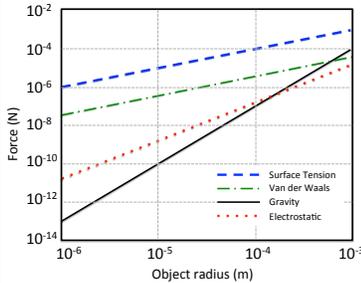


Motivation

- Perform fundamental research related to transitioning robotics manipulation from the macro-scale to the micro-scale.
- Lay the foundations for micro-robotic tools

	Macro-Scale Robotics	Micro-Scale Robotics
Phyics-Based Engines/Simulators	YES, open-source	NO
Motion-Planners with Length Scale Effects	YES, open-source	NO
Grasping Databases	YES, open-source	NO
ROS support/packages	YES	NO
Force Sensors	Yes, multi-axis commercially available	AFM (nN), single axis force probes (μN) commercially available, multi-axis in research only
Torque Sensors	Yes, multi-axis commercially available	NO

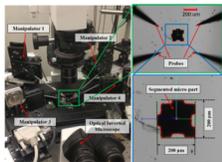


Micromanipulation Using a Learned Model

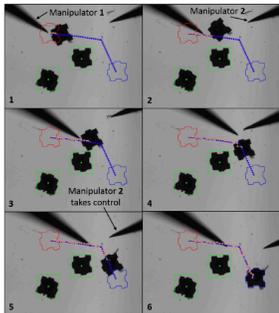
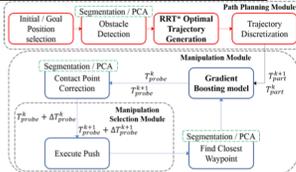
Motivation

- Motion primitives have been used in the past for 2D push-based micromanipulation
- Best motion primitives may not be intuitive
- Multi-contact problem, friction, interaction dynamics at micro-scale is difficult to model
- Goal: Learn how to manipulate micro-parts

Testbed

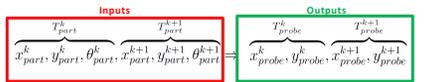


System Work Flow & Experimental Results



Micromanipulation Model

- Multi-target regression problem
- Gradient Boosting algorithm applied
- Input: initial and final configuration of part
- Output: Probe initial and final positions
- Separate model for each manipulator
- Contact modelled as a point contact

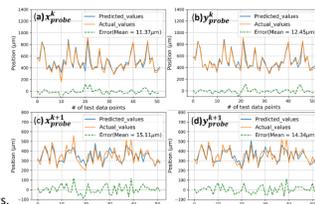


Implementation Considerations

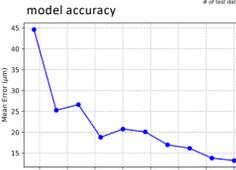
- Contact point correction routine to compensate for model inaccuracies
- Manipulator selection based on part workspace location and next waypoint
- Trajectory discretization to ensure spacing corresponding to training data pushes
- After every push, a waypoint on trajectory closest to current position is chosen as the final goal position for the next push

Model Results

- Cross-validation results



- Training samples vs. model accuracy



Current & Future Work

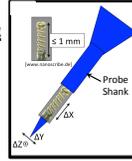
- Automated training and use of all 4 manipulators
- Incorporate micro-force data into learned models
- Apply surface coatings on substrate and common grounding for substrate and probes for more predictable motions
- 2D \rightarrow 3D $\mu\text{manipulation}$

Vision-Based Micro-Force Sensing

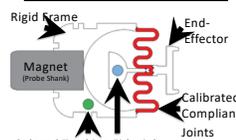
Goal 1

- Develop a new class of manipulation probes for use as 3D vision-based micro-force sensors

3D Vision-Based Micro-Force Sensing Probe Concept

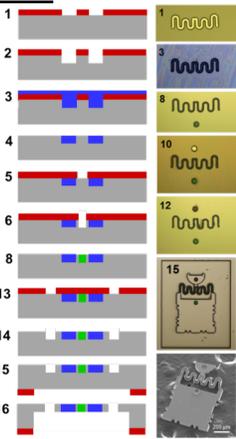


2D Mobile Microrobot Version



Microfabrication Process

- Multi-step photolithography process
- Trenches for the spring structure and tracking fiducials created
- Colored PDMS is then applied and cured sequentially.
- Rigid frame obtained by etching the silicon wafer
- Backside etching frees the structure
- Magnetic body (probe shank) manually assembled to the frame



Stiffness Calibration & Sensing Resolution

Robot #	Spring Color	Stiffness (N/m)	Sensing Range (μN)	Resolution (μN)			
1	Light Red	0.250	0.569	0.111	1.36	2.38	
2	Light Red	0.653	0.538	0.401	0.100	4.02	3.24
3	Dark Red	0.669	0.667	0.41	0.100	0.96	6.29
4	Dark Red	0.662	0.186	0.41	0.31	0.38	1.15
5	Dark Red	0.111	0.196	0.161	0.440	0.81	1.31
6	Light Blue	0.164	0.215	0.133	0.25	1.01	1.33
7	Dark Blue	0.687	0.111	0.133	0.360	0.55	1.60

Real-Time Tracking

- Color-based tracking of fiducials at 20 Hz
- Accuracy error less than $\pm 1 \mu\text{m}$

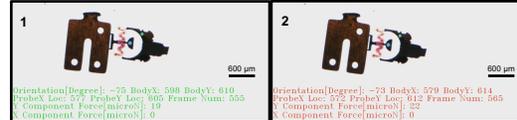


Current & Future Work

- Explore 3D stiffness designs
- Integrate into probe shank
- Testing with 3D vision-system

Experimental Results

- Apply desired micro-force to micro-part at specified location
- Provide real-time micro-force information to user



Goal 2

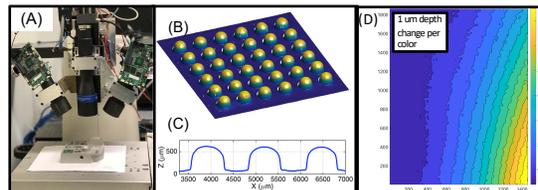
- Develop a multi-resolution 3D vision-system to provide sub-diffraction limit tracking for sensing in the micro-telepoperation and augmented reality system

Current Prototype

- Image Field of View: 75 mm x 75 mm
- Spatial resolution: 10 μm
- Depth resolution: 1 μm

Future Prototype

- Image Field of View: 25 mm x 25 mm
- Spatial resolution: 5 μm
- Depth resolution: 300 nm

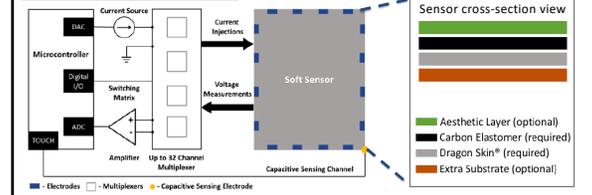


Sensing Skin for Human-Robot Interaction

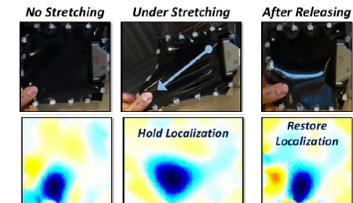
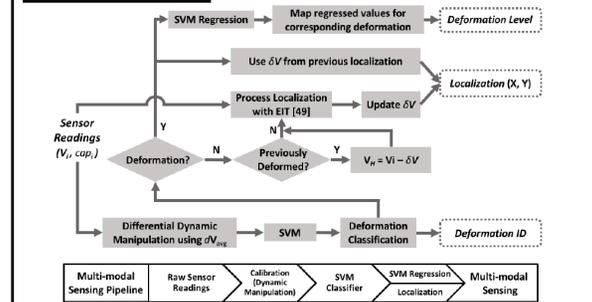
Goals

- Develop haptic tools/skins to accurately relay micro-scale manipulation forces to the teleoperator
- Capture manipulation and force data to develop new autonomous micromanipulation primitives

Multimodal Soft Sensor Concept



System Work Flow & Results



Current & Future Work

- Micro-telepoperation and AR experiments
- Develop interaction metaphors (glove, haptic tool, etc.) to provide manipulation intent
- Use sensing skin to develop data acquisition schemes to track interactions
- Combine sensing skin with haptic feedback on interaction tools

Sensing Skin Embedded into Human Interaction Tools



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