IIT ROORKEE

NPTEL ONLINE CERTIFICATION COURSE

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DEPARMENT OF ELECTRICAL ENGINEERING

Smart Needles for Percutaneous Interventions-I

Outline

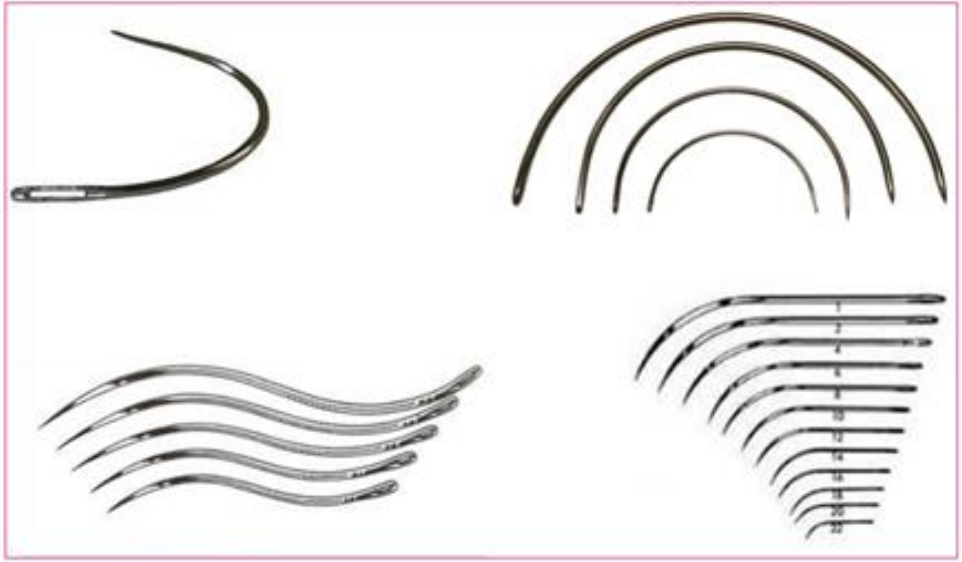
1. Introduction
2. Design 1
3. Design 2

Introduction

Contemporary Medical Practices

- Use of rigid needle for all procedures
- Pre-curved needles recently used for percutaneous medical procedures
- Risk of puncturing nearby organs
- Hence, **a shift is required from conventional surgical procedures to MIS**

Introduction (cont'd)



Rigid and curved needles used for surgical purposes

Source: https://www.amdnext.com

Introduction (cont'd)

Minimal Invasive Surgery

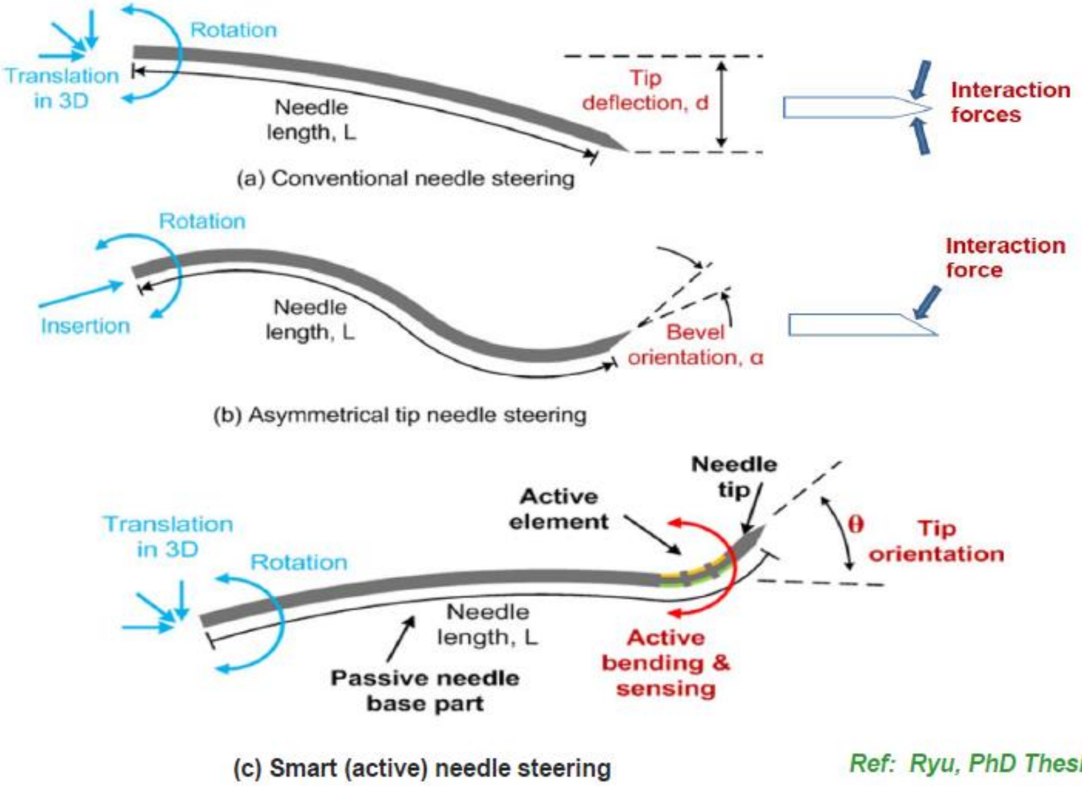
- Less risk of perturbing nearby organs and tissues
- Smaller surface incision
- Less exposure of organs during procedure
- Less chance of infection
- Less blood loss during insertion
- Faster recovery

Introduction (cont'd)

Why Self-actuating (Smart) Flexible Needles?

- *Incredibly* conforms to shape of the target organ
- *Significantly* improve drug dose delivery
- *Reduce* toxicity - avoiding normal anatomical tissues

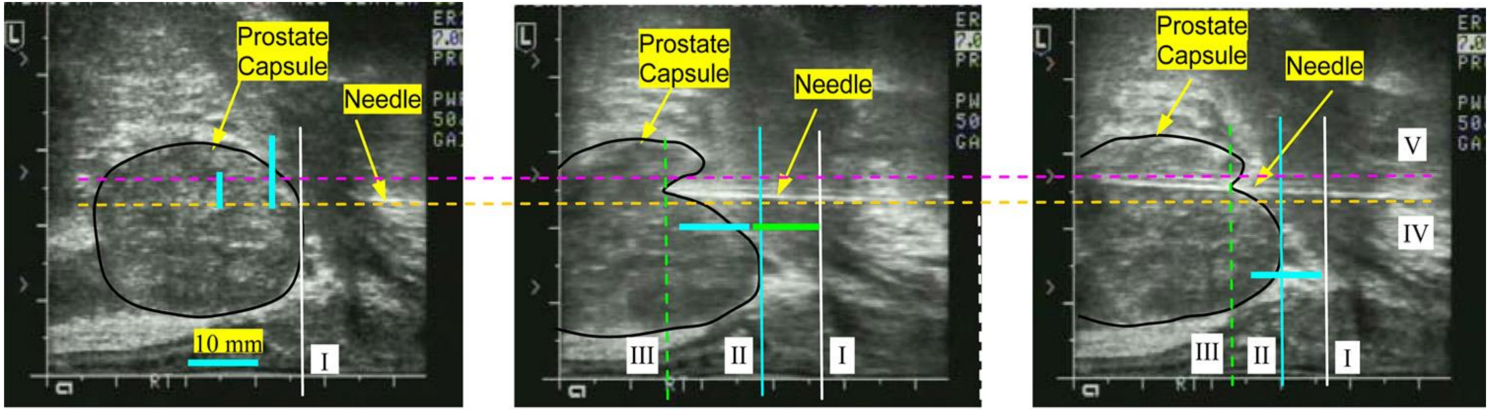
Concept of Needle Steering



Ref: Ryu, PhD Thesis, 2012.

Needle Steering in Prostate Gland

It is challenging to place a needle in the peripheral zone of the prostate

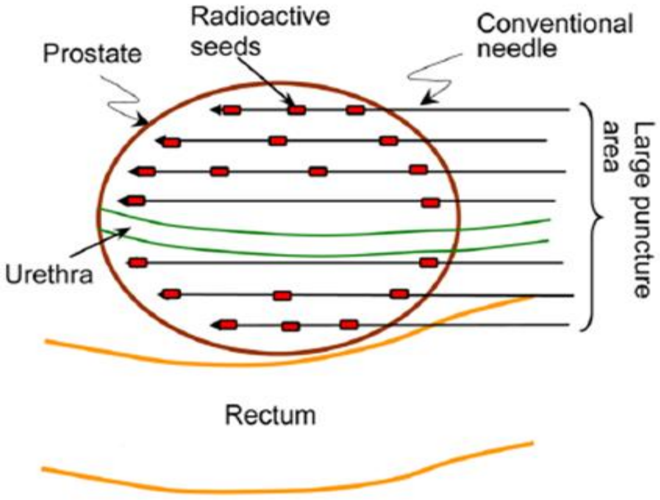


(a) Prior to capsule puncture (b) During capsule puncture (c) After full insertion

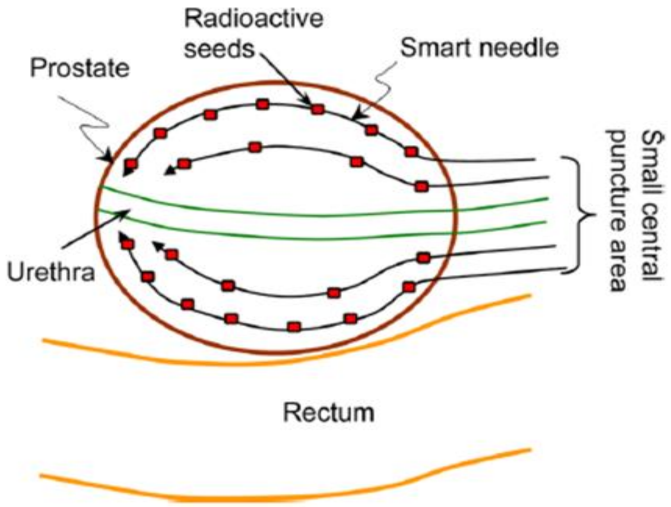
Ref: Podder et al, "A novel curvilinear approach for prostate seed implantation," MedPhys 2012, pp.(1887-1892)

Needle Steering in Prostate Gland

Prostate Brachytherapy



Conventional - Rectilinear



Curvilinear conformal smart needle insertion

Ref: Podder et al,"A novel curvilinear approach for prostate seed implantation," MedPhys 2012, pp.(1887-1892)

Needle Steering in Prostate Gland

TABLE I. Comparison of proposed curvilinear approach and conventional rectilinear approach.

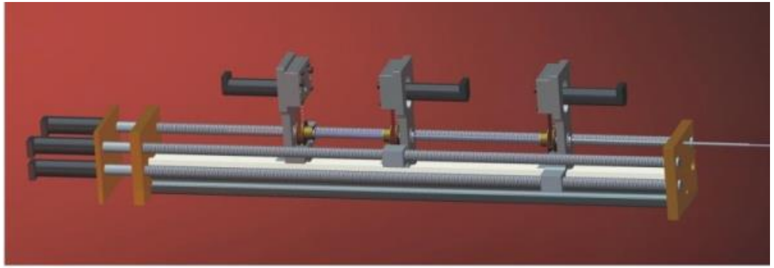
Parameter ($n = 20$)	Rectilinear method Average ± SD (range)	Curvilinear method Average ± SD (range)	Difference	p-value (two-tailed)
Total needle	19.2 ± 2.6 (14–23)	13.2 ± 1.4 (10–15)	−6.0 (−30.5%)	< 0.001
Total seed	62.5 ± 11.2 (43–85)	55.1 ± 10.4 (38–74)	−7.4 (−11.8%)	< 0.49
Total activity (mCi)	38.3 ± 6.3 (28.3–47.3)	33.8 ± 4.9 (25.3–40.3)	−4.5 (−11.8%)	< 0.37
Prostate (average = 41.3 cm^3, range = 26.6–53.2 cm^3):				
D_{90} (Gy)	198.7 ± 9.9 (182.9–215.2)	183.3 ± 6.8 (176.3–194.5)	−15.4 (−7.8%)	< 0.04
V_{100} (cm^3)	99.98 ± 0.06 (99.8–100)	99.97 ± 0.06 (99.83–100)	−0.01 (−0.01%)	< 0.85
V_{150} (cm^3)	80.9 ± 6.8 (68.5–89.8)	65.7 ± 5.3 (57.8–75.9)	−15.2 (−18.8%)	< 0.01
V_{200} (cm^3)	43.7 ± 6.0 (32.7–53.4)	28.9 ± 3.3 (26.0–35.5)	−14.8 (−33.9%)	< 0.001
Urethra:				
D_{10} (Gy)	209.9 ± 12.2 (186.2–228.7)	189.2 ± 8.1 (178.3–208.8)	−20.7 (−9.9%)	< 0.02
D_{30} (Gy)	205.1 ± 10.4 (184.3–219.9)	184.3 ± 7.4 (172.5–200.2)	−20.8 (−10.1%)	< 0.01
Rectum:				
D_5 (Gy)	160.2 ± 15.9 (137.9–196.8)	130.5 ± 12.3 (111.0–151.1)	−29.7 (−18.5%)	< 0.03
V_{100} (cm^3)	0.93 ± 0.51 (0.19–2.0)	0.21 ± 0.17 (0.03–0.61)	−0.72 (−77.8%)	< 0.001

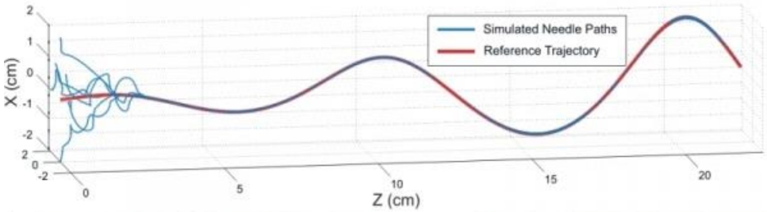
Ref: Podder et al,"A novel curvilinear approach for prostate seed implantation," MedPhys 2012, pp.(1887-1892)

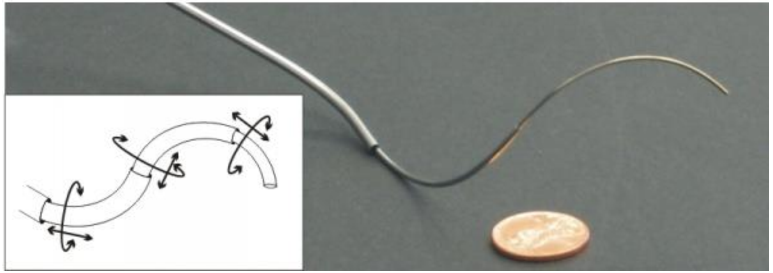
Merits of Curvilinear Approach

- Small puncture area
- Accurate needle placement
- Improved dose distribution
- Better sparing of OARs
- Less needles, seeds
- Expected less traumas
- Expected reduction of toxicities

Pre-curved Needle Continuum







The figures (from top to bottom) show-

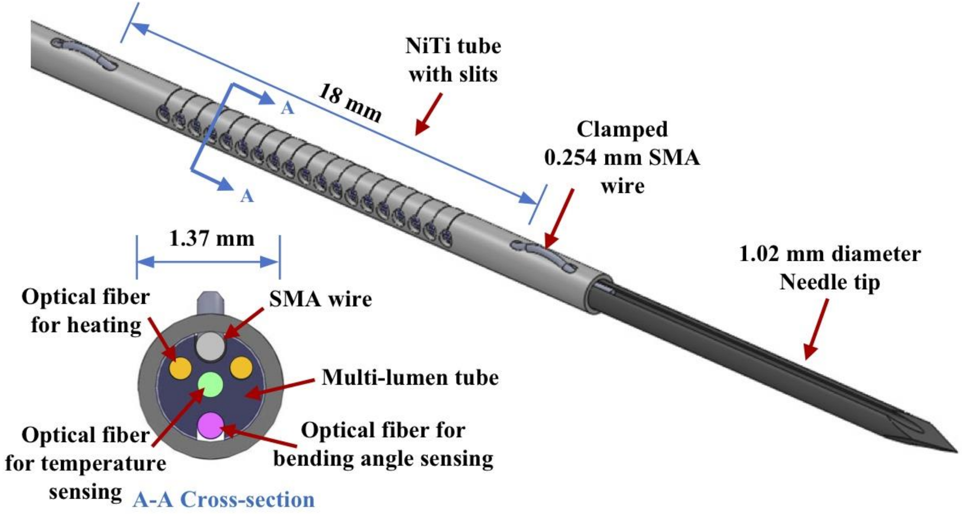
(1) a CAD drawing of a new active cannula or steerable needle actuation unit.

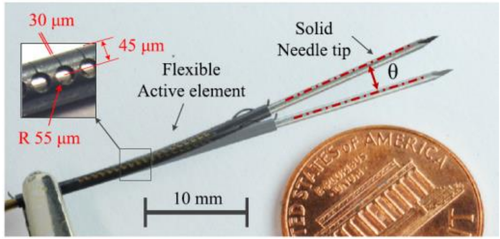
(2) a simulation showing that controller can stabilize bevel-steered needles to a 3D reference trajectory from various initial poses.

(3) an active cannula prototype with inset line drawing indicating DOF.

Webster et al., Vanderbilt University, MICCAI 2008

Optically Actuated MR-compatible Active Needle





Ryu et al., Stanford University ,
IEEE IROS, 2011

Motion Planning for Steerable Medical Needles

(a) Human Prostate, Tumor Target, and Obstacles

(b) Bevel-left Needle Trajectory Plan

(c) Bevel-right Needle Trajectory Plan

Example: MRI of the prostate, a biopsy needle attached to a rigid rectal probe (black half-circle) is inserted into the prostate (outlined in yellow) using simulation.

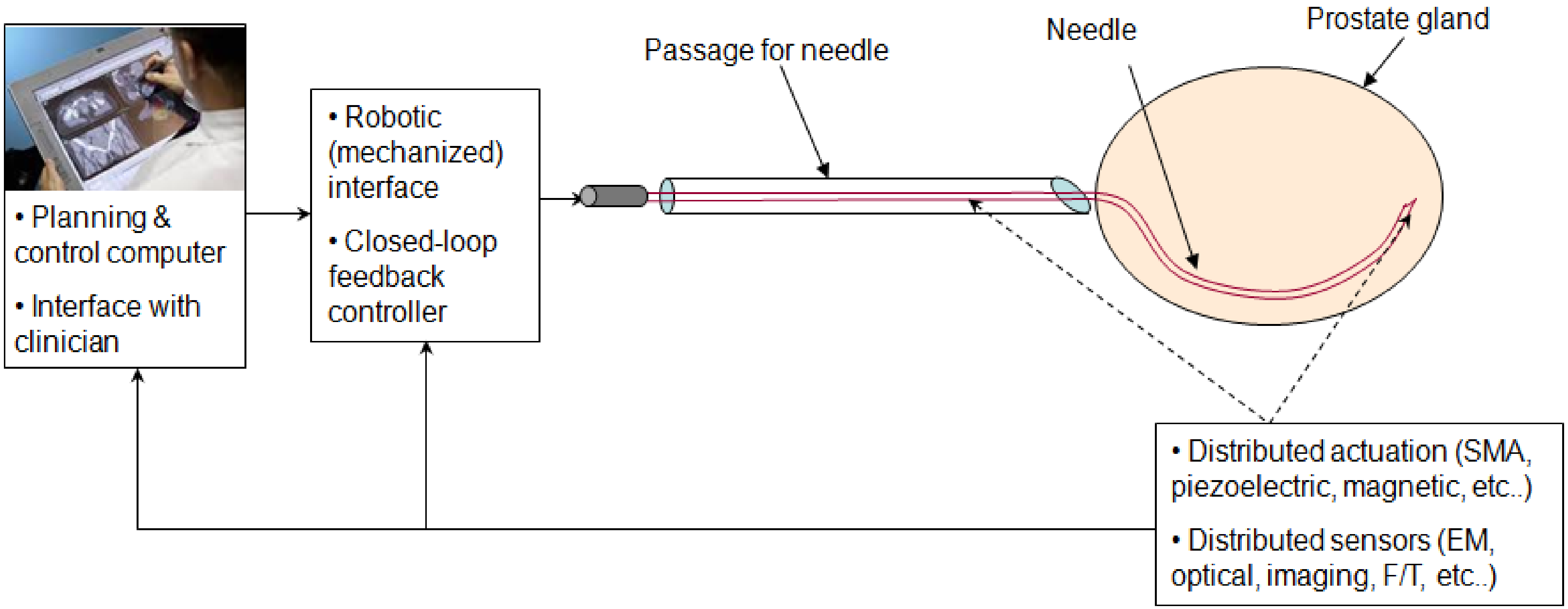
(a). The target is not accessible from the rigid probe by a straight line path without intersecting obstacles.

(b). Using different initial conditions, the planner generates a plan for a bevel-right needle

(c). Due to tissue deformation - needle paths do not have constant curvature.

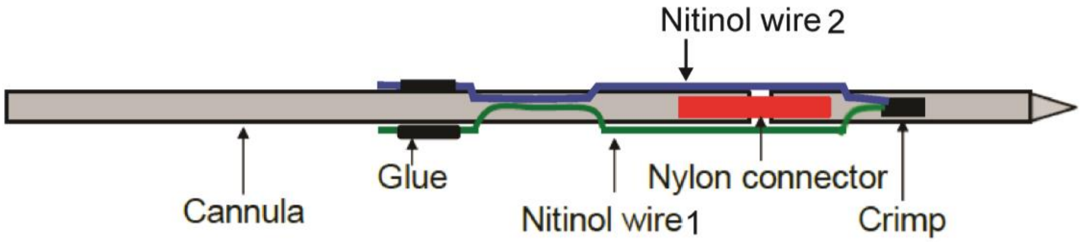
Alterovitz et al., UC Berkeley, MICCAI 2008

Percutaneous Cancer Intervention Concept Using Smart Needle with Three Control Loops



SMA Actuated Smart Needle

Design Concept



Ref: Felix Orlando et al., ASME, Journal of Medical Devices, June, 2015

Shape Memory Alloy wire as Actuator

- These alloys have a ‘**Shape Memory Effect**’ because of which they can be deformed when in normal temperature conditions and they return to original remembered shape when heated.

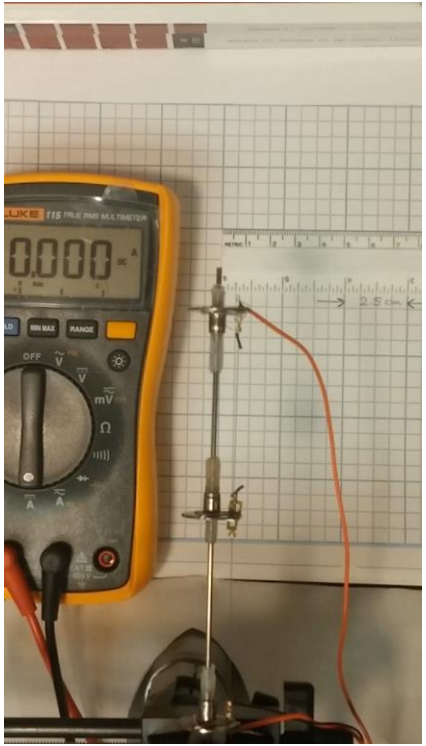
- Shape memory effect is a temperature and stress dependent shift that occurs in crystalline structure of the material.

- It transfers between two phases Martensite (low temperature phase) and Austenite (High temperature phase).

SMA Actuated Smart Needle Experimentation

- SMA actuator parameters
  - ✓ Length: 70 mm
  - ✓ Diameter: 0.25 mm
  - ✓ Heating Pulling Force: 891 g
  - ✓ Cooling Deformation Force: 356 g
  - ✓ Resistance: 1.3 ohm

- Needle parameters
  - ✓ Material: Aluminium
  - ✓ Mass: 20 g
  - ✓ Length: 200 mm
  - ✓ Diameter: 1.7 mm

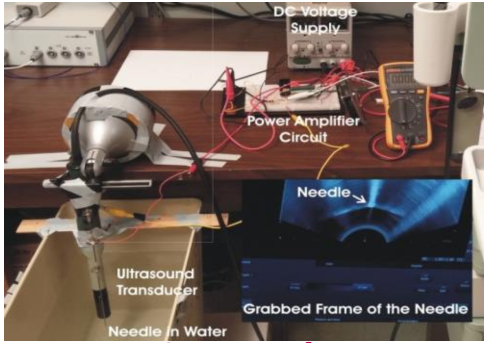


SMA Actuated Smart Needle Control

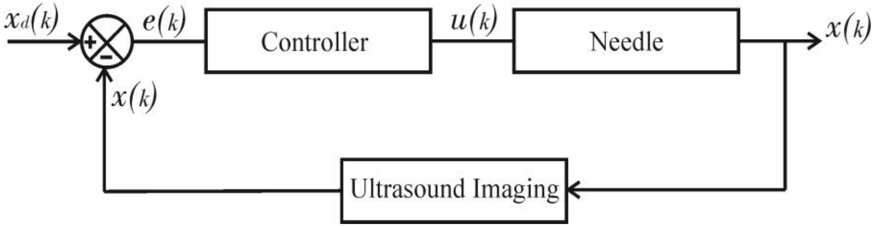
Multimodal Feedback Control Strategy:

1) Imaging (ultrasound)
2) Electromagnetic (EM)
3) Vision/ optical

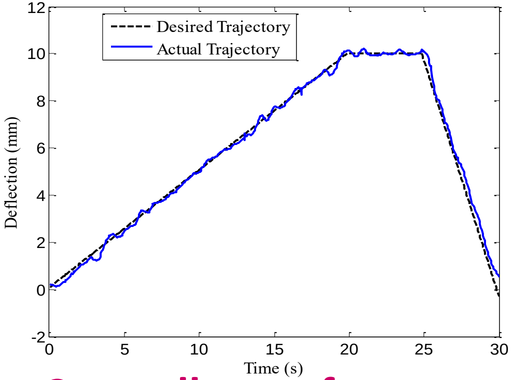
Ultra sound



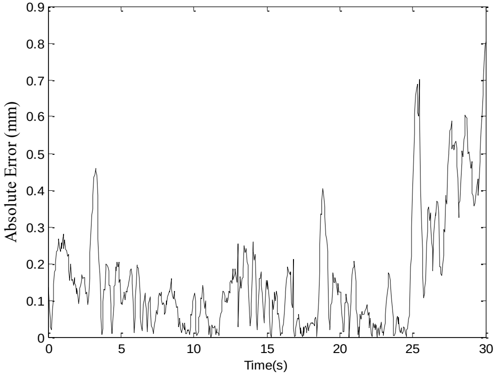
Experimental setup



Control block diagram



Controller performance

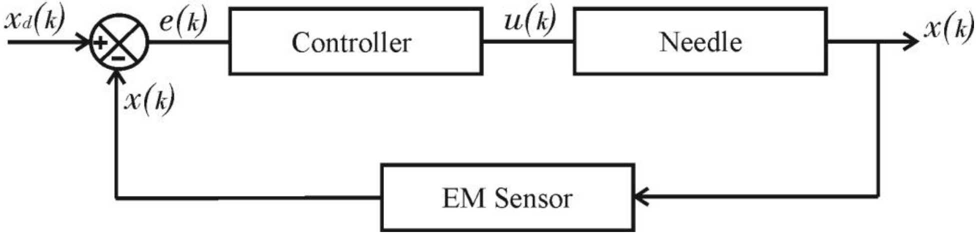


Error

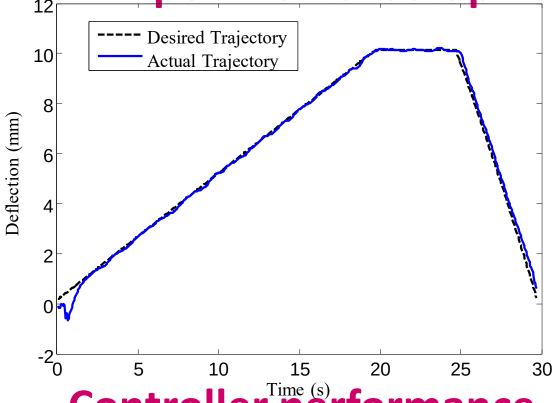
Felix Orlando et al., "Control of Shape Memory Alloy Actuated Flexible Needle using Multimodal Sensory Feedbacks," JOACE, 2015

EM Sensory Feedback

Experimental setup

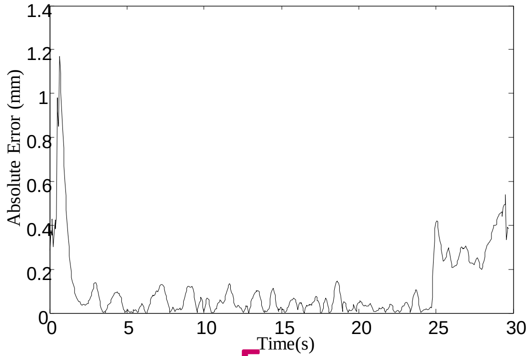


Control block diagram



Controller performance

RMSE = 0.1128 mm



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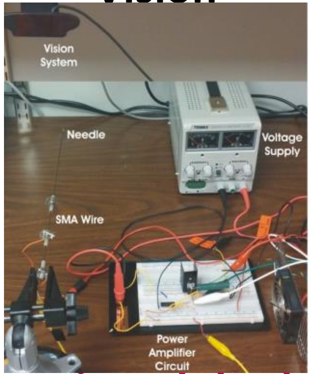
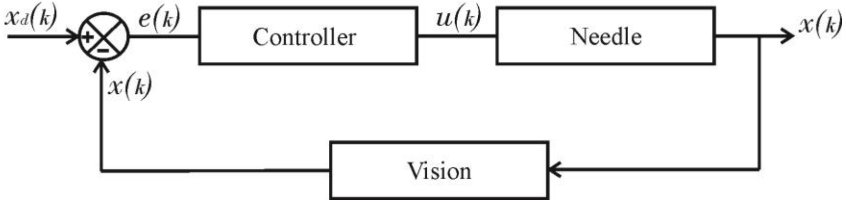
Felix Orlando et al., "Control of Shape Memory Alloy Actuated Flexible Needle using Multimodal Sensory Feedbacks," JOACE, 2015

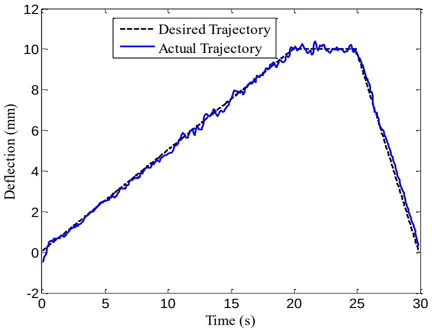
Vision



Experimental setup

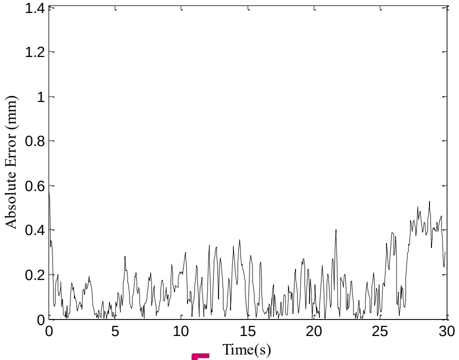


Control block diagram



Controller performance

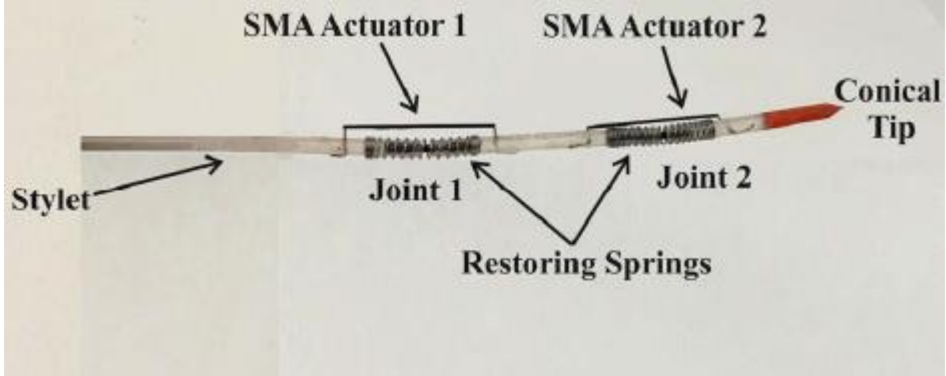
RMSE = 0.1508 mm

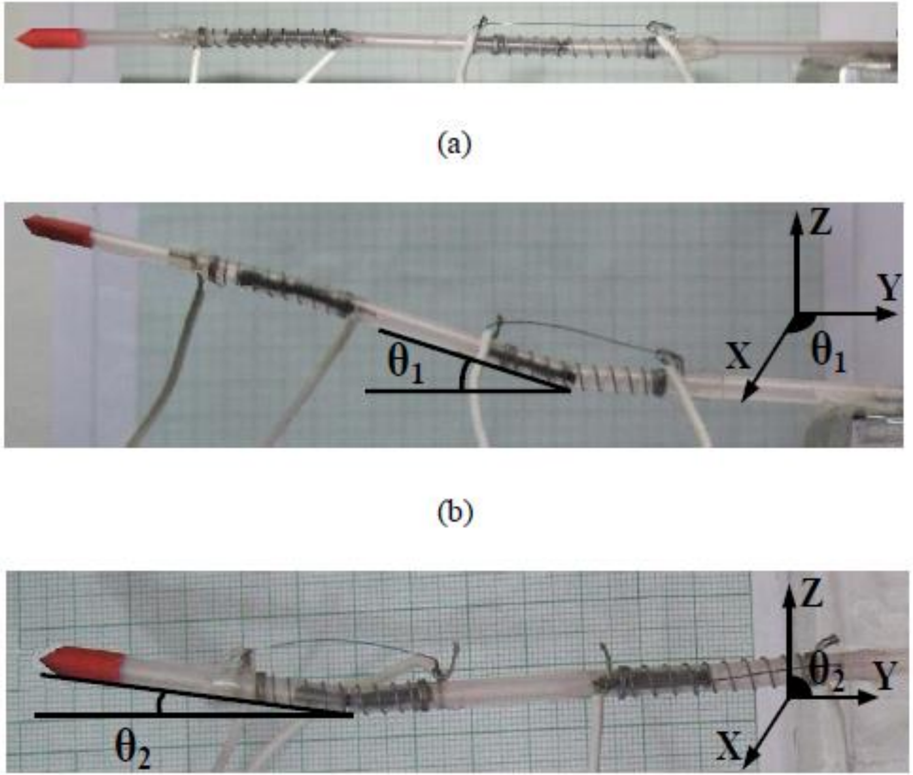


Error

Felix Orlando et al., "Control of Shape Memory Alloy Actuated Flexible Needle using Multimodal Sensory Feedbacks," JOACE, 2015

Smart Needle – Design 1





(a)

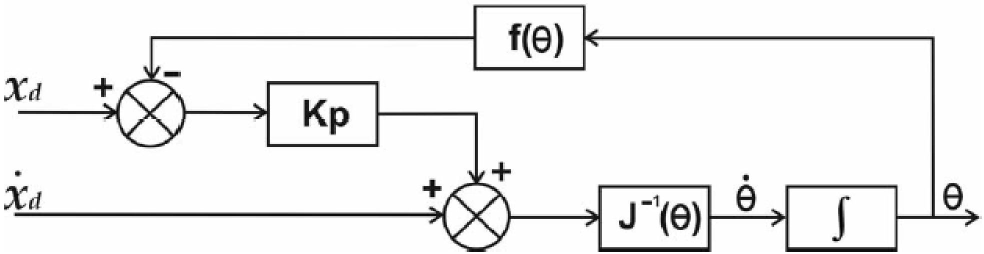
(b)

(c)

TABLE I. D-H PARAMETERS.

Frames	a_i	α_i	d_i	θ_i
{Base} – {0}	L_0	90°	0	90°
{0} – {1}	L_1	-90°	0	θ_1
{1} – {2}	L_2	0°	0	θ_2

Inverse kinematic control of a smart needle



$$\dot{q} = J_A^{-1}(q)(\dot{x}_d + Ke)$$

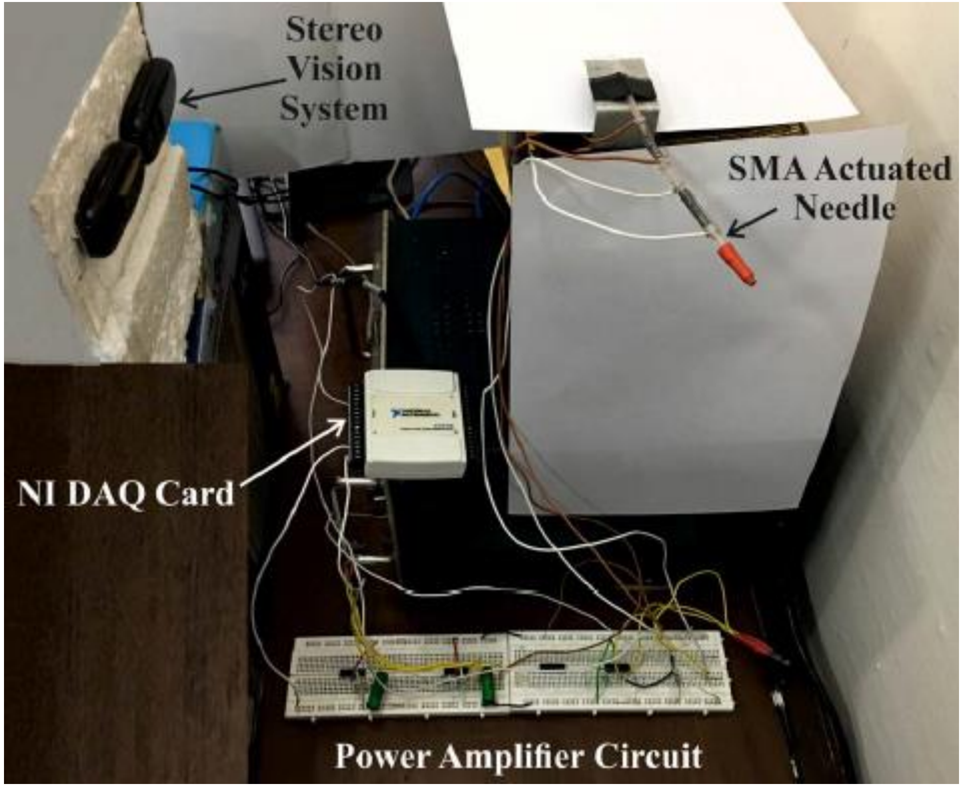
$$\dot{e} + Ke = 0.$$

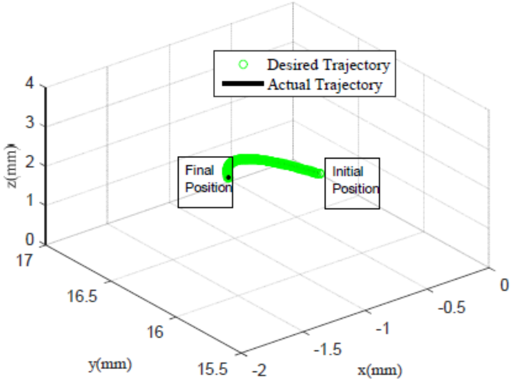
$$e = x_d - x = x_d - k(q)$$

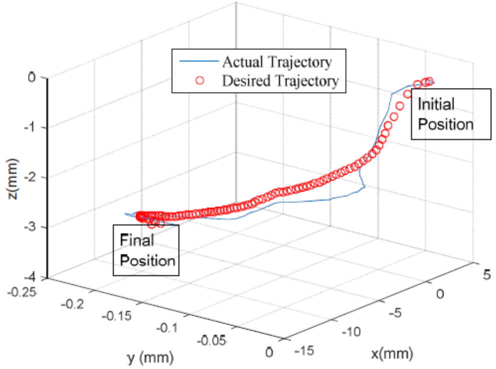
$$\dot{e} = \dot{x}_d - \dot{x}$$

$$\dot{e} = \dot{x}_d - J_A(q)\dot{q}.$$

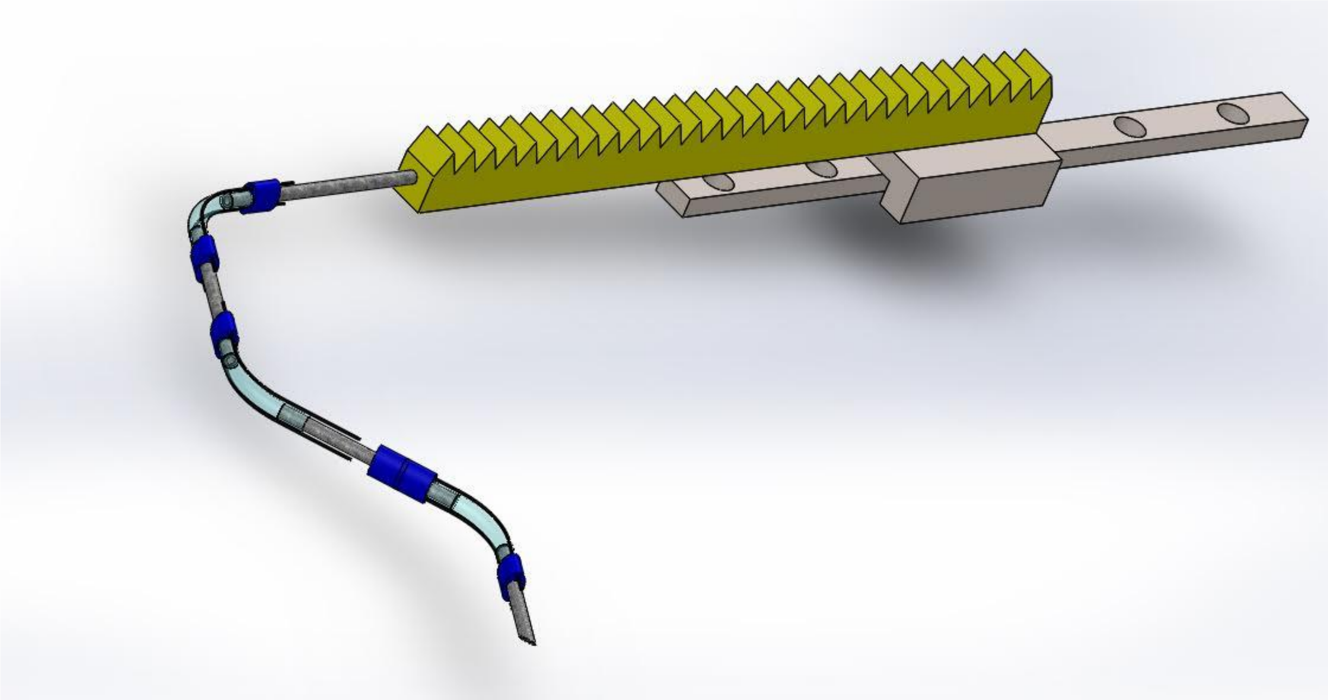
Inverse kinematic control of a smart needle



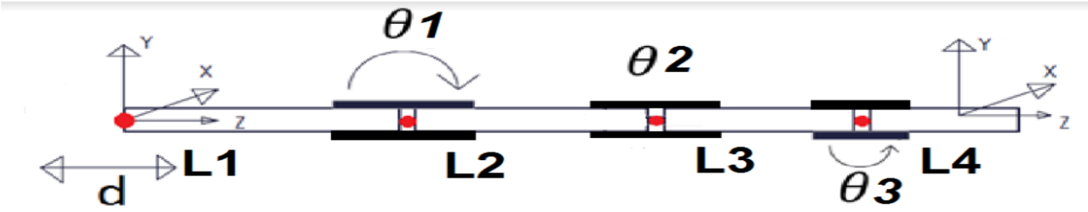


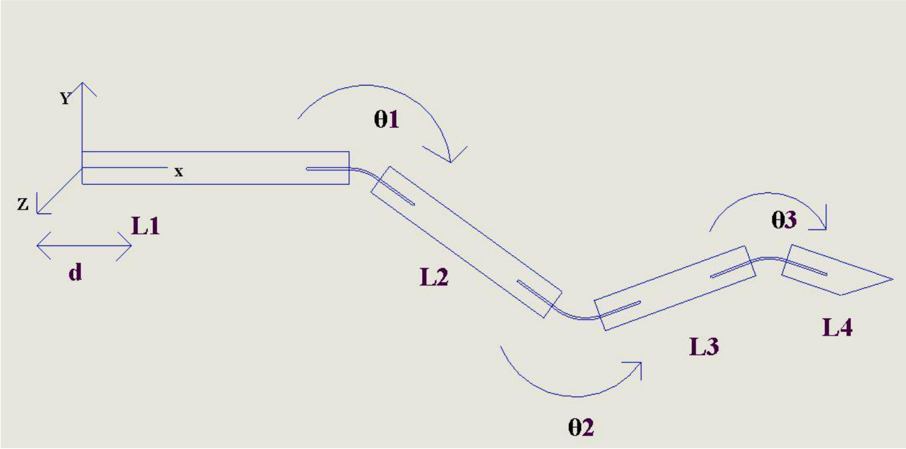


Design 2

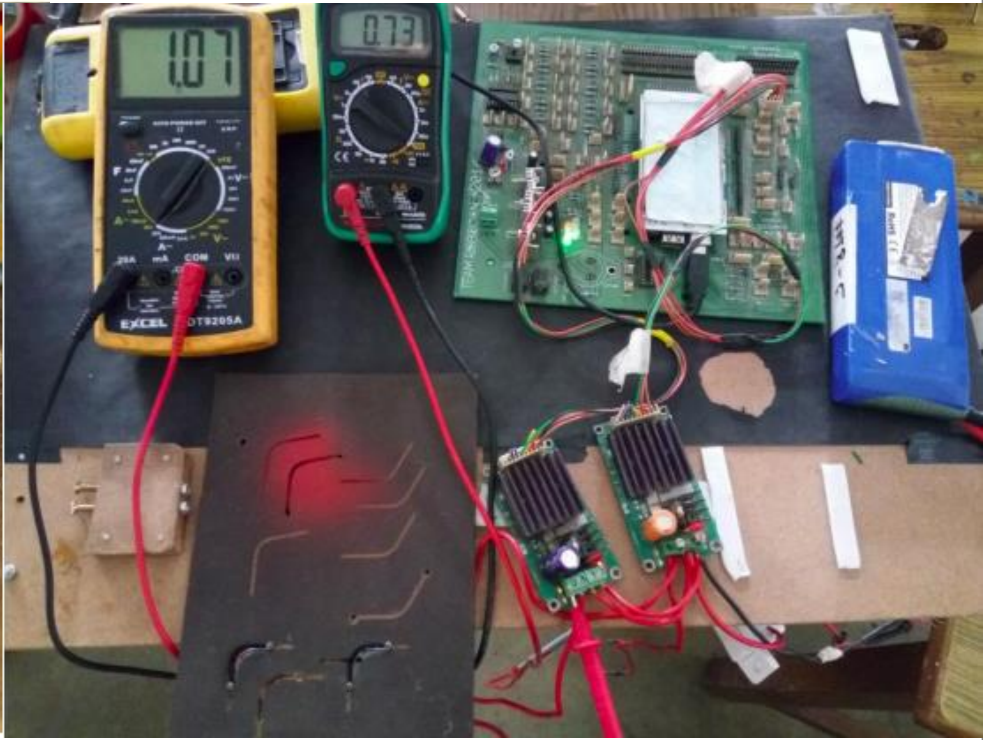


Kinematic Modeling



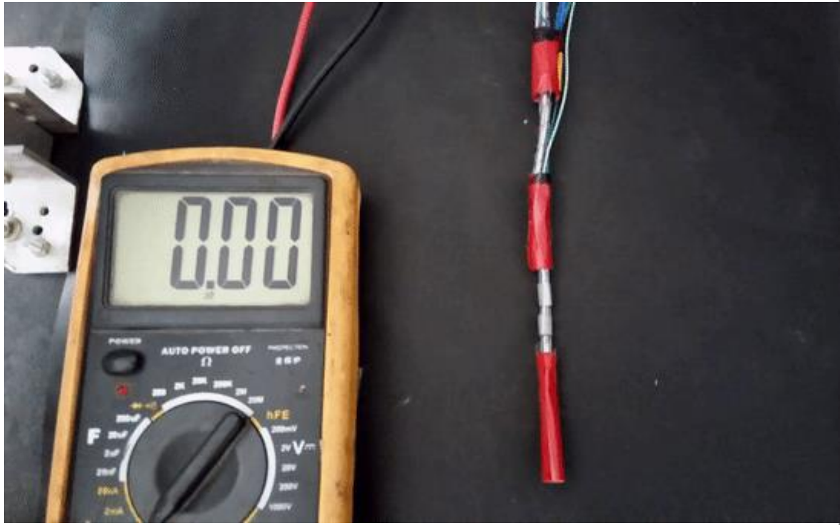


Shape Setting of SMAs

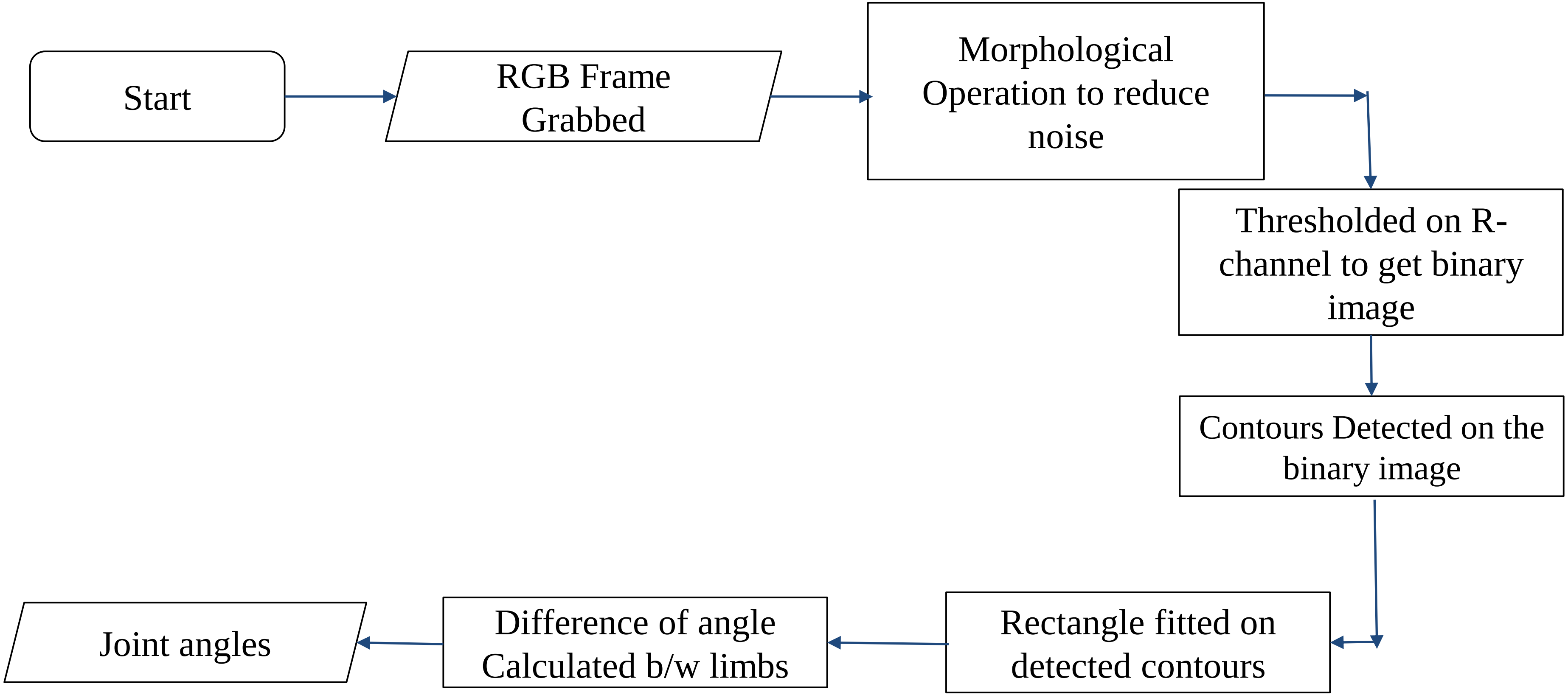


Actuation in SMAs

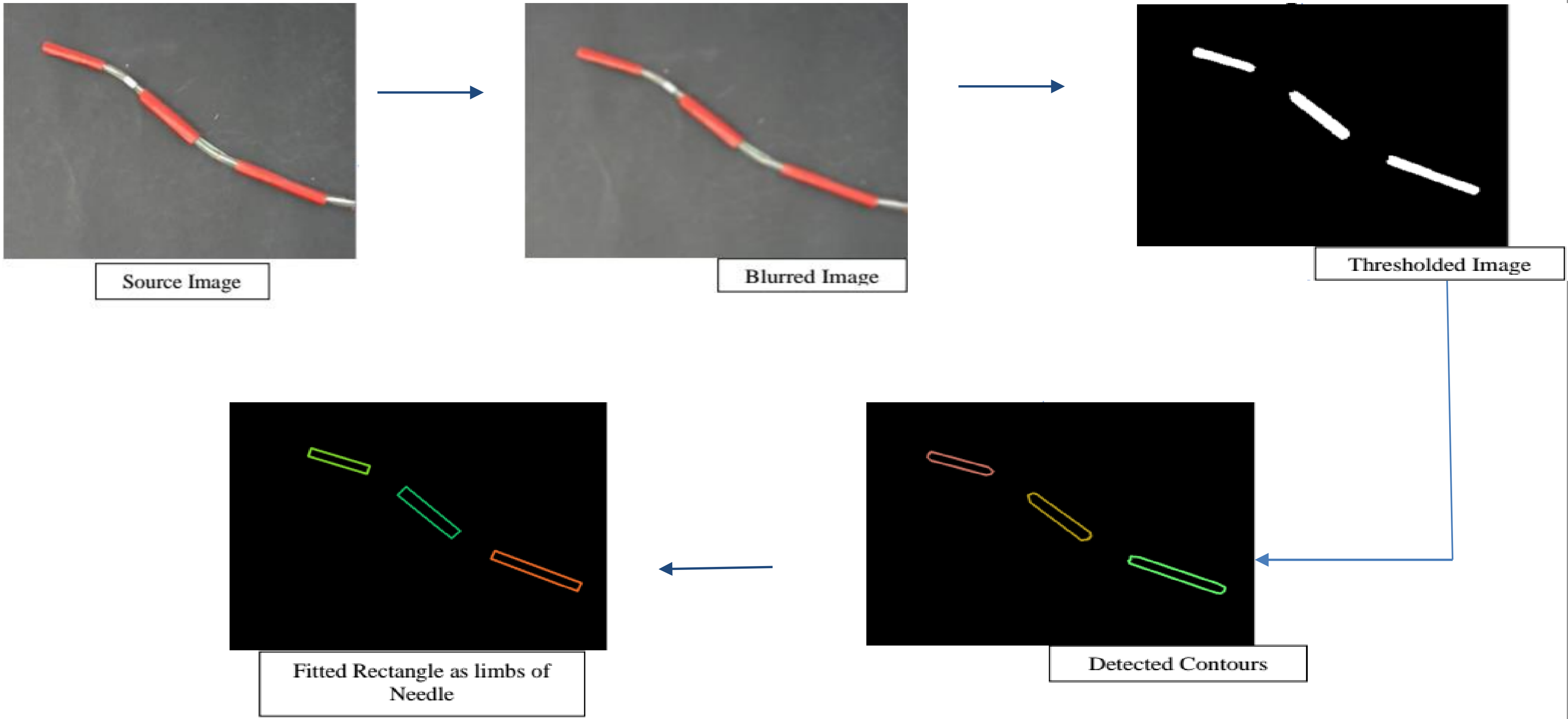
- Two ends of an SMA wire are connected across every joint.
- Revolute joint is realized as shown.
- SMA wire is heated by passing current and bends the joint as shown.



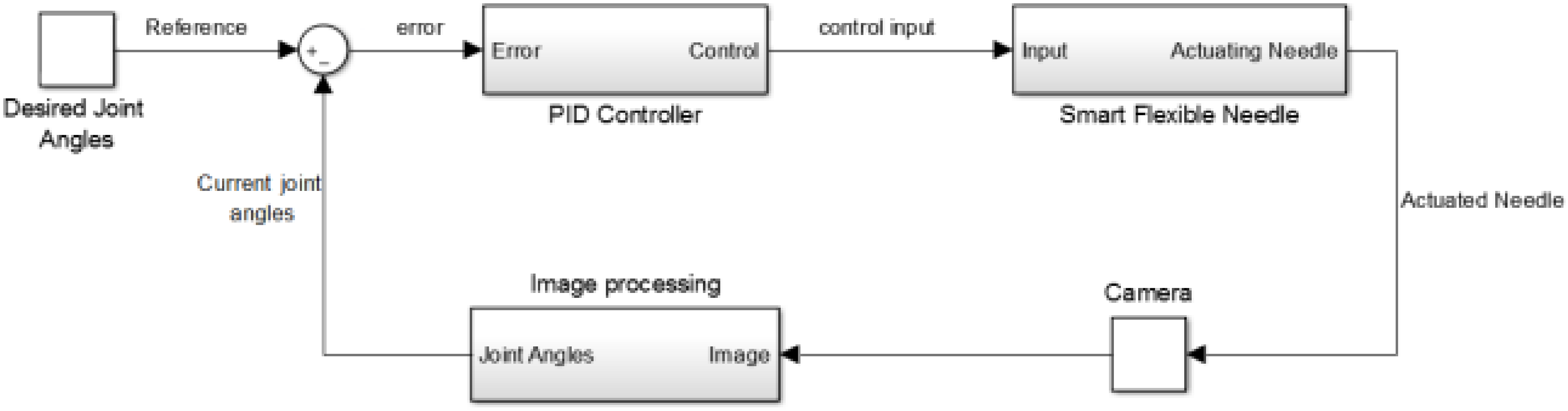
Vision Based Angle Feedback



Joint Angle Detection using Image



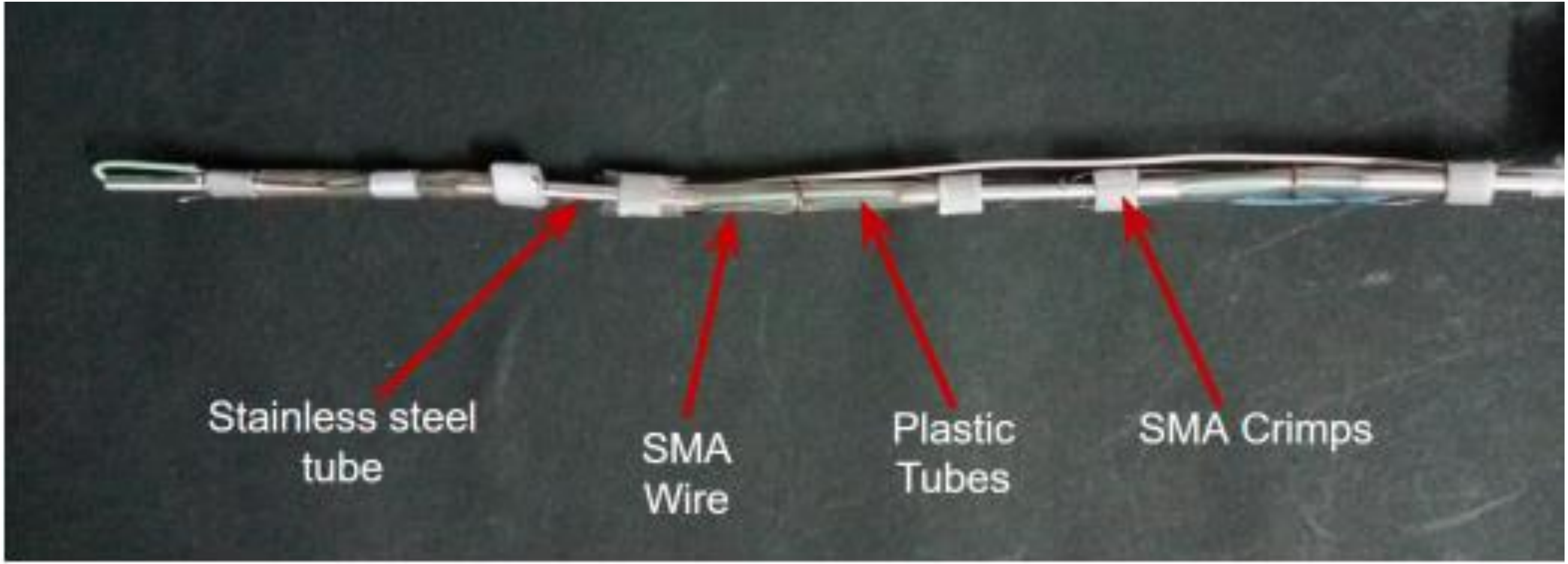
Control Strategy



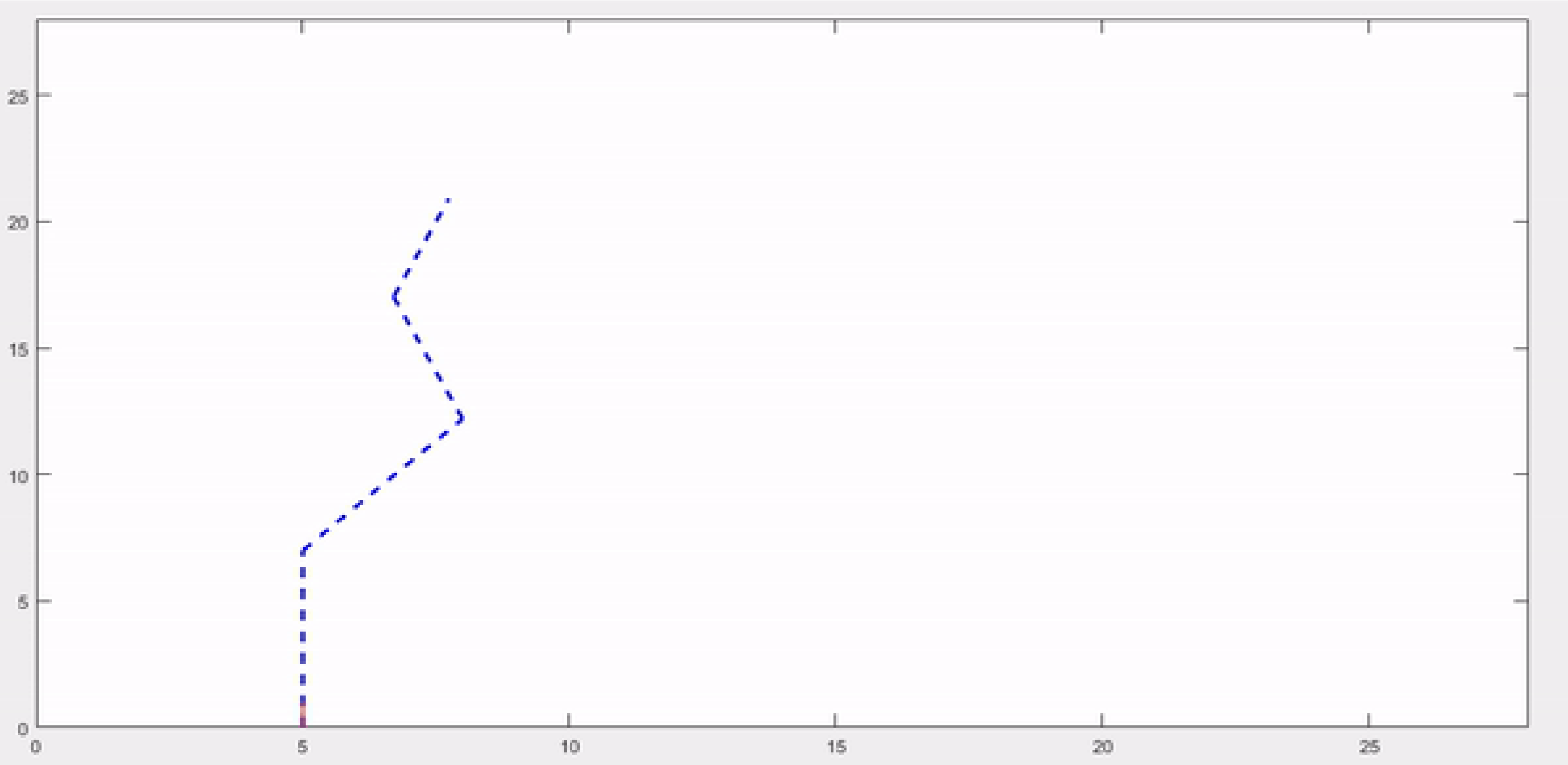
PD Implementation

$$I_i = k_p(\alpha^i{}_{desired} - \alpha^i{}_{current}) + k_d \left\{ \frac{d(\alpha^i{}_{desired} - \alpha^i{}_{current})}{dt} \right\}$$

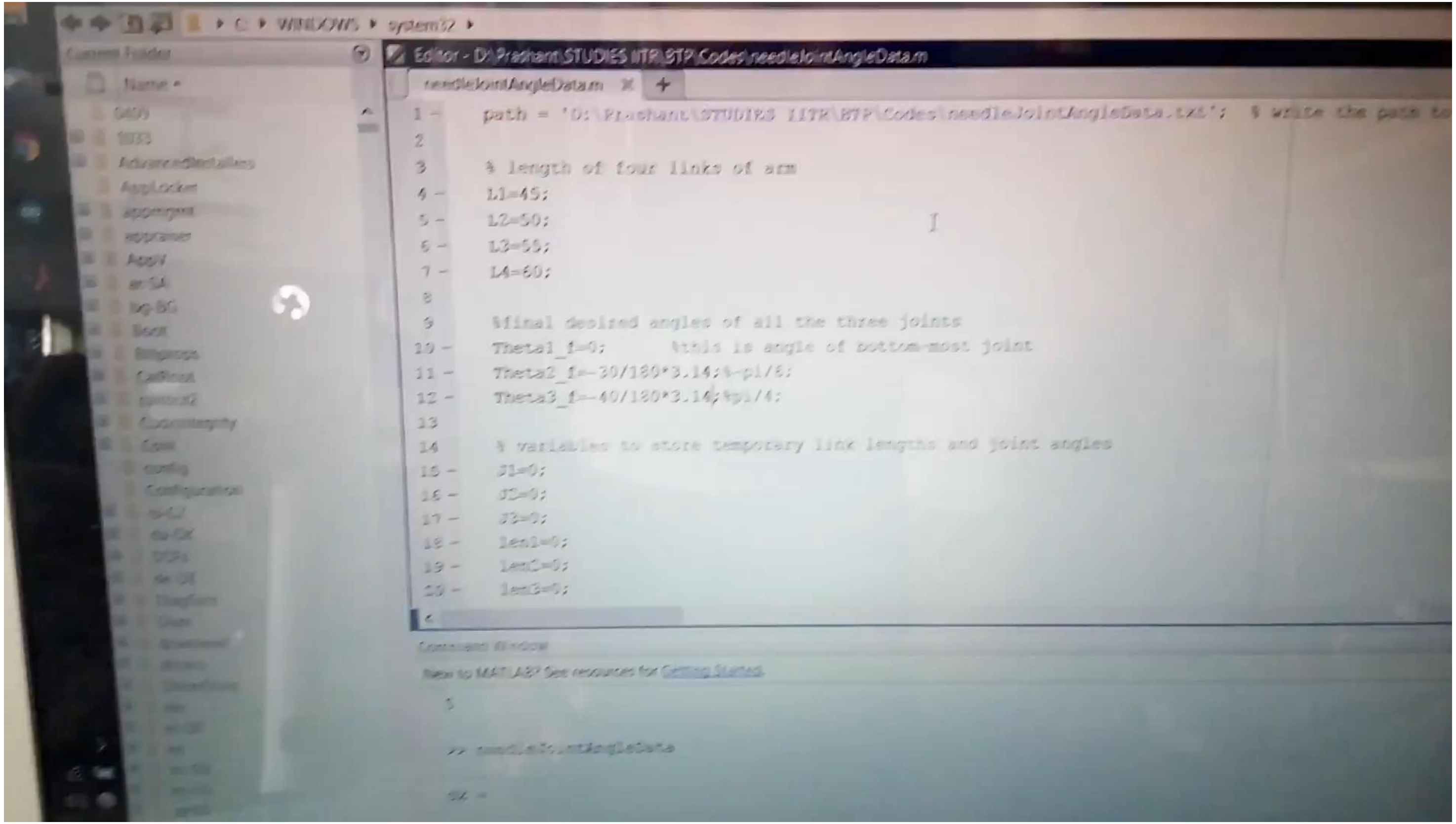
Fabricated Needle



Simulation



Working Demo



Thank You!