Soft Robot Motion Simulation in 2D Vascular-mimicking Network

Team 8

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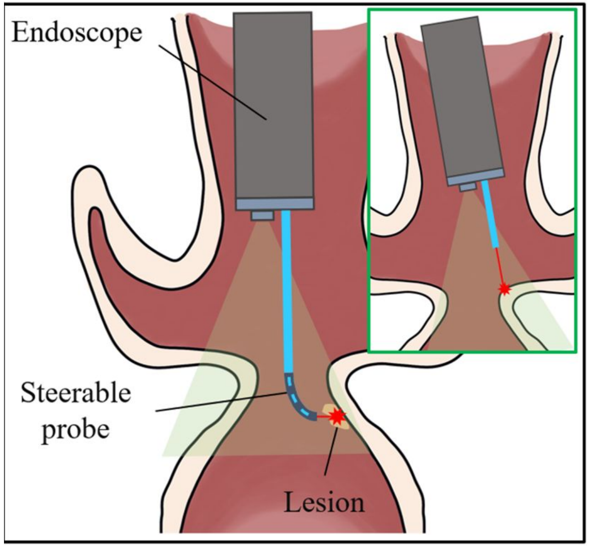
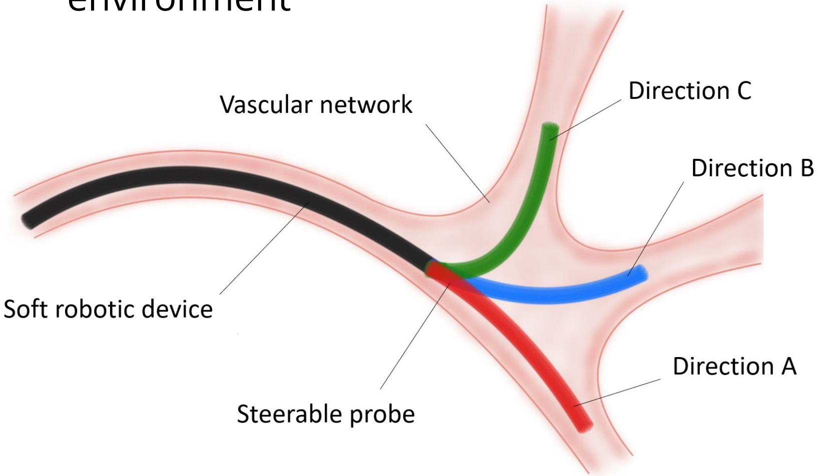
I: Introduction

- Soft robots in medical applications
  - Minimally Invasive surgery (MIS), endoscopic devices
  - Challenges: Limited accessible area



- Soft robots with steerable probe
  - Actuation: Tendon-drive, Magnet-drive
  - Unpredictable in real clinical procedure

- **Solution /Goal:** Simulation of soft robots with steerable probe navigating within complex environment



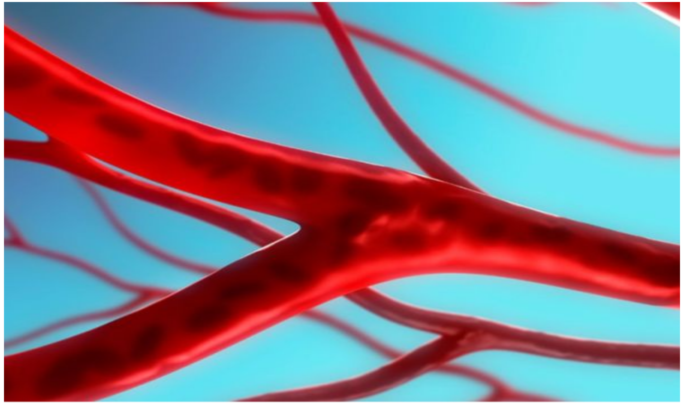
II: Design Method

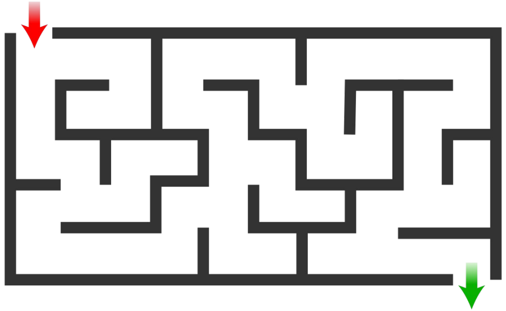
II: Design Method
Steps to Solve the Problem

1. Create 2D vascular mimicking environment
2. Robot Model Characterization
3. Controller Design
4. DER Calculation

II: Design Method
Vascular-mimicking Environment Model

- 2D Vascular-mimicking Environment
- Starting point to desired end point
- Square Maze (90 degree bending angle)





II: Design Method
Soft Continuum Robot Model

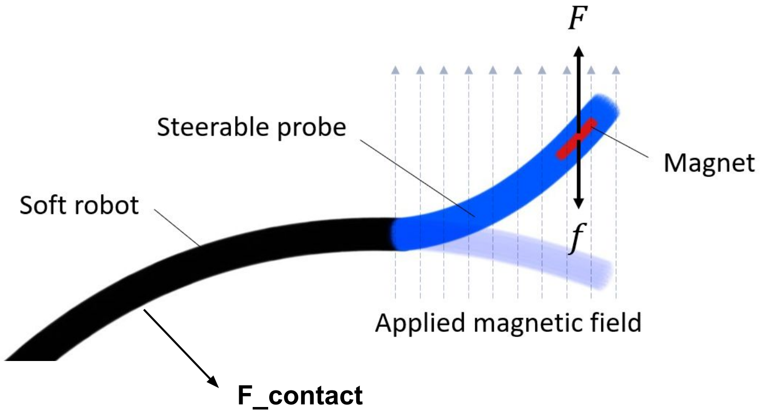
- Magnetically-driven distal steerable probe
- Driven by External Magnetic Field
- Soft Robot Body using PDMS material
- Fluid resistance:

$$f = -\frac{1}{2}\rho v^2 A C_d$$

- Equation of Motion:

$$f_i = m_i \frac{q_i(t_{k+1}) - q_i(t_k)}{dt^2} - m_i \frac{\dot{q}_i(t_k)}{dt} + \frac{\partial}{\partial q_i}(E_k^s + E_k^b) + F + f + F\_contact$$

- Time marching & Newton-Raphson iteraton method



Parameter	Value
Young's Modulus	1.47 MPa
Poisson's Ratio	0.48
Shear Modulus	0.497MPa
Density	980kg/m3
Length	0.5m
Outer radius	2mm
Inner radius	1mm

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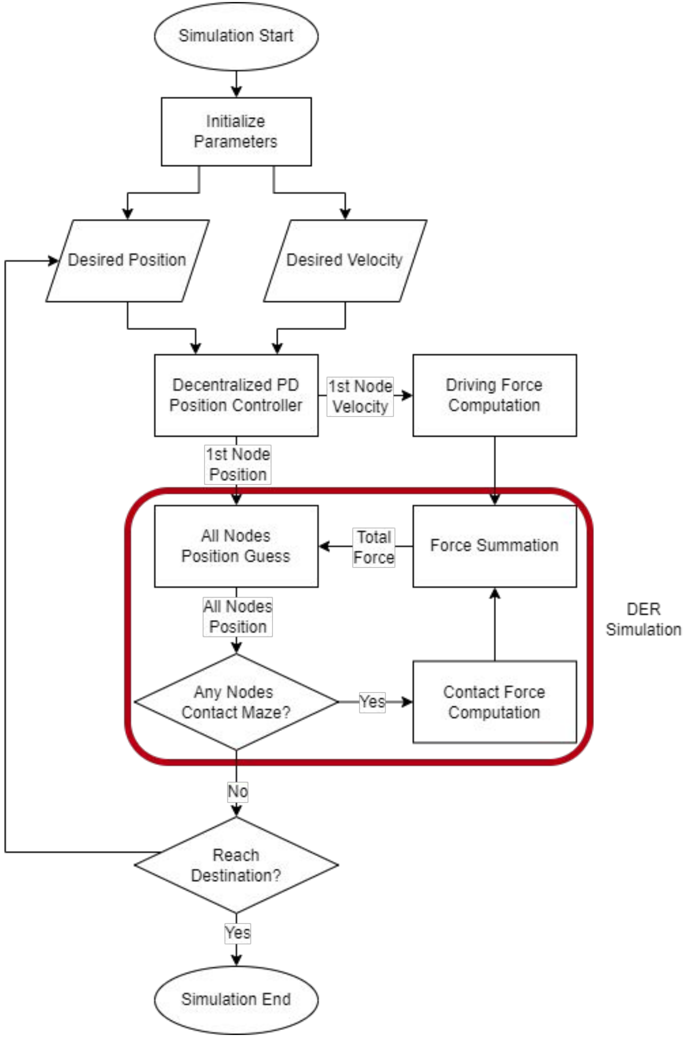
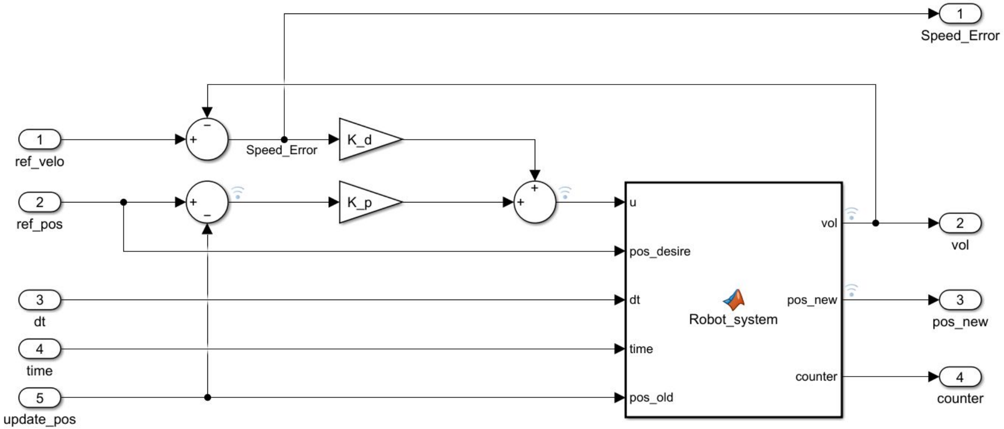
III: Algorithm

III: Algorithm Flow chart



III: Algorithm
PD control



Algorithm 2 First Node Decentralized PD Controller

Require: K_p, K_d ▷ Gain values
Require: $v1(t_{i-1})$
Require: $q_{1\_update}(t_{i-1})$
Require: $ref\_q1(t_i), ref\_v1(t_i)$ ▷ Desired position and velocity
Ensure: $F_{1st\_Node}, q_{1\_new}(t_i), v1(t_i)$

function FIRST_NODE_CONTROL($F_{1st\_Node}, q_{1\_new}(t_i), v1(t_i)$)
  for $k \leftarrow 1 : t_{end}$ **do**
    Compute $ref\_F1(t_i)$
    $pos\_error \leftarrow ref\_q1(t_i) - q_{1\_update}(t_{i-1})$
    $vel\_error \leftarrow ref\_v1(t_i) - v1(t_{i-1})$
    Compute $extra\_F1(t_i)$
    $F_{1st\_Node} = ref\_F1(t_i) + extra\_F1(t_i)$
    $u \leftarrow pos\_error \times K_p + vel\_error \times K_d$
    $q_{1\_new}(t_i) \leftarrow ref\_q1(t_i) + u$
    $v1(t_i) \leftarrow (q_{1\_new}(t_i) - q_{1\_update}(t_{i-1}))/dt$
  end for
  return $F_{1st\_Node}, q_{1\_new}(t_i), v1(t_i)$
end function

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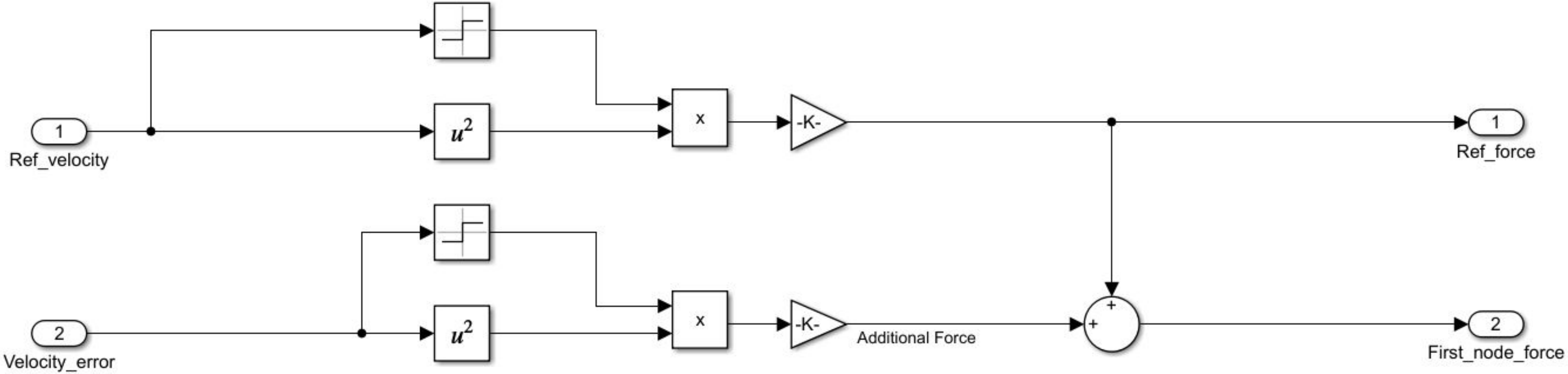
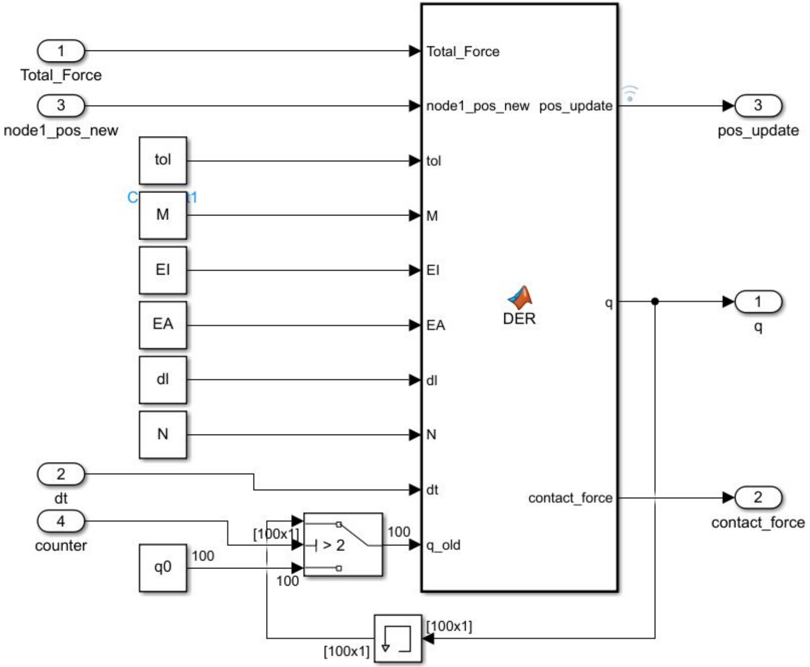
III: Algorithm
Actuation Force

$$f = -\frac{1}{2}\rho v^2 A C_d$$



III: Algorithm DER Calculation



Algorithm 1 DER Calculation

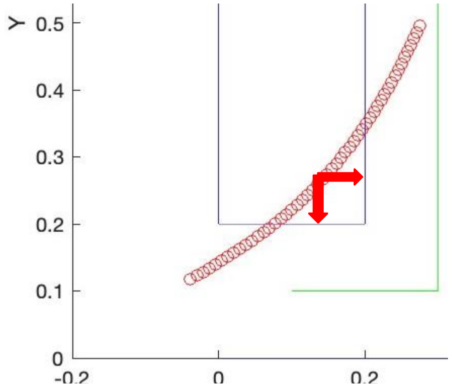
Require: F_{1st_Node} ▷ 1st Node Force Calculated from PD Controller
Require: EA, EI ▷ Elastic stiffness
Require: M ▷ Mass Matrix
Require: $q_{1\_new}(t_i)$ ▷ 1st Node Position Calculated from PD Controller
Ensure: $q(t_i), q_{1\_update}(t_i)$
Ensure: $F_{contact}(t_i)$

function DER_SIMULATION($q(t_i), q_{1\_update}(t_i), F_{contact}(t_i)$)
  for $k \leftarrow 1 : t_{end}$ **do**
    Guess: $q(t_i) \leftarrow q(t_{i-1})$
    $q(t_i)(1:2) \leftarrow q_{1\_new}(t_i)$ ▷ Update 1st node position
    $u \leftarrow (q(t_i) - q(t_{i-1})/dt$
    while $error > tol$ **do**
      Compute F and J
      for $k \leftarrow 1 : N-1$ **do** ▷ Stretching Energy
        $ind \leftarrow$ locations of x_k, x_{k+1}
        [dF, dJ] $\leftarrow$ gradEs_hessEs(x_k, x_{k+1})
        F(ind) $\leftarrow$ F(ind) + dF
        J(ind) $\leftarrow$ J(ind, ind) + dJ
      end for
      for $k \leftarrow 2 : N-1$ **do** ▷ Bending Energy
        $ind \leftarrow$ locations of x_{k-1}, x_k, x_{k+1}
        [dF, dJ] $\leftarrow$ gradEb_hessEb(x_{k-1}, x_k, x_{k+1})
        F(ind) $\leftarrow$ F(ind) + dF
        J(ind) $\leftarrow$ J(ind, ind) + dJ
      end for
      Compute $F_{contact}(t_i)$ ▷ See Contact_Force Calculation
      $Ex\_Force(1:2) \leftarrow F_{1st\_Node}$ ▷ Actuation force
      $Ex\_Force(t_i) \leftarrow Ex\_Force(t_i) + F_{contact}(t_i)$
      $F(t_i) = F(t_i) + Ex\_Force(t_i)$
      $\delta q(t_i) \leftarrow J_{free} \backslash F_{free}$
      error $\leftarrow sum(abs(F_{free}))$
    end while
    $q_{1\_update}(t_i) \leftarrow q(t_i)(1:2)$
  end for
  return $q(t_i), q_{1\_update}(t_i), F_{contact}(t_i)$
end function

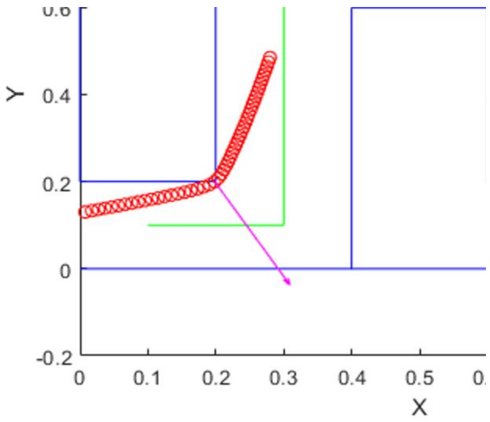
III: Algorithm
Contact force

- Contact Force Calculated through iteration
  - K_f: Step Force Gain Constant
  - Force x = Force x + K_f*dy
  - Force y = Force y + K_f*dx
- Smaller K_f value brings smoother turning at corner. However, slower computation

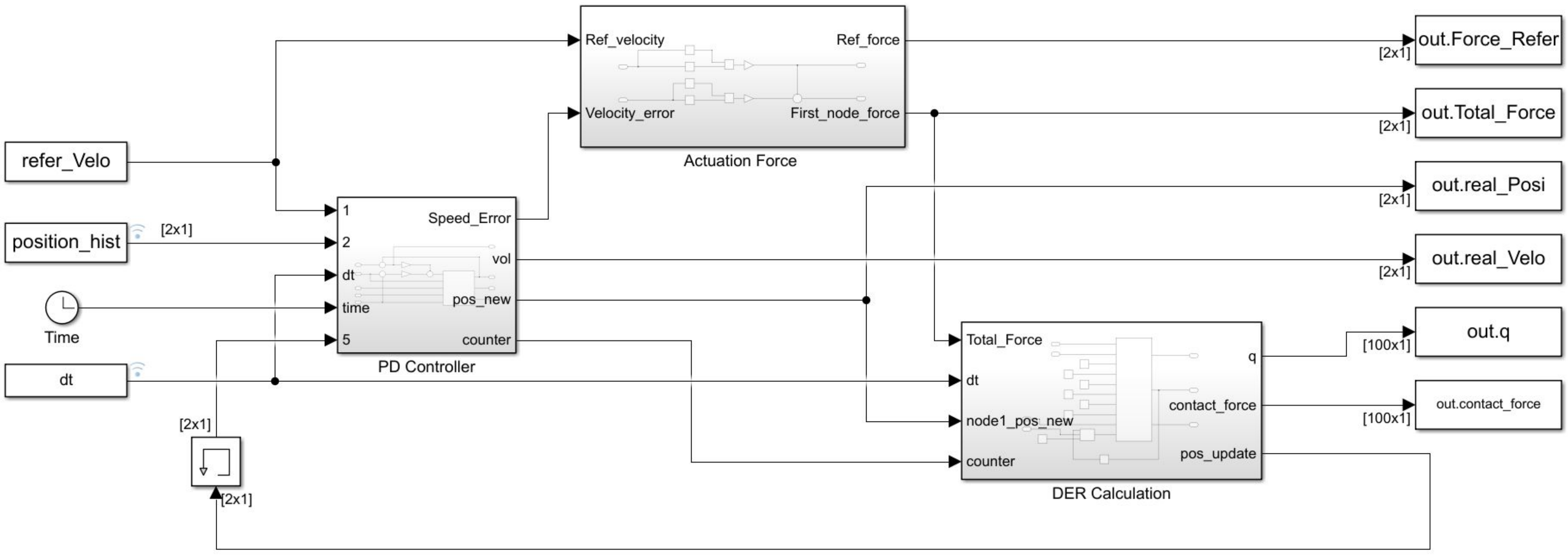
Without Contact Force



With Contact Force



III: Algorithm



IV: Simulation Result

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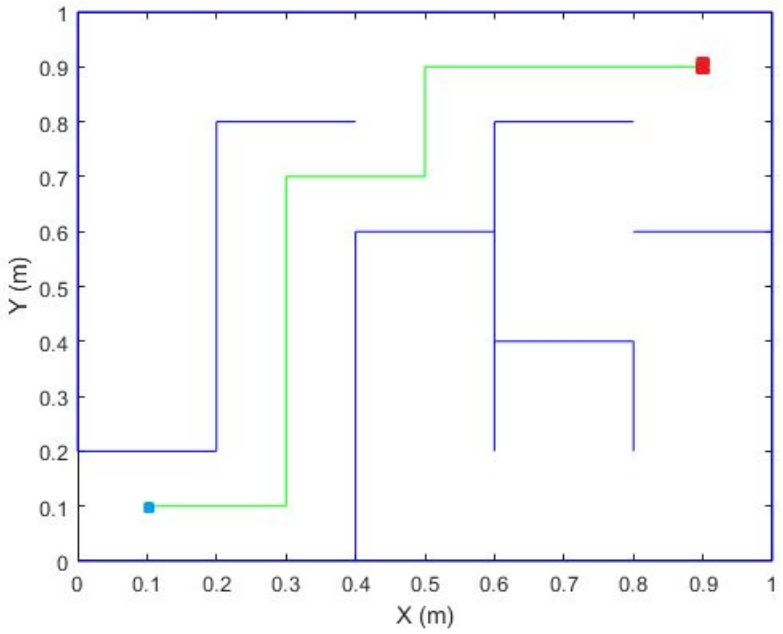
IV: Simulation Result
Environment & Robot Model

1. Create 2D Blood Vessel Maze Simulation
2. Solving Maze & Creating Trajectory
3. First Node Feedforward PD Control
4. Simulate Discrete Elastic Rod
5. Adding Contact Force

IV: Simulation Result
Block Diagram

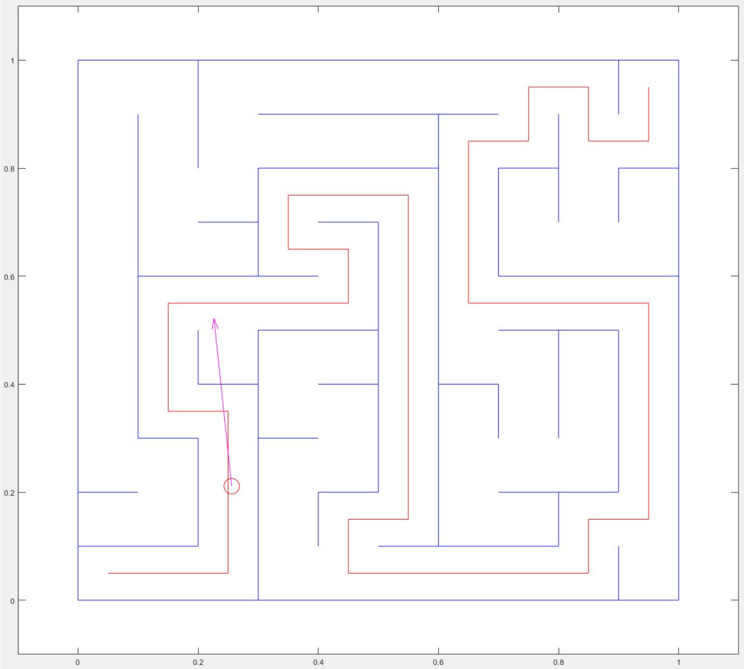
1. We first Create a 5*5 Maze
2. Solving the Maze
3. Starting: Green. Ending: Red
4. Creating Trajectory for soft robot 1st node
5. Output: Desire Position & Velocity



IV: Simulation Result

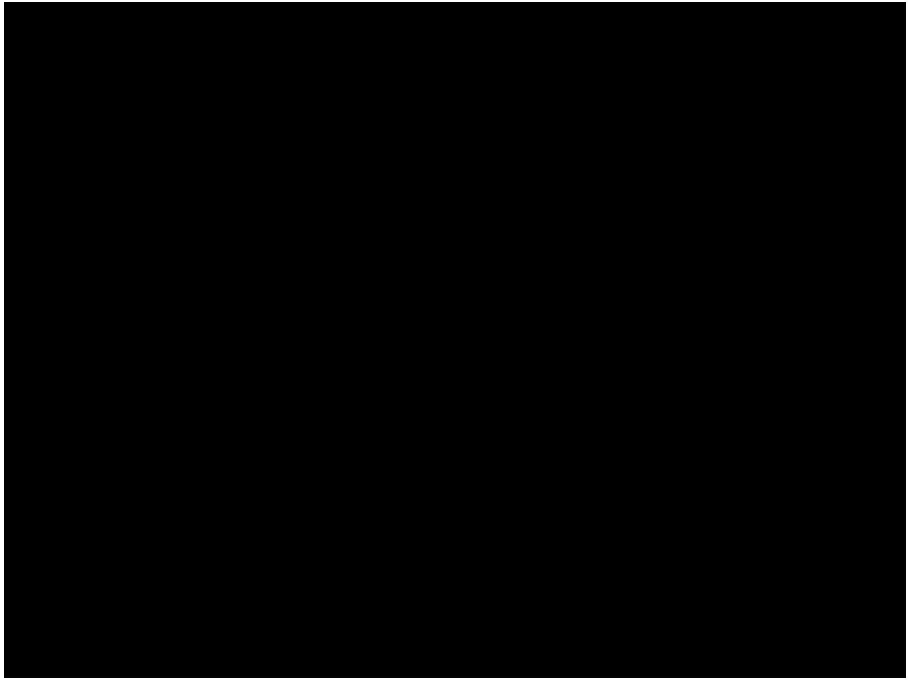
1 Node Robots Simulation

1. Desired Position & Velocity feed into Feedforward PD controller. For Real Position and Velocity
2. Sine wave disturbance added
3. Driven force Direction & Magnitude shown in arrow



IV: Simulation Result

1 Nodes Robots Simulation



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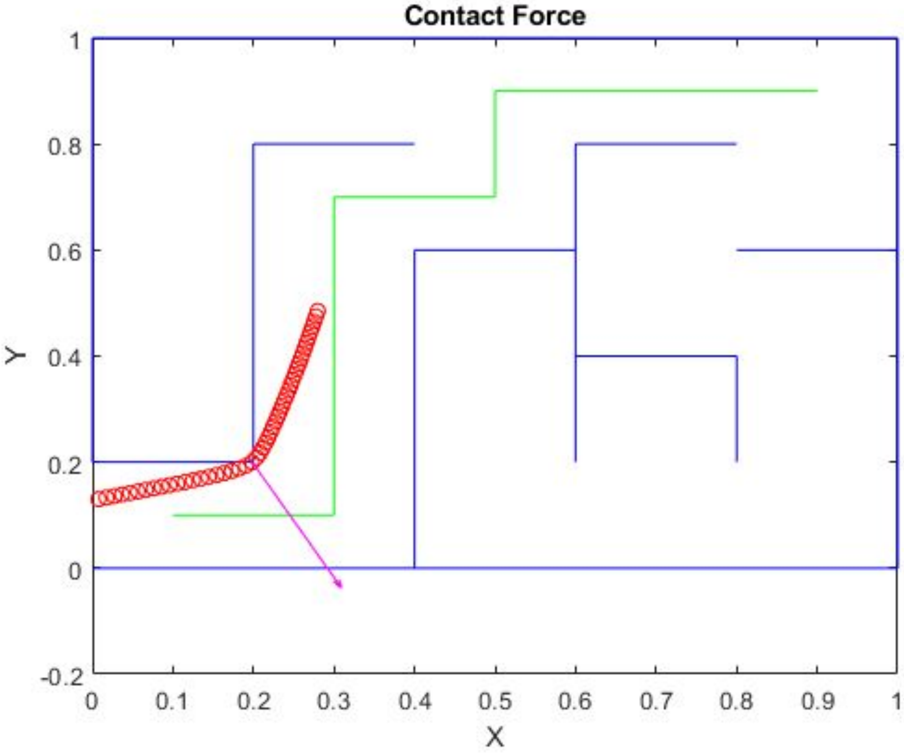
IV: Simulation Result
Contact Force Identification

1. The First Node position & force feed into DER simulator.
2. Contact Force Calculated During DER process as External Force



IV: Simulation Result
50 Nodes Robots Simulation

Without Contact Force

With Contact Force

V: Discussion & Future Work

1. Vascular-mimicking environment iteration
   a. More complex route (corners with different angles)
   b. 2D -> 3D
   c. Real vascular mimicking
2. Animation rendering
3. Adding friction between walls & robot
4. Robot model and magnetic force refinement

VI: Reference

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Thank you