Real-Time 3D Reconstruction of Dexterous Continuum Surgical Robots

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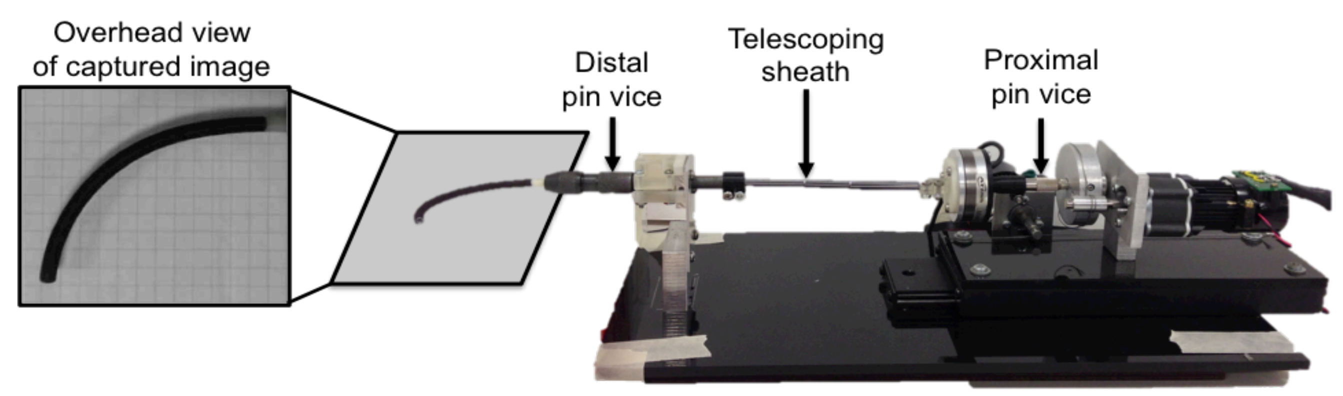
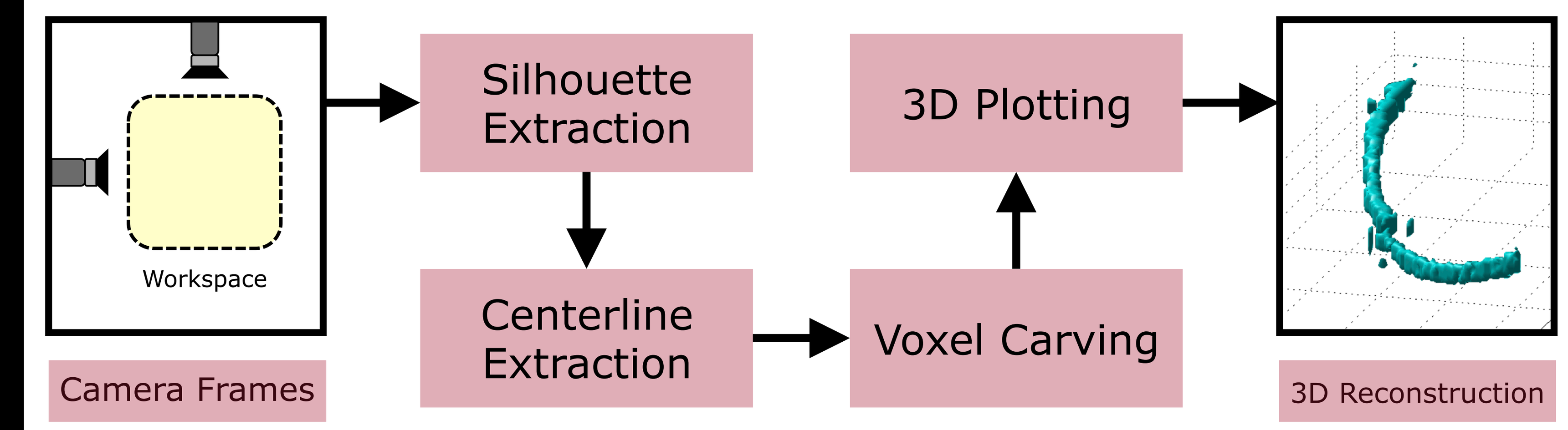
Background & Motivation

A class of dexterous continuum robots known as concentric tubes has been used for a wide variety of applications. Researchers in the medical field have focused on their use as surgical tools, due to their ability to reach remote areas within the body by moving in highly curved paths. They consist of hollow, pre-curved elastic tubes that fit concentrically, each one inside the next. As the tubes are rotated and inserted relative to each other, their curvatures interact to change the robot's overall shape as well as its tip position [1,2]. Although there are numerous models for the mechanical behavior of concentric tube robots, in practice, knowing the actual configuration at a given instant is a challenge.



Pipeline



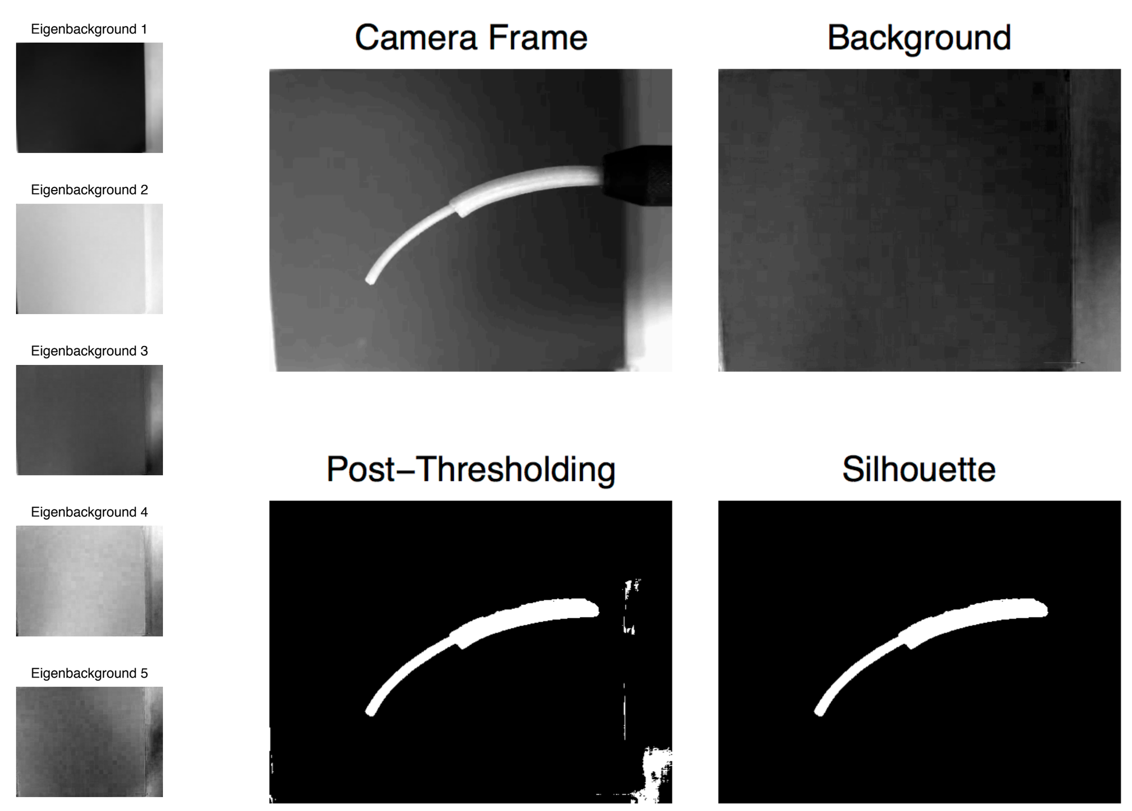
Silhouette Extraction

Pre-Computation

1. record background video to capture:
   - lighting variations
   - camera jitter
2. create eigenbackgrounds via Sirovich & Kirby algorithm
3. select N = 5 eigenbackgrounds with largest eigenvalues

Online Computation

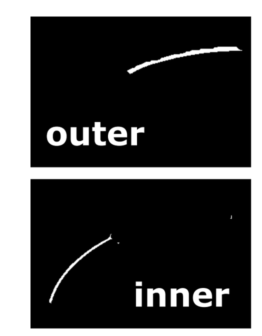
1. project current frame into eigenspace, preserving only background elements
2. project back from eigenspace into full image-space
3. subtract back-projected frame from original frame
4. binarize via thresholding
5. remove all 1-regions except one with most pixels



Morphological

1. erode with a circular SE to eliminate inner tube, then subtract result from original image

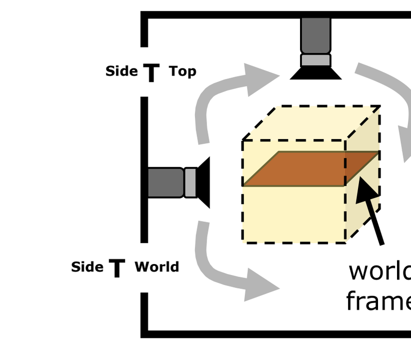
2. perform 2 erosions:
   1. on eroded image using a large circular SE to extract centerline of outer tube
   2. on difference image using a small circular SE to extract centerline of inner tube

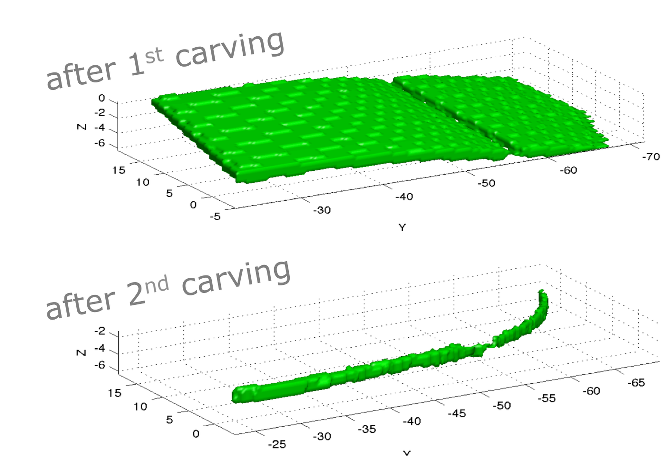


3. remove small regions and combine images to create centerline for entire tube robot

Voxel Space

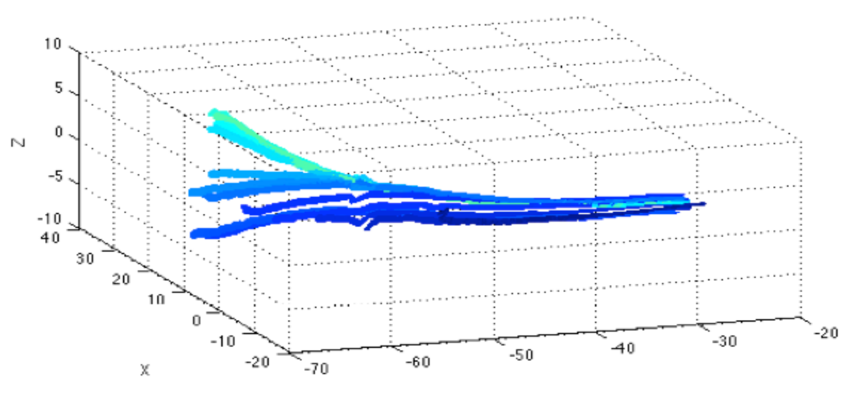
1. calibrate cameras (offline) to obtain intrinsic and extrinsic parameters for transformation matrices
2. create volume of voxels based on size and location of silhouettes
3. project voxels into side image frame
4. "carve" away those voxels with projections that fall outside of side image centerline
5. project remaining voxels into top image frame
6. "carve" away those voxels with projections that fall outside of top image centerline
7. clean up final set of voxels and draw 3D reconstructed backbone

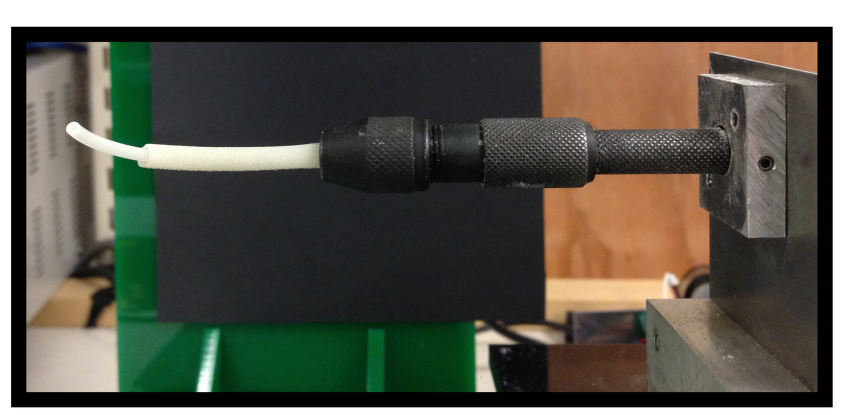




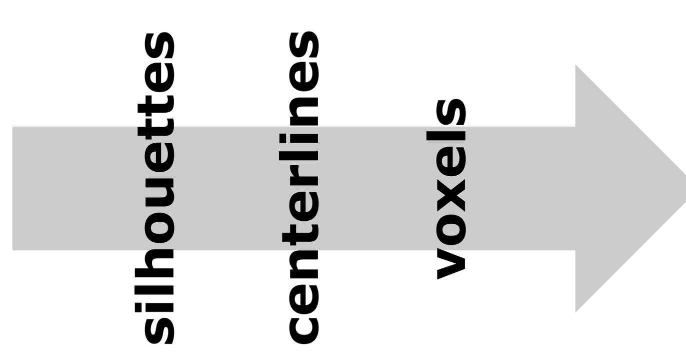
Results

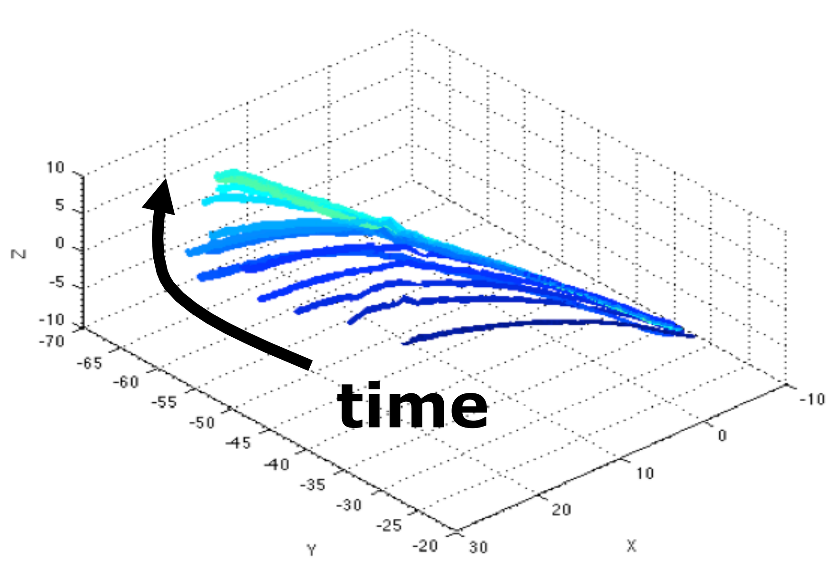
The image processing algorithms described above were integrated with the live streaming of video from the top and side cameras, along with the automated insertion and rotation of a 2-tube concentric tube robot. The current pipeline grabs a frame from each camera every time a reconstruction is completed. This loop has not yet been optimized for speed, and runs at about 15 seconds per frame. Based on this rate, the inner tube was inserted and rotated (using the 2-DOF actuation unit pictured), and the resulting reconstructions are shown. The color progresses from dark to light blue with increasing time.





The final configuration of tube robot as viewed from the side.





Future Work

- improving visualization with smoother plotting
- increasing speed and efficiency of the processing pipeline, perhaps via model-based reconstruction or "eigentubes"
- incorporation of a check for temporal consistency between video frames
- real-time display in an Oculus Rift VR headset for a more immersive experience and more realistic representation of the robot
- using reconstructions to assess the accuracy of newly developed kinematic models

Acknowledgments

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