Human-Supervised Manipulation of Deformable Objects

Next Generation Collaborative Medical Robotic Systems Towards Intelligent Robotic Surgical Assistants

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PROJECT GOAL

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

- **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 THRUSTS

- **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

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RESEARCH HIGHLIGHTS

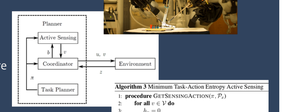
Task Action Entropy Based Active Sensing

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(·, P_t)
  for all v ∈ V do
    h_v := 0
    for i = 1, ..., M do
      sample x from P_t
      sample z from p(z|x, v)
      P'_t := MeasurementUpdate(P_t, v, z)
      h_v := h_v + h_{P'_t}(u)
    end for
  end for
  return argmin_v h_v
end procedure
```

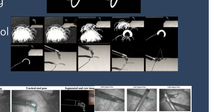
Dynamic Tracking of Surgical Needle, Thread, and Tools

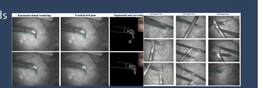
Research Challenges

- Success of suturing task relies heavily on the accuracy of needle, thread, and tissue grasping
- Substantial uncertainty in a priori pose information
- Handle complex topology, such as, overlaps and knots
- Tracking of one dimensional deformable objects for thread tracking
- 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, tools, and thread are tracked in real-time





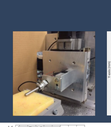
Needle-Tissue Interaction Force State Estimation

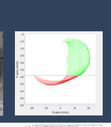
Research Challenges

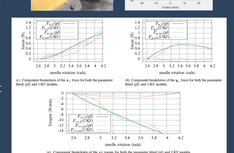
- Successful needle drive minimizes tissue trauma
- As needle moves through the tissue it sweeps out an area that create internal tissue stresses
- No direct way of measuring tissue deformation forces, as force sensor data will also include cutting and friction forces

Approach

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







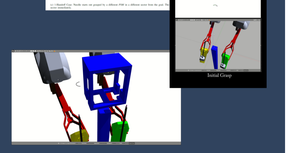
Dual-Arm Needle Manipulation

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



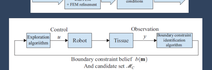
Estimation of Boundary Constraints and Tissue Parameters

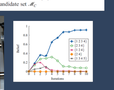
Research Challenges

- Response of deformable object models used by motion planners depend heavily on boundary constraints and material parameters
- Knowledge of anatomical configuration is limited
- Inter- and intra- subject variability of tissue parameters
- Environment modified in unpredictable ways during surgical manipulation

Approach

- Identification and active exploration of boundary constraints
- Estimation of mechanical parameters from manipulation data





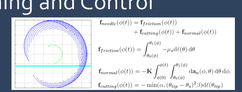
Needle Path Planning and Control

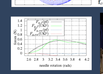
Research Challenges

- 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





Video at x3 speed

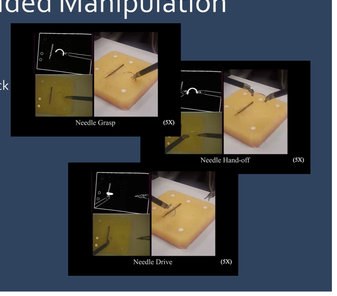
Visually-Guided Manipulation

Research Challenges

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

Approach

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



Autonomous Knot Tying

Research Challenges

- Managing uncertainties
- Minimize real-time sensory feedback
- Dexterity limitations
- Bimanual coordination with limited calibration

Approach

- Specialized knot tying strategies for managing uncertainties
- Vision-guided control at key steps

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