# Human-Supervised Manipulation of Deformable Objects

## Next Generation Collaborative Medical Robotic Systems Towards Intelligent Robotic Surgical Assistants

M. Cenk Çavuşoğlu, PhD

Department of Electrical, Computer, and Systems Engineering
Case Western Reserve University, Cleveland, U.S.A.

http://engr.case.edu/cavusoglu_cenk/
http://robotics.case.edu/

**This is a Collaborative Research Project supported by the National Science Foundation National Robotics Initiative under awards IIS-1524363 (Cavusoglu, CWRU) and IIS-1524420 (Berenson, Univ. of Michigan).**

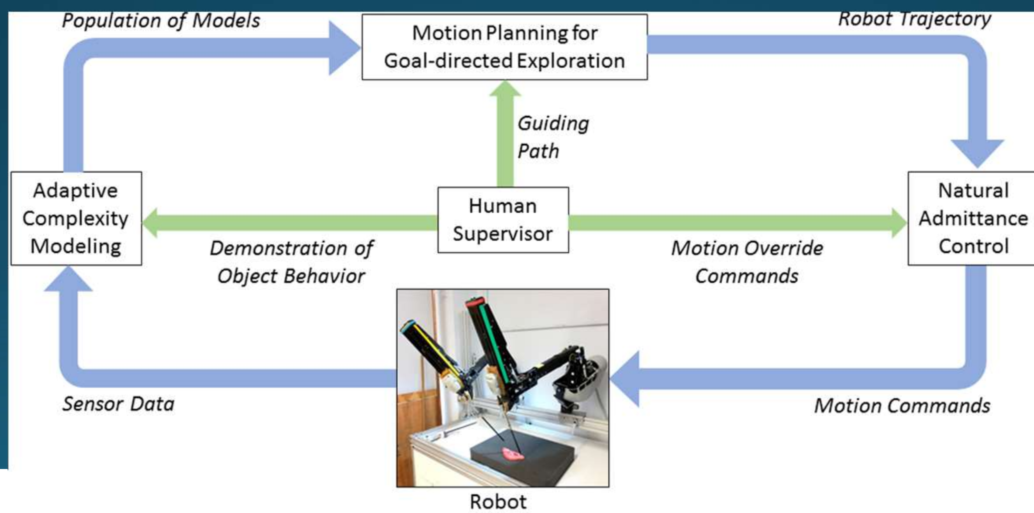
# *Human-Supervised Manipulation of Deformable Objects*

*Goal:*

- Develop algorithms that enable human-supervised robotic manipulation of deformable objects under substantial uncertainty

*Research Thrusts*

- **Modeling:** Modeling deformable object dynamics and associated uncertainty,
- **Planning:** Planning algorithms for integrated exploration and task execution,
- **Control:** Control algorithms for robust manipulation of deformable objects under uncertainty,
- **Human Supervision:** Algorithms for effective human supervision of robotic manipulation of deformable objects



# Intelligent Robotic Surgical Assistants

GOAL: Robotic system to act more like an assistant and less like a follower

- Provide robotic surgical systems with low-level task automation capabilities
- Surgeon will have a high-level interaction with the system rather than low-level direct teleoperation
- System assist in basic manipulation tasks, such as, retraction, dissection, exposure, suturing
- Reduce tedium from simple, repetitive tasks; assist in complex manipulation tasks; reduce cognitive load

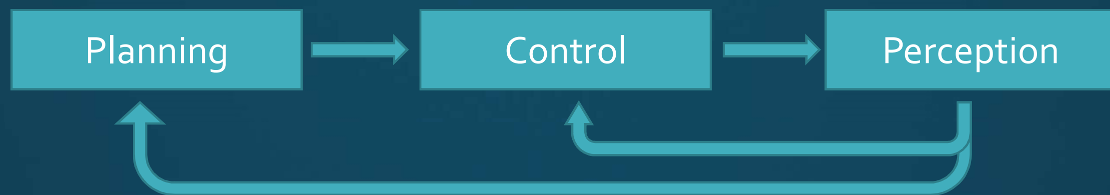
# Research Focus

- Low level surgical manipulation capabilities for delicate deformable objects

**Target tasks:**

- Retraction
  - Key skills / algorithms for manipulation of deformable objects
- Surgical suturing + knot tying
  - Arguably most complex dexterous bimanual manipulation task in minimally invasive surgery

# Research Focus




- **Perception**
  - Estimation of deformable object boundary constraints and material parameters
    - For simultaneous manipulation and planning
  - Localization and tracking of surgical thread, needle, and tools
    - For vision based control
  - Needle-tissue interaction force state estimation
    - For force based control
- **Planning**
  - Needle path planning
  - Optimal needle grasp and entry port planning
  - Dual-arm needle manipulation planning
- **Control**
  - Visually-guided manipulation
  - Knot tying

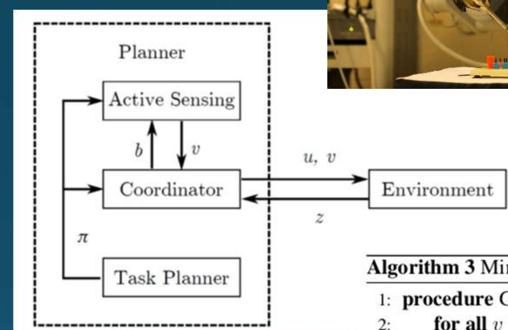
# Task Action Entropy Based Active Sensing

## Research Challenges

- Planning under uncertainty
  - POMDP – general but online solution not practical for high dimensional systems
- Decouple state estimation from planning
  - (Active) sensing for state estimation
  - Belief state planning
- Active sensing for state estimation answers "Where am I?" rather than "Do I know what to do next?"

## Approach

- Control actions partitioned to sensing actions and task actions
- Sensing actions are chosen to minimize the conditional entropy of future task actions




**Algorithm 3** Minimum Task-Action Entropy Active Sensing

**procedure** GETSENSINGACTION($\pi, \mathcal{P}_x$)
  **for all** $v \in \mathcal{V}$ **do**
    $h_v = 0$
    **for** $i = 1, \ldots, M$ **do**
      sample $x$ from $\mathcal{P}_x$
      sample $z$ from $p(z|v, x)$
      $\mathcal{P}'_x = \text{MeasurementUpdate}(\mathcal{P}_x, v, z)$
      $\mathcal{P}_u = \pi(\mathcal{P}'_x)$
      $h_v \mathrel{+}= h_{\mathcal{P}_u}(u)$
    **end for**
  **end for**
  **return** $\text{argmin}_v\, h_v$
**end procedure**

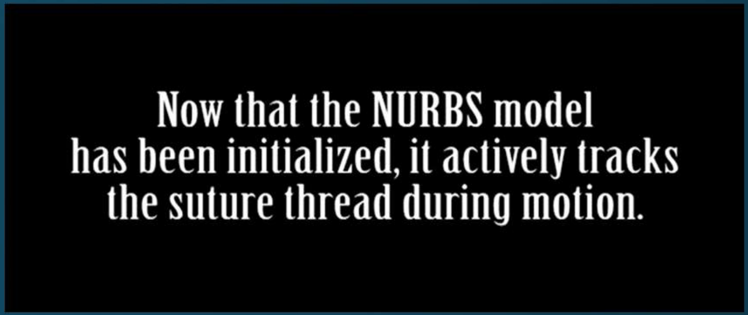
# Dynamic Tracking of Surgical Threads

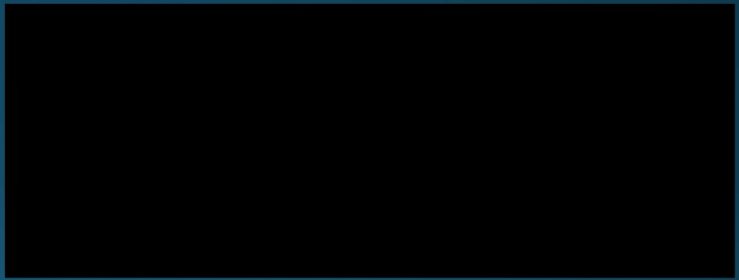
### Research Challenges

- Tracking of one dimensional deformable objects
- Computationally efficient algorithm for use in visually guided control
- Not rely on detailed a priori knowledge of parameters and material properties
- Handle complex topology, such as, overlaps and knots

### Approach

- The suture thread is modeled as a NURBS curve
- Image segmented using a thin feature extraction method which identifies local thread direction
- The model is projected into stereo image space
- The model deforms using image energy
- The model tracks the suture thread in real-time



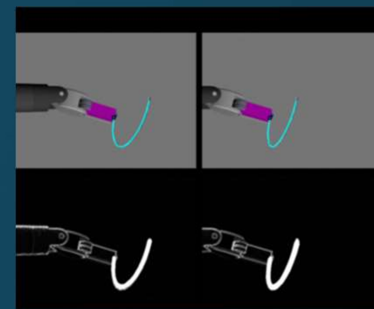
# Dynamic Tracking of Surgical Needle

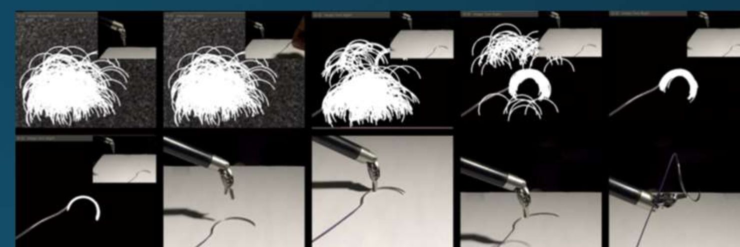
## Research Challenges

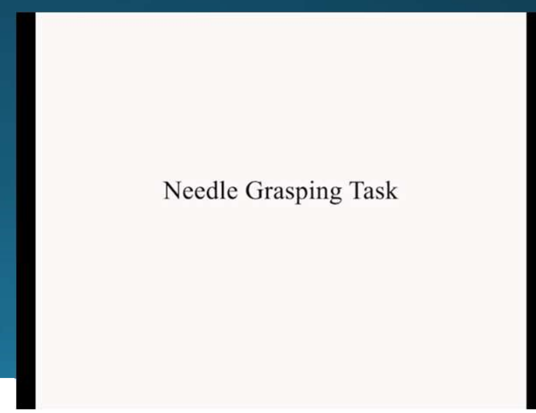
- Success of needle driving task relies heavily on the accuracy of needle grasp
- Substantial uncertainty in a priori needle pose
- Frequent occlusions with tools and tissue
- Computationally efficient algorithm for use in visually guided control

## Approach

- Vision-guided Bayesian state estimation from stereo endoscopic image streams
- Image segmented using a thin feature extraction methods
- Kinematic information of the tools provides needle motion prediction
- The model is projected into stereo image space
- Image space similarity measure
- Needle pose is tracked in real-time



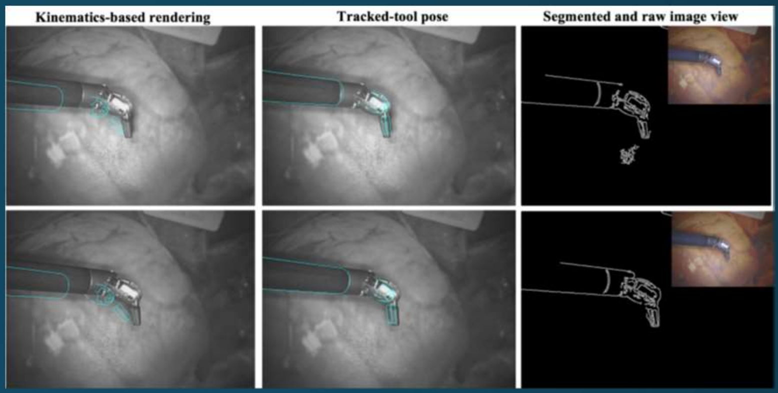




# Dynamic Tracking of Robotic Surgical Tools

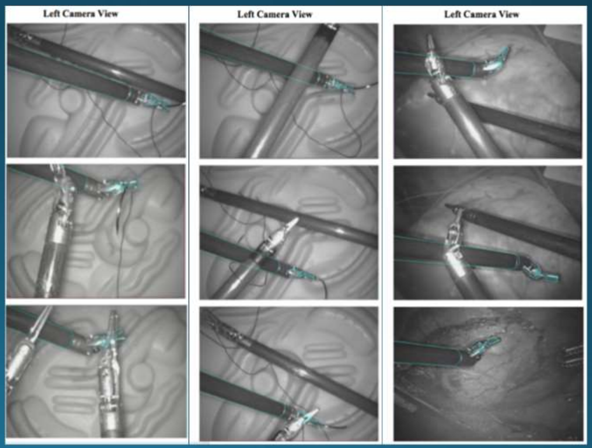
### Research Challenges

- Uncertainty in hand-eye (i.e., robot-camera) calibration
- Frequent occlusions of tools
- High dimensional state estimation problem
- Computationally efficient algorithm for use in visually guided control




### Approach

- Vision-guided Bayesian state estimation from stereo endoscopic image streams
- Kinematic model of the robotic system provides tool motion prediction
- Image space similarity between the predicted tool image and the observed image



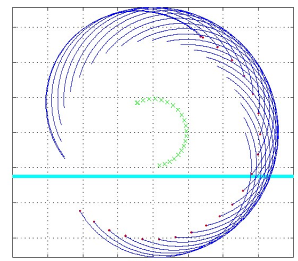
# Needle Path Planning and Control

## Research Challenges

- Minimize tissue tear and trauma
- Substantial uncertainty in geometry
- Needle sweeps out an area that create internal tissue stresses
    - No direct way of measuring due to cutting and friction forces

## Approach

- Modeling of interaction forces
    - Computationally efficient for real-time planning and control
- Unscented Kalman Filter to estimate different force components
- Select needle driving trajectories that minimize tissue tearing forces

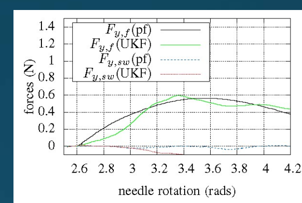


$$\mathbf{f}_{needle}(\phi(t)) = \mathbf{f}_{friction}(\phi(t)) + \mathbf{f}_{cutting}(\phi(t)) + \mathbf{f}_{normal}(\phi(t))$$

$$\mathbf{f}_{friction}(\phi(t)) = \int_{\theta_0(\phi)}^{\theta_1(\phi)} -\mu_s \mathrm{d}\ell(\theta)\, \mathrm{d}\theta$$

$$\mathbf{f}_{normal}(\phi(t)) = -\mathbf{K} \int_{\phi(0)}^{\phi(t)} \int_{\theta_0(\phi)}^{\theta_1(\phi)} \mathrm{d}\mathbf{a}_n(\phi, \theta)\, \mathrm{d}\theta\, \mathrm{d}\phi.$$

$$\mathbf{f}_{cutting}(\phi(t)) = -\min(\alpha, (\theta_{tip} - \theta_s)^2 \beta) \mathrm{d}\ell(\theta_{tip})$$





Video at x3 speed

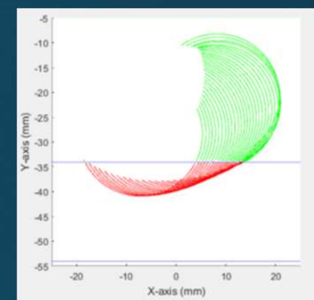
# Needle-Tissue Interaction Force State Estimation

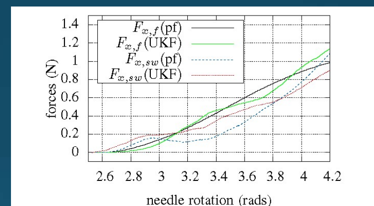
## Research Challenges

- Successful needle drive minimizes tissue trauma
- As needle moves through the tissue it sweeps out an area that create internal tissue stresses
- No direct way of measuring tissue deformation forces, as force sensor data will also include cutting and friction forces

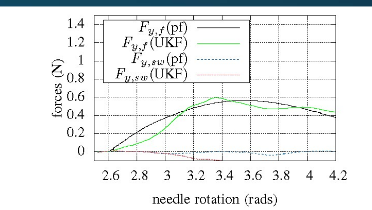
## Approach

- Unscented Kalman Filter to estimate different force components
- Validated using experiments with phantom and *ex vivo* tissue

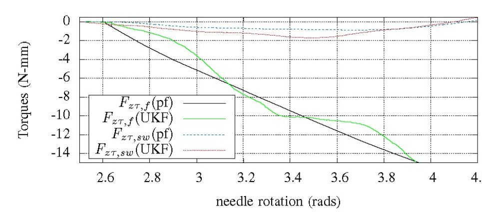



(c) Component breakdown of the $x_n$ force for both the parameter fitted (pf) and UKF models.




(d) Component breakdown of the $y_n$ force for both the parameter fitted (pf) and UKF models.




(e) Component breakdown of the $z\tau$ torque for both the parameter fitted (pf) and UKF models.

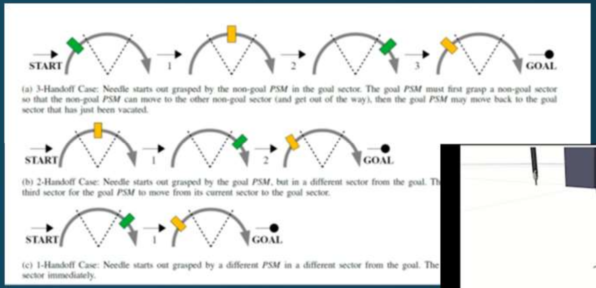
# Dual-Arm Needle Manipulation

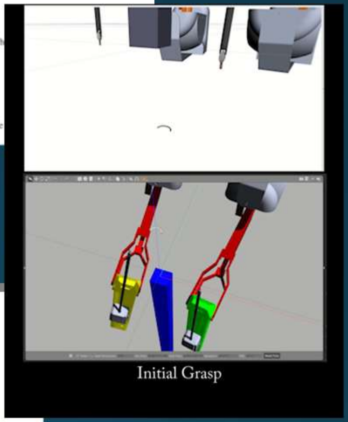
## Research Challenges

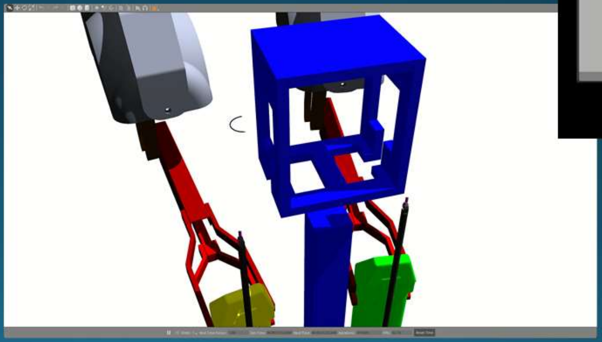
- Needle grasping and re-grasping requiring multiple needle handoffs
- Each handoff introduces uncertainties
- Limited workspace

## Approach

- Hybrid state space motion planning using RRT
- Visual guidance coupled with local partial replanning



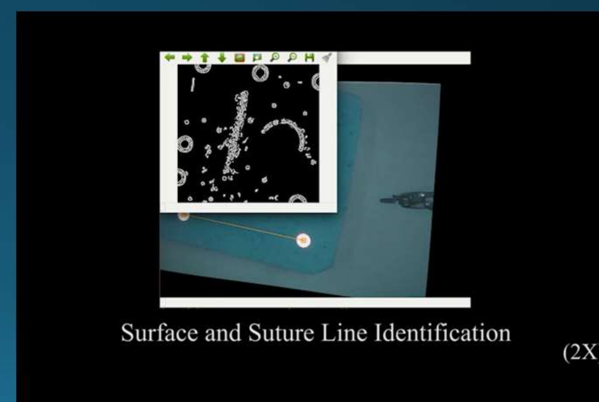
# Visually-Guided Manipulation

## Research Challenges

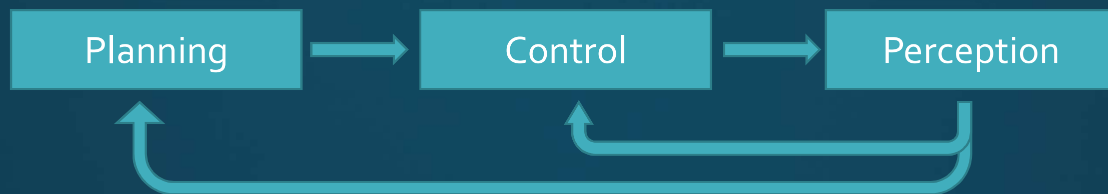
- Managing uncertainties
- Minimize real-time sensory feedback
- Limited calibration

## Approach

- Supervisory control
- Model-based tracking of key
- Vision-guidance at key steps

# Next Steps




- Further advances in task automation
  - More tightly integrated perception+planning+control
  - Planning of more complex manipulations
  - Compliant motion control based manipulation algorithms
- More complex manipulation tasks
- Effective user interfaces
- Implementation on the dVRK system and open source release of the algorithms