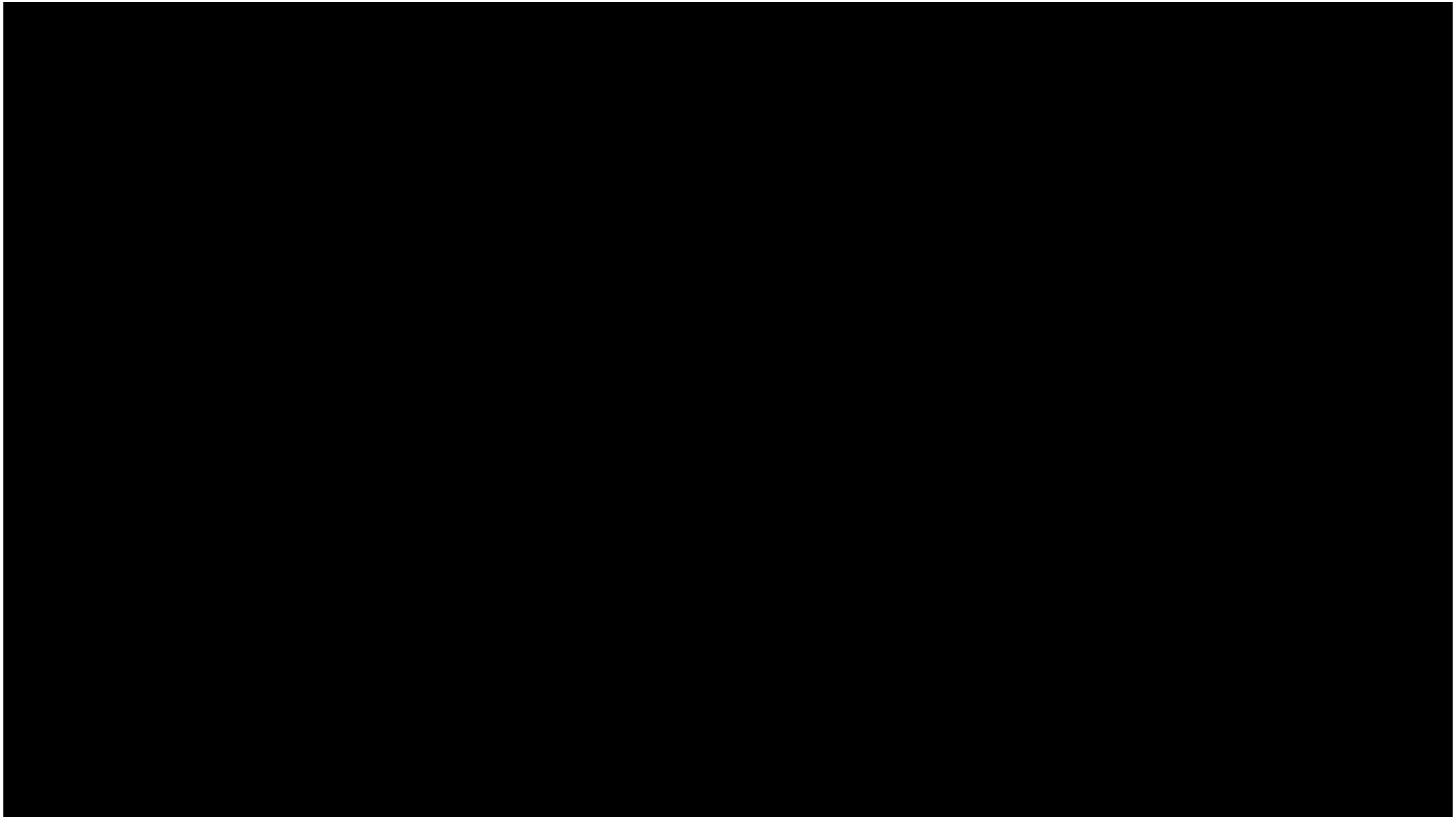


Experiment Video 2



Experiment Video 3

Experiment Video 4



System Manipulation

KEY ISSUES

- Kinematics Modeling

- Influence of gravity

- Influence of Surroundings Environment

- Dynamics Modeling

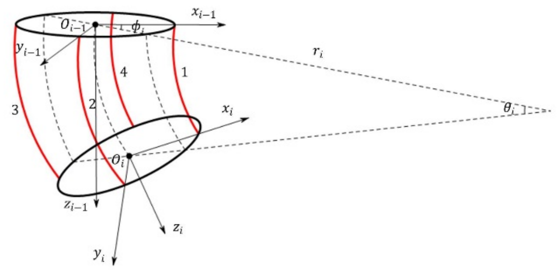
- Modeling Method

- Calculation efficiency

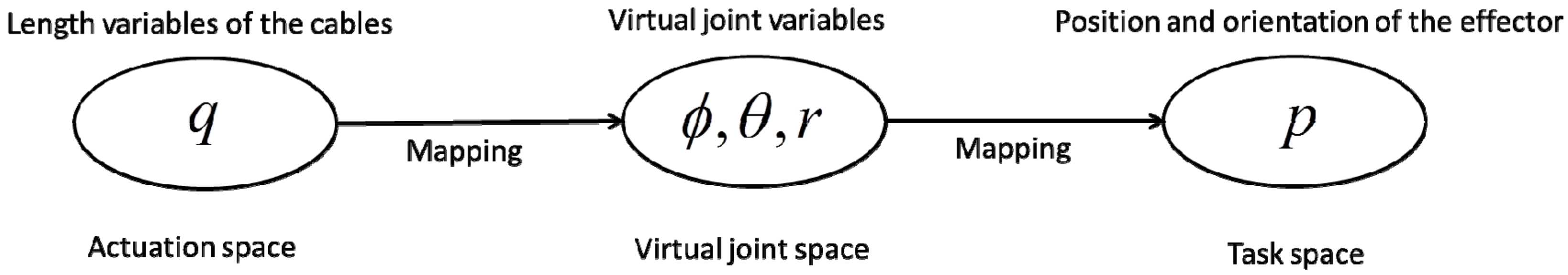
- Controller

Constant curvature hypothesis

Constant curvature hypothesis :dividing the whole body of the soft robotic manipulator into n segments, and each segment can be treated as a cylinder that the radius of section is constant



three spaces and two mappings



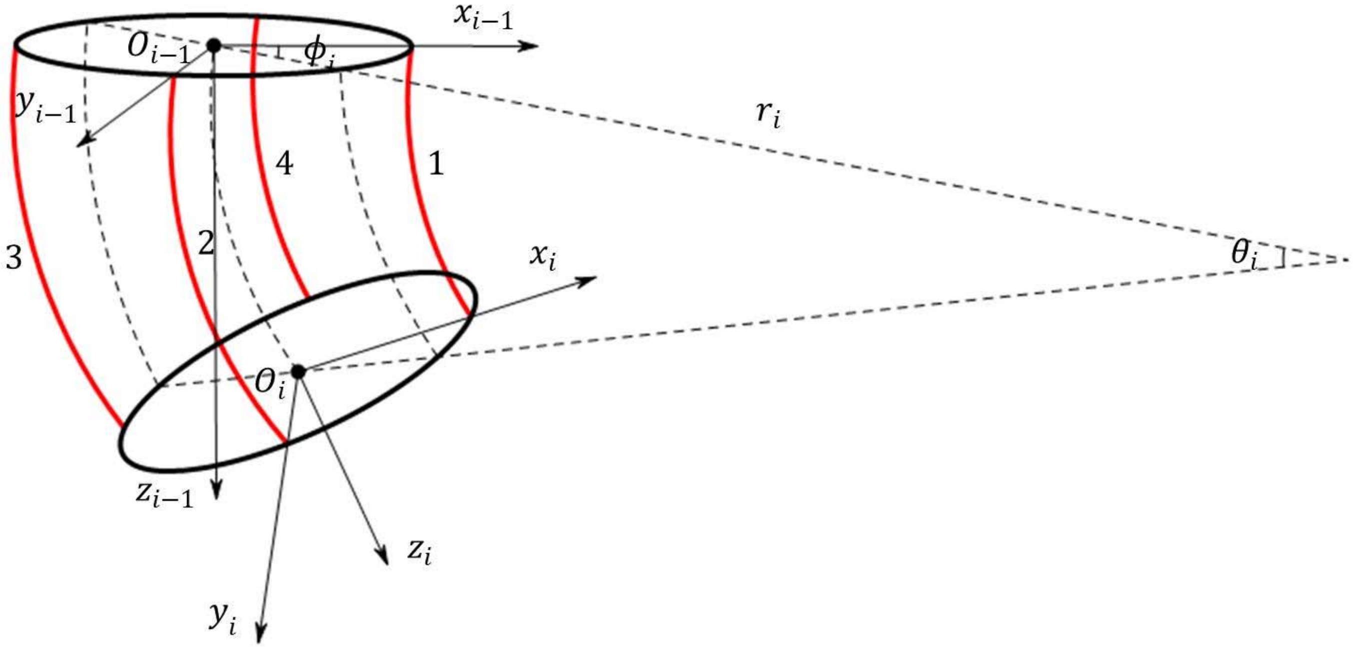
ϕ *denotes the angle between the bending plane and the positive direction of x axis,*

θ *denote the curvature angle of the bending plane respectively.*

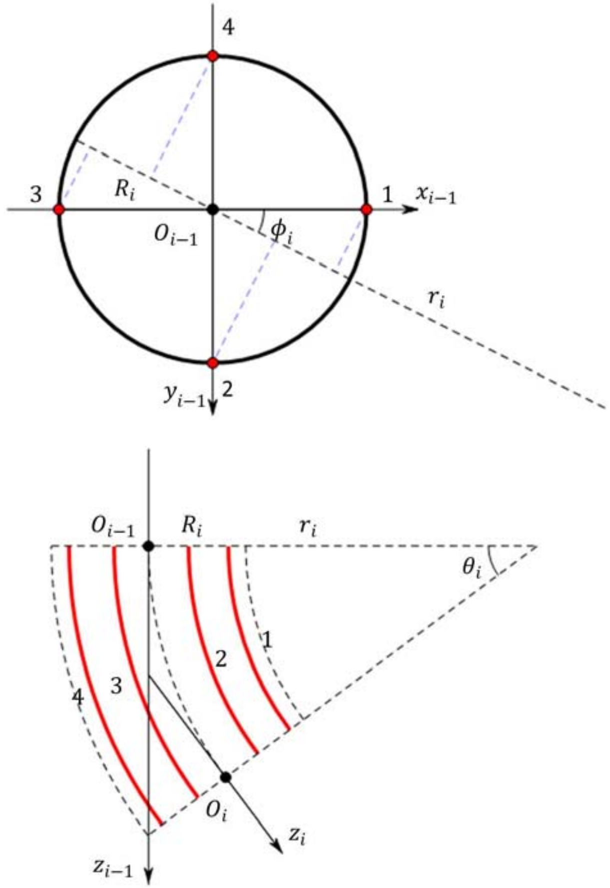
r *denote the curvature radius of the bending plane respectively.*

Kinematics

- For i-th segment
  - the length variables of 4 cables: q_1, q_2, q_3, q_4
  - the current length of 4 cables: $\frac{l_1}{n}, \frac{l_2}{n}, \frac{l_3}{n}, \frac{l_4}{n}$
  - the central axis of the i-th segment $\frac{l}{n}$



Actuation space - Virtual joint space

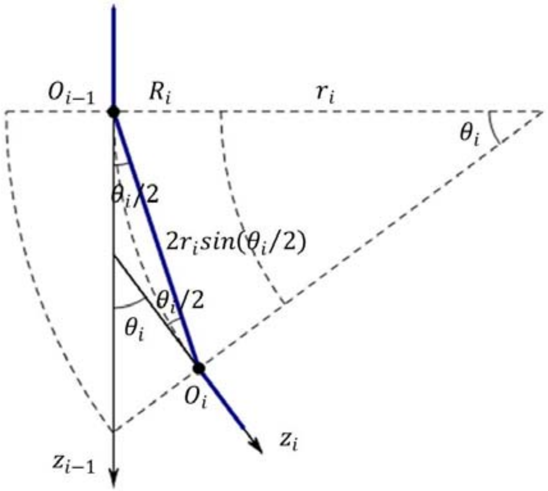


$$\phi_i = \tan^{-1} \frac{q_4 - q_2}{q_3 - q_1}$$

$$\theta_i = \frac{\sqrt{(q_3 - q_1)^2 + (q_4 - q_2)^2}}{2nR_i}$$

$$r_i = \frac{2(L - q)R_i}{\sqrt{(q_3 - q_1)^2 + (q_4 - q_2)^2}}$$

Virtual joint space – Task space



$$
{}^{i-1}T_i = A_{i1}A_{i2}A_{i3}A_{i4}A_{i5}
$$

$$
= \begin{bmatrix} c^2\phi_i\left(c\theta_i - 1\right) + 1 & s\phi_i c\phi_i\left(c\theta_i - 1\right) & c\phi_i s\theta_i & r_i c\phi_i\left(1 - c\phi_i\right) \\ s\phi_i c\phi_i\left(c\theta_i - 1\right) & s^2\phi_i\left(c\theta_i - 1\right) + 1 & s\phi_i s\theta_i & r_i s\phi_i\left(1 - c\phi_i\right) \\ -c\phi_i s\theta_i & -s\phi_i s\theta_i & c\theta_i & r_i s\theta_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
T = {}^0T_1\,{}^1T_2 \cdots {}^{i-1}T_i
$$

Perspective Projection

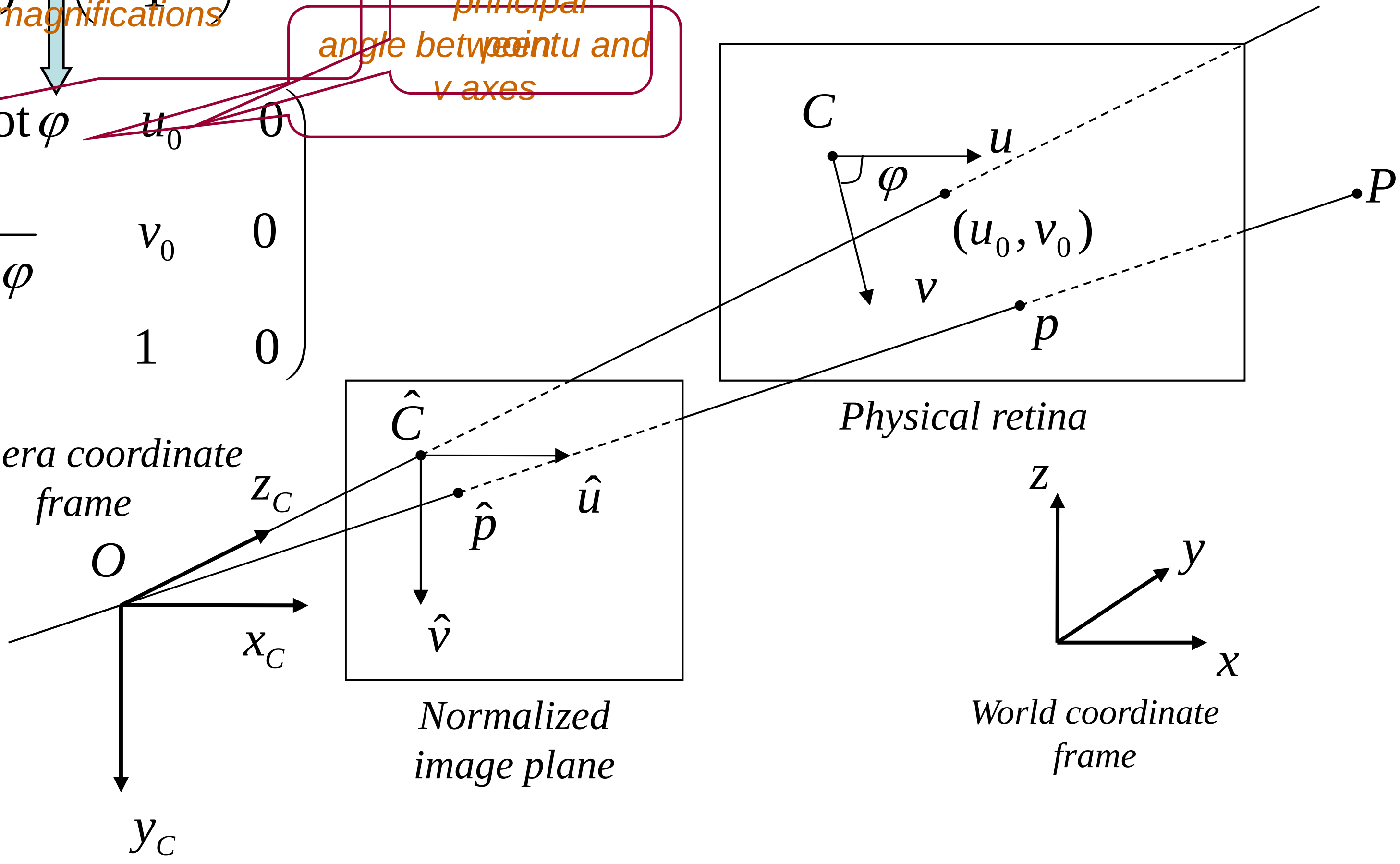
$$\begin{pmatrix} u(t) \\ v(t) \\ 1 \end{pmatrix} = \frac{1}{{}^{c}z(t)} \mathbf{\Pi} \begin{pmatrix} {}^{c}\mathbf{x}(t) \\ 1 \end{pmatrix}$$

the magnifications

principal point

angle between u and v axes

$$\mathbf{\Pi} = \begin{pmatrix} \alpha & -\alpha\cot\varphi & u_0 & 0 \\ 0 & \dfrac{\gamma}{\sin\varphi} & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$



Projection Model

– the projection of the feature point on the image plane

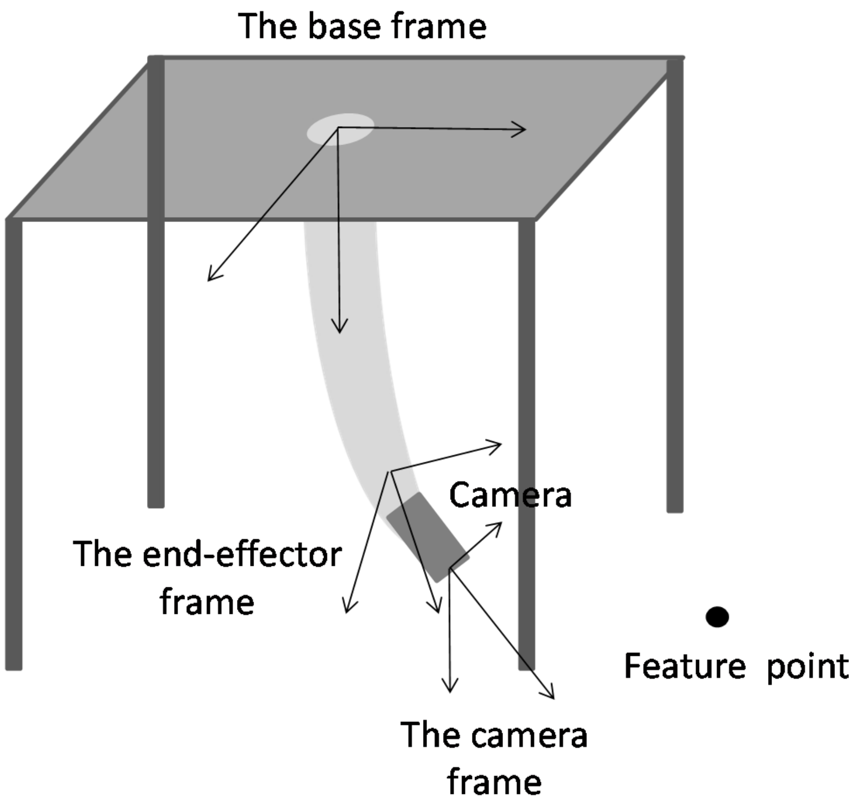
$$y(q(t)) = \frac{1}{z(q(t))} P \begin{bmatrix} {}^{e}x(t) \\ 1 \end{bmatrix}$$

$$z(q(t)) = m_3^{\ T} \begin{bmatrix} {}^{e}x(t) \\ 1 \end{bmatrix}$$

– Interaction matrix

$$\dot{y}(q(t)) = \frac{1}{z(q(t))} A(y(t), q(t)) \begin{bmatrix} v(t) \\ w(t) \end{bmatrix}$$

$$\dot{z}(q(t)) = b(q(t)) \begin{bmatrix} v(t) \\ w(t) \end{bmatrix}$$



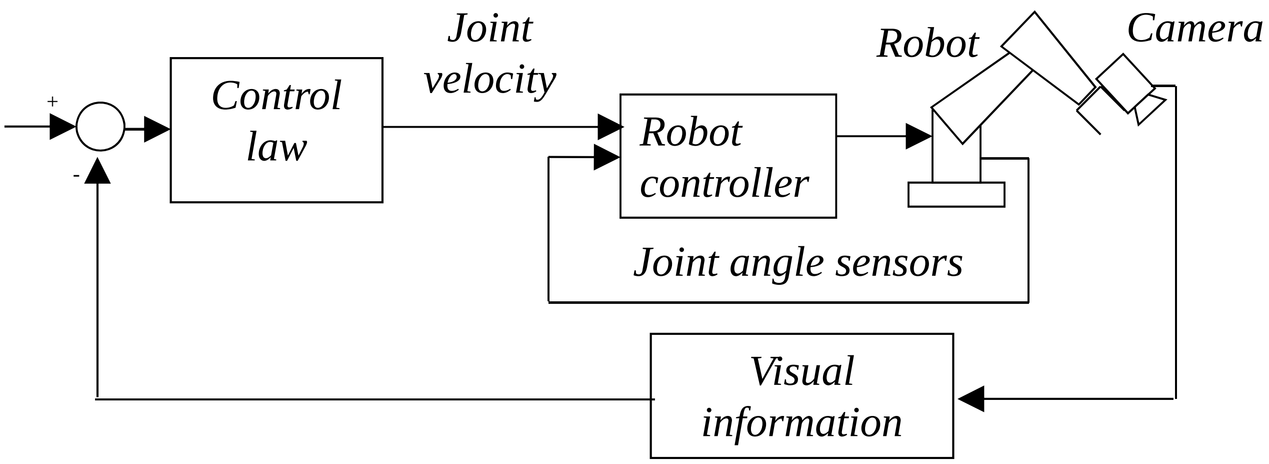
Property 1

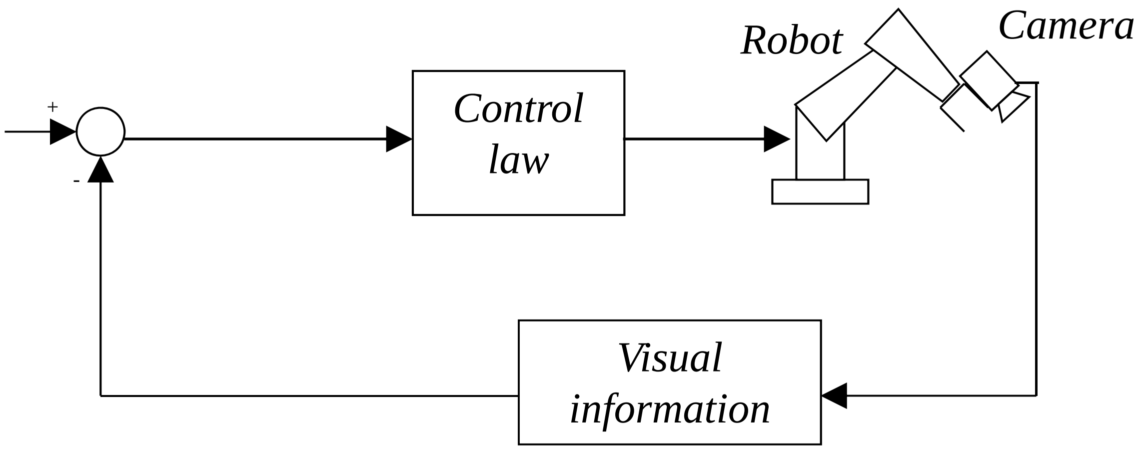
For any homogenous vector $\boldsymbol{\rho}$ *, the* $\mathbf{A}(t)\boldsymbol{\rho}$ *product can be written in the following form:*

$$\mathbf{A}(t)\boldsymbol{\rho} = \mathbf{Q}(\boldsymbol{\rho}, \mathbf{y}(t))\boldsymbol{\theta} + \boldsymbol{\sigma}$$

where $\mathbf{Q}(\boldsymbol{\rho}, \mathbf{y}(t))$ *is a regressor matrix without depending on the unknown parameters.*

Kinematic-based and Dyanmic Visual Servoing





Kinematic-based Visual Servoing

– Kinematic-based controller

$$\dot{q}(t) = -J^T(q(t))\hat{A}^T(y(t), q(t))K_1\Delta y(t) - \frac{1}{2}J^T(q(t))\hat{b}^T(q(t))\Delta y^T(t)K_1\Delta y(t)$$

– Adaptive law

$${}^b\dot{\hat{x}}(t) = -\Gamma^{-1}Y^T(y(t), q(t))\dot{q}(t)$$

Stability analysis

- Applying the image-based visual servo controller and adaptive algorithm, it can be proved that the position error of the feature point on the image plane will be convergent to zero when time approaches to the infinity

$$\lim_{t\to\infty} \Delta y(t) = 0$$

- a Lyapunov-like function is defined as follows:

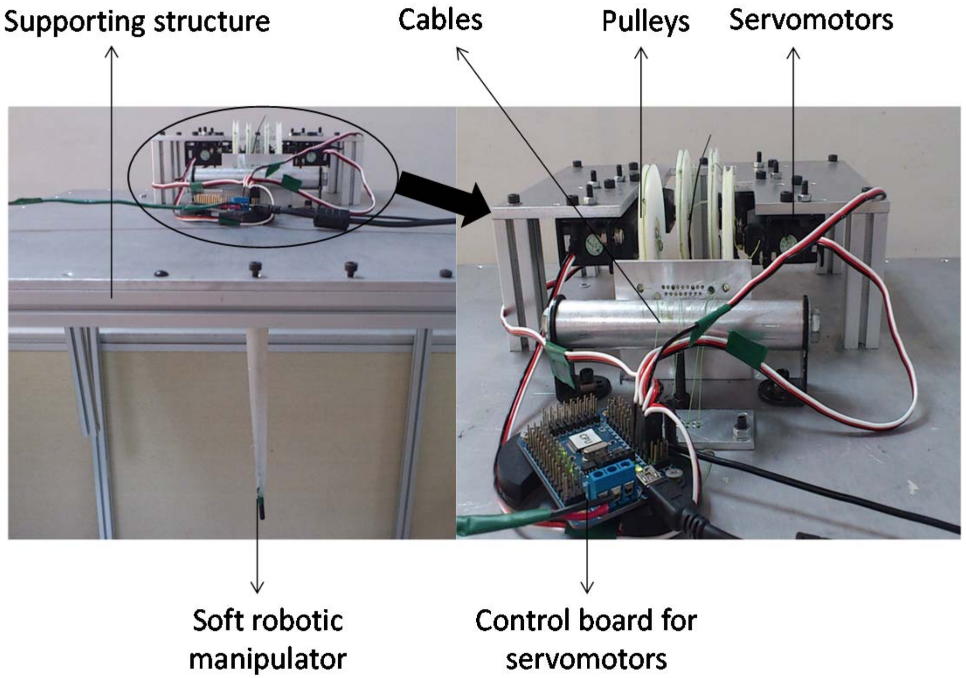
$$V(t) = \frac{1}{2}\Delta y^T(t) K_1 z(q(t)) \Delta y(t) + \frac{1}{2}\Delta^b x^T(t) \Gamma \Delta^b x(t)$$

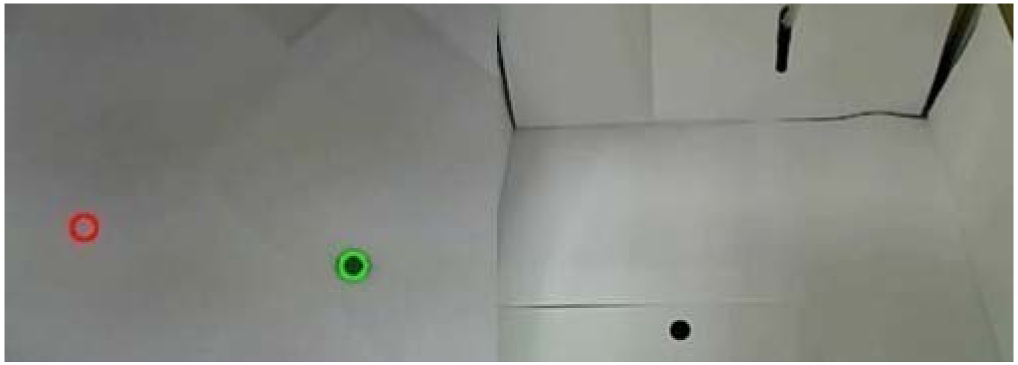
- Finally

$$\dot{V}(t) = -\Delta y^T(t) \hat{D}^T(y(t), q(t)) J K_1^2 J^T \hat{D}(y(t), q(t)) \Delta y(t)$$

- By Babarrat's Lemma, the stability could be proved.

Experimental system

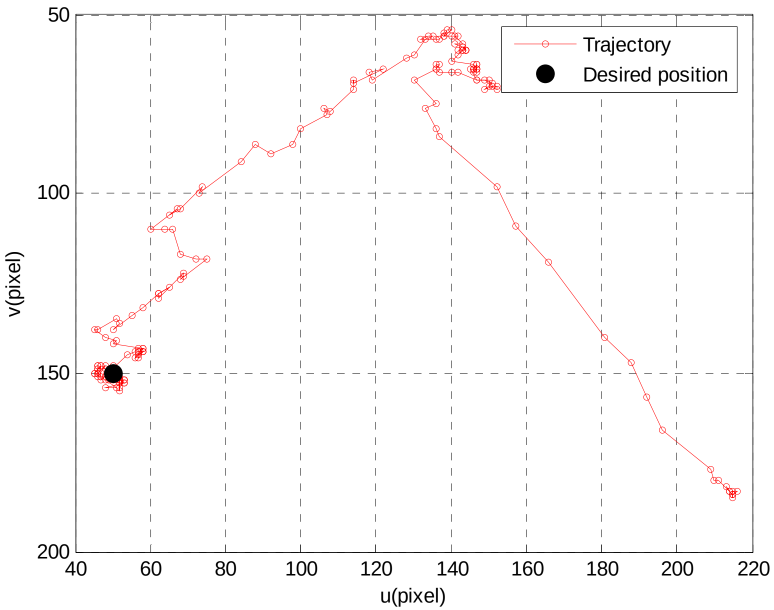




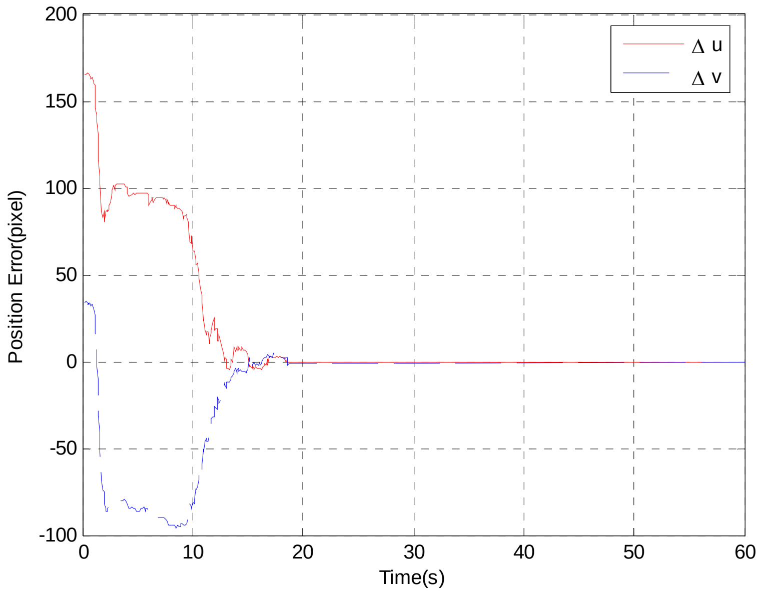
Experimental results

Experimental Results

- Initial position: $y(0)=(208,166)^T$
- Desired position: $y_d=(50,150)^T$
- Initial estimated feature 3D position: ${}^b x(0)=(0.0 \quad 0.0 \quad 0.62)^T$
- gains: $K_1=3.0\times10^{-6} \qquad \Gamma=100$



The trajectory of the feature point on the image plane.



The image errors between current position and desired position.

Conclusion and future work

- A cable-driven soft manipulator for cardiac ablation

  -completely made of soft materials

  -high degree of freedom

  -high flexibility
- A modified behavior-based control method is presented crowded pericardial environment
- A kinematic model of the soft robotic manipulator with the concept of piecewise constant curvature is presented.
- An adaptive controller for image-based visual servoing of the soft robotic manipulator is developed.
- The performances of the proposed method are verified by experiments on a soft robotic manipulator.
- Future work includes considering dynamic visual servoing and environment effects on the robot.

Thank you!

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2014 IEEE International Conference on Robotics and Biomimetics

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- Jun. 30, 2014 Submission of organized focused theme session proposals
- Sep. 15, 2014 Notification of paper and organized session acceptance
- Oct. 15, 2014 Submission of final papers and advance registration

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