Academic Program and Career Goals

In general, what is your area of focus within your field of study? (50 words max)

My research uses robots to inspect and maintain space habitats like the International Space Station and the Deep Space Gateway. Robotics is a multidisciplinary field. Its subdisciplines include areas such as actuation, sensing, manipulation, locomotion, localization, navigation, human-robot interaction, dynamics, and control. I focus on sensing and manipulation.

If you have a dissertation/major show/project associated with your doctorate, provide the title and a lay summary. (200 words max)

Representing and Manipulating Deformable Linear Objects

My thesis work develops algorithms to perceive and manipulate deformable objects with robotic arms. Examples of this for humans are reaching for a wire to plug in or unpacking a briefcase; people perform these actions using active sensing. Humans use their hands to feel for grasp points and their eyes to obtain real-time feedback on the object's state. My goal is to give robots these skills to prepare them to care for human habitats. I focus on deformable linear objects, for instance wires, because they are ubiquitous in space and on Earth; wire maintenance is paramount to safe exploration of extreme environments. Deformable objects present unique manipulation challenges as they do not follow simplified models of physics that describe rigid body motion. Any force applied by a robot to a deformable object induces both motion and shape change. A large body of work studies deformable object physics modeling, but these models must be computed offline and cannot be used in real time. Humans do not explicitly know how a deforming object's shape will change under contact but solve this problem through sensing, feedback, and practice; robots need to learn to do the same.

What milestones towards your doctorate do you have left to complete (coursework, boards/exams, dissertation steps, etc.)? Show expected dates. (100 words max)

Milestone	Expected Date
Conference and journal submissions	2023-2024
International Astronautical Congress conference presentation	October 2023 October 2024
Complete seminar attendance requirement (final course requirement)	May 2023
Assemble thesis committee	Spring 2023
Preliminary Examination	December 2023
International Conference on Robotics and Automation conference presentation	May 2024 May 2025
Final Examination	Summer 2025
Thesis Deposit and Graduation	Summer 2025

What led you to this field of study/profession/degree, and what excites you about it? (150 words max)

In 2017, I joined NASA Marshall's Artemis risk assessment team. I watched the Artemis program develop from a unique vantage through visiting partner sites in Utah, Florida, and Texas and attending design reviews. During one review, I realized a design modification risked mission loss and I presented my assessment to the Chief Safety Officer. Because of my observation, the system impacted was thoroughly tested for reliability and I received a leadership award from astronaut Jan Davis. This inspired my goal of advancing space technology for *human space exploration*. It led me to graduate school at Stanford and UIUC where I researched robot autonomy for NASA Ames's Astrobee robot. Astrobee inspires me as NASA's only robotic assistant dedicated to improving astronaut efficiency rather than serving as a substitute for a human on an exploration mission. I want to create a future in space where humans are helped by robots, not replaced.

What led you to the choice of your current university? (150 words max)

I selected the University of Illinois at Urbana-Champaign (UIUC) for graduate studies based on its strong departmental reputations (top-ten rankings) in aerospace engineering, electrical engineering, computer engineering, mechanical engineering, and computer science. My research is in the multidisciplinary field of robotics. UIUC's reputation for conducting high-caliber research and attracting top talent in these related fields was an important consideration. The university's community of collaborators, advocates, and early adopters is important to increasing the impact of my research. I chose to work with Dr. Tim Bretl because of his reputation for deploying innovative systems for the betterment of society. The work of Dr. Bretl's students is distinguished by its game-changing and applied nature: students can create innovative solutions that develop from idea to useful product in the short time span of their studies. Dr. Bretl and I share an aligned vision for the roles autonomous systems should play in the future.

What are your specific career goals, and what impact do you hope to have? (100 words max)

I intend to use robots to help humans explore and develop extreme environments. Beginning with postdoctoral research, I hope to accomplish this at a national robotics research institution such as NASA (space), NOAA (ocean), or the NSF (Antarctic). In these environments, robots will automate tasks in dangerous conditions where exposure to radiation, temperature, dust, or micrometeoroids poses health risks. Robots need to automate routine maintenance tasks so workers can focus on more challenging problems. Ultimately, I aspire to become an astronaut, collaborating with robots on other worlds, such as the moon or Mars, to establish permanently inhabited space outposts.

If you were to receive the Scholar Award, for what expenses would you allocate the funds? As a reminder, use of funds is for <u>necessary expenses</u> incurred while pursuing a doctoral-level degree; funds are not to be used for debt reduction (educational or personal). No detailed budget needed, but be as specific as you can. Please refer to PSA policies. (200 words max):

I plan to use a portion of the scholarship funds to pay for necessary research equipment, including a research computer designed to train deep learning models for object detection which can meet the processing requirements of real time perception (~$7,000). A portion of the scholarship funds will offset expenses associated with disseminating research findings through participation in international space and robotics conferences, namely:

- The 2023 International Astronautical Congress in Baku, Azerbaijan (~$3,000)
- The 2024 International Astronautical Congress in Milan, Italy (~$3,000)
- The 2025 AAS/AIAA Space Flight Mechanics Meeting in Kaua'i, Hawai'i, USA (~$3,000)

The remainder of the funds will offset duplicated living expenses incurred during the planned ten-week Visiting Technologist Experiences (VTEs) to NASA Johnson Space Center and NASA Ames Research Center. During these experiences, I face expenses related to maintaining my residence at my university.

Proposal

Describe your research. Include an overview of 1. your project; 2. your methodology; 3. the source of your data; 4. the significance of the project; 5. other information of relevance, including findings, patents, etc. Avoid scientific/technical jargon. (1000 words or less).

Project

My thesis work develops algorithms to perceive and manipulate deformable objects with robots. My goal is to give robots these skills to autonomously care for future space habitats such as Gateway, the Artemis Base Camp, and Mars missions. Robots caring for space habitats must be able to identify the types of objects (e.g., "ethernet wire") and specific instances of these objects (e.g., "EW-001") from raw images to gain actionable information. I focus on deformable linear objects, such as wires, because they are ubiquitous: wires appear in all settings where energy or information is transmitted. Wire management is paramount to the safety and functionality of human environments.

Manipulation is an agent's control of its environment through contact. It involves motion: picking up, moving, and modifying objects. Deformable objects present unique manipulation challenges since they do not follow simplified models of physics that describe rigid body motion. Manipulation of deformables is especially challenging for robots which lack the same understanding of physics humans learn through interaction with their environment. However, robots can perceive motion and shape change in camera imagery. I develop autonomous network inspection and maintenance with robots which identify a hardware failure using perception, integrating three research thrusts:

1. *Instance segmentation*. This is detecting, classifying, localizing, and segmenting individual objects. The key technical challenge is obtaining quality segmentation masks for wires which may be occluded and lack visual features.
2. *Grasp planning*. This is identifying contact points on objects for manipulation. The key technical challenge is identifying a grasp strategy which results in only desired object motion.
3. *Tracking*. This is tracking the motion of wires as they are manipulated. The key technical challenge is tracking partially occluded wires.

Data and Methodology

Instance segmentation

Instance segmentation identifies and locates objects in a scene. It is an input to grasp planning and wire tracking. I created a dataset of annotated images of network devices and ethernet wires against a blank background and used data augmentation to scale the number of images in the dataset. The dataset was used to train an instance segmentation deep learning model and evaluate its performance. A model trained on data annotated without object occlusion explicitly represented in the data ("Object Segment Semantics" or OSS annotations) yielded better performance than a model trained on data which explicitly included occlusion for the same images. The object instance segmentation masks were applied to depth imagery to obtain a 3D description of the shape of individual objects in complex scenes (Figure 2).

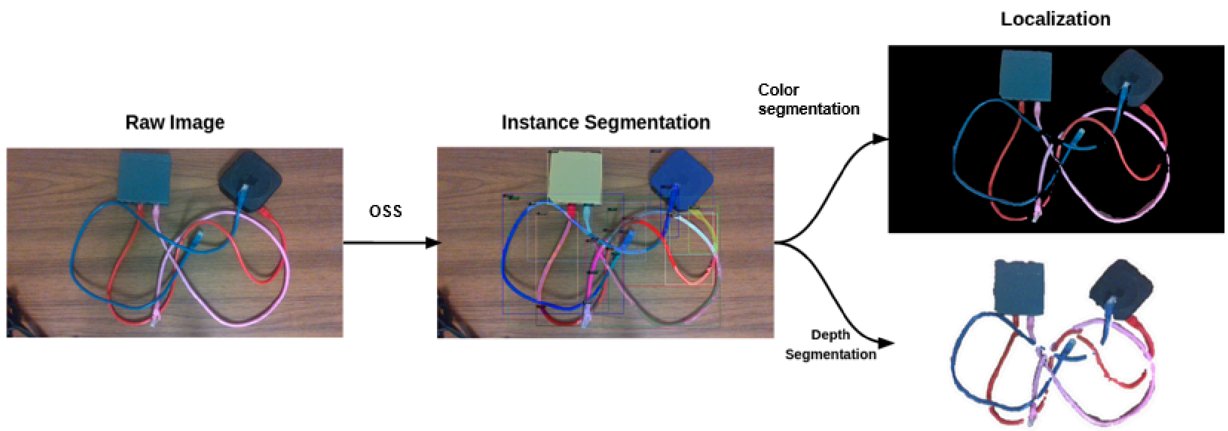

Figure 2: An image is segmented using a model trained on our dataset with OSS annotations. The predicted instance segmentation is used to segment the corresponding depth image to obtain a 3D description of the shape of individual objects.

Grasp planning

Grasp planning is finding the pose of an object so that a robot can grasp it. The 3D wire shape description from instance segmentation was used to locate the wire in the robot's world frame and identify a tip point, the point in the 3D shape description farthest from all other points. The points closest to this tip point were used to geometrically compute the orientation of the tip. Given the object's pose, the robot was aligned with the tip to grasp it. This tip computation method was validated in experiments with a real robot arm (Figure 3).

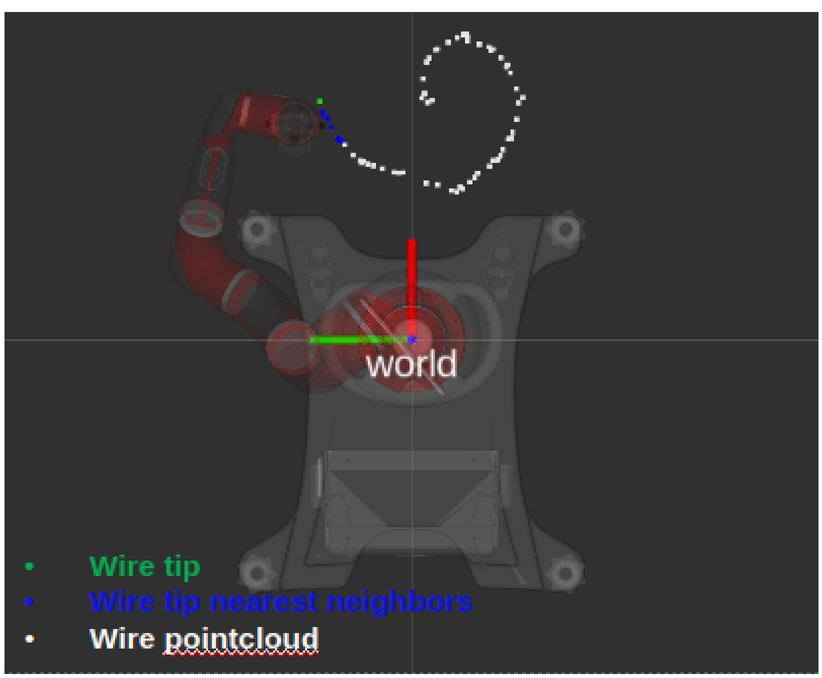

Figure 3: The wire tip was computed from the wire 3D shape description using geometry.

Tracking

Tracking is estimating the state of an object through time as forces are applied and it moves. The 3D wire shape description from instance segmentation is an input, which registers nodes to points along the segmented wire. Tracking produces the positions of these nodes – they are estimated and updated as the wire moves. I coauthored the "TrackDLO" algorithm. The algorithm introduces a new notion of distance along the wire to smooth the tracked motion, ensures the wire is not stretched or shrunk beyond a tolerance to make tracking estimates feasible, and interpolates the occluded tip's velocity from visible portions to accurately track this hidden part. TrackDLO yields a ten-fold improvement in tracking error versus the State of the Art (SOTA) for tracking under occlusion (Figure 4).

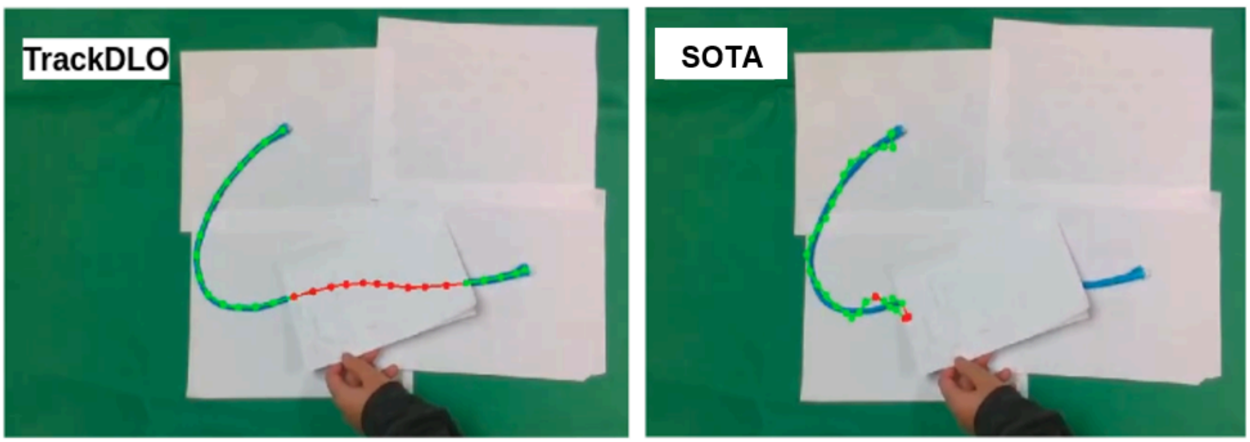

Figure 4: TrackDLO preserves total wire length to estimate the shape of the wire under occlusion without compressing the wire length. The SOTA algorithm does not preserve total wire length, increasing tracking error.

Findings

First, I automated dataset generation for training deep learning object detection models, and I made the procedure openly available for public use. Using conventional image processing techniques, I produced a labeled image dataset with thousands of unique images in only a few hours of computing. Similar manually generated datasets required tens of thousands of worker hours to produce. Second, I fully integrated two robot arms, two grippers, cameras, networking equipment, and a server computer in both hardware and software. I successfully demonstrated grasp planning in this system for grasping the tip of a wire. Finally, I coauthored a state-of-the-art method for wire tracking in real-time without physics modeling. This method enables new research directions in wire shape control during manipulation.

Significance

This research uses perception for autonomous equipment maintenance with caretaking robots. Wires lack visual features, can admit complex shapes, and present perception challenges that are difficult even for humans to resolve. However, wires are everywhere – on earth and in space.

Wire manipulation is an important skill for robotic assistants. Research toward wire perception and manipulation not only develops autonomy for human habitat caretaking, but also for applications such as drone power line avoidance; cable manufacturing; and mobile robot tether management. These new autonomous perception capabilities not only enable perception and manipulation of wires, but also introduce technologies for perception and manipulation of other categories of deformable objects such as cargo bags. A robot endowed with these new tools will be able to recognize and interact with objects efficiently and react to anomalies to ensure the safety and functionality of space habitats.