Personal, Background, and Future Goals Statement

Intellectual Merit

Attending a NASA Jet Propulsion Laboratory (JPL) Open House as a child was my "Aha!" moment that inspired me to pursue a career in STEM. Through grade school, I held my passion for space exploration close to heart through watching NASA broadcasts, participating in STEM clubs, and yearly visits to NASA centers. Working on a space mission became my dream job. Remarkably, about a decade later, I would attend Caltech and fulfill my dream of working on space missions at NASA JPL.

Early in my Caltech journey, I thought my career would follow this path of developing robotic rovers to explore faraway planets and moons. However, after three years at Caltech, my dream job has widened beyond what I imagined as a child. Now, my passion is to become a robotics researcher investigating the cutting-edge technologies that make space science research possible, while also improving life here on our home planet. For example, my research at NASA JPL on geologic sample analysis for NASA rovers is immediately applicable to the complex problems in perception for quality assurance on an assembly line.

With my new goal to enable scientific discoveries with robotics, understanding the interplay between engineering and science in the aerospace realm is essential. As such, I chose the unique path of majoring in Mechanical Engineering and minoring in Planetary Science. Over the past four years, I have contributed to conference and journal publications in three distinct fields that overlap in the topic of robotics: engineering, planetary science, and data science. As I prepare for graduate studies towards a Ph.D. in Aerospace Engineering at Stanford, Caltech, or MIT, I plan to focus my research towards investigating new computationally intensive techniques and technologies that address the current challenges in robotic autonomy. To prepare for my graduate studies, I sought experience in three key domains of robotics: perception, motion planning, and control systems.

My primary experience with perception systems comes from work at JPL starting at the end of my freshman year in the summer of 2018 and throughout the 2018-2019 school year. As part of the Europa Lander sampling team, I led the software and hardware development of a sample inspection station for the team's cryogenic vacuum chamber. Inside, a robotic arm excavates cryogenic ices and deposits the collected samples at the sample inspection station. The station had to overcome a multidisciplinary perception challenge of employing a cost-effective LIDAR system to recover the sample properties of robotically collected ices, while also battling a harsh 70K cryogenic environment. To surmount this challenge, I successfully developed a novel volume estimation technique, and I devised a hardware setup to match the software's needs. With such a large-scale research and engineering effort, I had to communicate design changes to many stakeholders beyond my immediate team. Interfacing across mechanical, manufacturing, thermal, operations, robotics, and software engineering teams, I learned the importance of teamwork, integrity, and accountability in STEM. This experience gave me the confidence to tackle complex interdisciplinary problems that are commonplace in perception and robotics research.

More recently, I took a deep dive into the motion planning sub-field of trajectory optimization in Prof. Zachary Manchester's Robotic Exploration Laboratory (REx Lab) at Stanford, which recently moved to Carnegie Mellon University. The software engineering skills and the awareness of the interdisciplinary nature of aerospace engineering that I learned at JPL, directly enabled me to investigate fast and robust methods for trajectory optimization for the rocket-soft landing problem. Through this computationally challenging research, I developed a novel augmented lagrangian solver from scratch in the Julia programming language that can achieve both the speed and robustness needed for real-time rocket landing applications. The method is also general enough to handle second-order cone constraints in other trajectory optimization applications, such as the friction problem in legged walking-robots. To wrap up the summer research, I presented my work at the Caltech SURF Conference and I am continuing my research with the REx lab to produce a conference paper for the 2021 International Conference on Robotics and Automation, a highly competitive conference in the robotics field.

As the fall term starts, I am beginning my senior thesis in Prof. Chung's Aerospace Robotics Lab at Caltech to expand my knowledge in control systems. Over the next year, I plan to build upon the lab's computational expertise to research spacecraft trajectory planning and control with learned dynamics and chance constraints for small body missions. This thesis will leverage recent developments in stochastic optimal control and neural networks to learn unknown system dynamics during flight. This research motivation came from enabling scientifically valuable orbits around small bodies, such as asteroids. However, the research is directly applicable to the unknown drone or vehicle dynamics experienced during adverse weather. By the end of this academic year, I will have combined my background in perception, motion planning, and control systems into a single project at the cutting edge of space engineering and robotics autonomy.

Complementing my engineering background, my unique path of minoring in planetary science has afforded me the ability to better connect research advances in the aerospace field with the broader impact on end-users in the scientific community. For example, as a project for a planetary formation and evolution class, I proposed a novel satellite constellation system for gas giants that extends the scientific efforts of Prof. Fuller's Saturn ring seismology work at Caltech using technologies from Prof. Chung at Caltech and Prof. D'Amico's research at Stanford in formation flying spacecraft. More recently, I have customized my planetary science coursework to better understand the interplay of remote sensing on spacecraft trajectories in the pursuit of Earth and planetary science research.

In summary, to pursue my goal of enabling scientific discoveries with robotics, I have simultaneously expanded my research skills in both hardware and algorithm development while also widening my theoretical knowledge in the fields of engineering and planetary science. With this robotics background, alongside my space flight project experience at NASA's JPL, I am uniquely positioned to make significant contributions to the field of aerospace robotics through support from the National Science Foundation.

Broader Impacts

The new generation of STEM leaders must champion initiatives to invite more people from diverse backgrounds to the STEM field. Too often, I have entered a room where only the loudest voices speak, and everyone approaches a technical problem in the same way. When asked about why diversity is important, I often hear the remark that "diverse teams are more productive." But this misses the mark. Diversity without equally including all team members and listening to their voices does not produce the needed change. Instead, I seek to champion diversity and inclusivity to build productive teams.

As a first-generation American of Spanish descent, I have heard my fair share of derogatory statements and generalizations that I, the only Hispanic in the room, must therefore determine what all Hispanics believe about a topic. My story as a minority is certainly not a unique story, but it highlights that diversity cannot just be a metric of existence, it must be a measure of inclusivity. Fortunately, the mentors in my life have supported me and helped me overcome these obstacles.

Being a Hispanic engineer who grew up in urban California but attended a small and diverse high school in Michigan, I bring a unique perspective to the aerospace engineering field. While in high school, I was fortunate that Dean Gallimore at the University of Michigan Ann Arbor, allowed me to join his lab for a summer research opportunity. This gesture put me on the path towards a future in research. Upon arriving at Caltech, I noticed that many peers from underrepresented backgrounds lacked these kinds of research opportunities and I wanted to help. In my sophomore year, I became a representative of Caltech's student-run Academics and Research Committee, a student leadership group tasked with improving the undergraduate academic and research experience on campus. Soon after I joined the committee, my first goal was to build a software tool and a complimentary peer-to-peer FAQ page to connect students to academic year research. After a bit under a year of development, emails, and management, the site deployed in the 2019-2020 school year and now resides on the committee's main webpage. Within the first week, almost a fifth of the Caltech undergraduates had used this website tool to access and explore research opportunities on campus.

In my junior year, I was a year-long teaching assistant for the sophomore level mechanics and dynamics courses. Following the example of inclusive STEM leaders, such as Dean Gallimore, I sought to practice inclusive teaching and leadership for my students. As an underclassman, I noticed that extroverted students, especially those who had a stronger high school background, dominated the atmosphere in class, office hours, and recitation sections. As a TA, I made an effort to reach out to reserved students and those with a weaker STEM background to ensure that they too were able to obtain the guidance that they deserved. Exceeding the normal job requirements, I regularly put in the extra hours or set up one-on-one sessions with these students. I remembered the opportunities that Prof. Gallimore and other mentors gave me and sought to put into practice the inclusive teaching that was necessary to ensure an even playing field.

Concurrently, in my junior year, I became the first diversity representative of my on-campus residence, serving as a liaison to the Caltech Center for Inclusion and Diversity. When the world moved virtual, I seized the moment as an opportunity for growth. I used my dual position on the Academics and Research Committee and as the diversity representative to support students most affected by the inequities of the remote environment. Among other support structures, this included advocating for iPad loaners, whiteboard tools, online graders, and a new learning management system. The student leadership team and I also handled course concerns and surveyed students. With issues of inclusion, diversity, and injustice shifting to the forefront in the public eye at the end of spring, I leveraged my roles to bring national conversations to my dorm at Caltech. Most recently, a team of three student leaders and I led discussions within my residence about societal injustice in Caltech's history and about new efforts within Caltech to support future generations of students. I am proud of the work I have led and championed at Caltech, and I am committed to continuing this work as a graduate student and as a new leader in STEM.

Future Work

Through these diversity and inclusion efforts, I am answering the call for inclusion in STEM. I firmly believe that the Caltech I am graduating from is more just and equitable than the one I entered in 2017. My passion for enabling scientific discoveries, my experience with computationally intensive research in space robotics, and my drive to diversify STEM is quite unique in the aerospace and robotics realms. The NSF Graduate Research Fellowships Program would provide me with the autonomy and resources to further explore this cross-section of fields in my Ph.D. and beyond while maintaining my promise of championing inclusion initiatives.

<u>Graduate Research Plan Statement</u>

Robust Online Low-Thrust Trajectory Optimization with Learned Dynamics and Chance Constraints for Spacecraft Constellations and Drone Swarms

Background and Motivation

Robust online trajectory optimization for low-thrust small satellites and drones is an enabling robotics technology for low-cost missions, especially in the Earth and planetary sciences. New CubeSat systems increasingly adopt low-thrust propulsion due to the miniaturization of cold-gas, ion, and Hall thrusters. Unlike traditional rocket engines, low-thrust engines require control over long horizons to change or maintain orbit. [1] Similarly, drone technologies are pushed to their thrust limits when carrying heavy payloads and require long horizon planning to adapt to a changing environment. Existing research predominantly uses model-based controllers in the aerospace industry to optimally control a system while maintaining dynamic feasibility. However, unknown dynamics such as unknown gravity fields around asteroids or unknown ground effects during drone landing invalidate the model and present a safety risk. Recent work in learned dynamics within a larger sequential convex optimization framework has shown promise in addressing these problems [2]. For end-users, such as spacecraft operators, instrument engineers, and drone pilots, there is a need for robust online low-thrust trajectory optimization solutions that learn unknown dynamics online and acknowledge probability constraints from the robot state estimator or uncertainties in the environment. However, currently, no open-source software package with these capabilities is available for on-board trajectory optimization.

Research Aims

1. Formulate the low-thrust problem as a convex problem or a sequential convex problem. Ideally, I would losslessly convexify the problem to preserve the optimization integrity while ensuring a global solution. From there, I would work to determine the convergence bounds for different machine learning frameworks (e.g. a full black box or a structured dynamics equation with learned parameters)
2. Research novel multi-agent on-board low-thrust spacecraft and drone trajectory optimization techniques and compare the computational costs in memory and runtime of these techniques.
3. Experimentally test these optimization strategies on flat floor spacecraft simulator testbeds and netted drone facilities, such as those at Caltech, Stanford, MIT, or JPL, either through my PI or collaborations.
4. Develop a well-documented open-source flight software package and assess its performance on spacecraft simulator testbeds, netted drone facilities, and, future funding permitting, in orbit.

Research Approach

To achieve aim 1, I will develop novel on-board low-thrust spacecraft and drone trajectory optimization techniques and investigate theoretical robustness guarantees (such as cases of asymptotic stability in the sense of Lyapunov) and overall trajectory convergence. To achieve aim 2, I will leverage two aspects of my previous work. First, I will build upon research with the Robotics Exploration Lab in augmented lagrangian frameworks, differential dynamic programming, and model predictive control [3, 4]. Second, to address learning of unknown dynamics, I will extend upon my spacecraft control and dynamics research from my senior thesis [2]. To achieve aim 3, I will use the hands-on skills with spacecraft simulator testbeds from my senior thesis. All algorithms developed through this research will be extensively compared to other baseline algorithms, using Monte Carlo analyses to assess runtime performance and memory costs [5]. Lastly, I will assess the cost savings and risk reduction from this open-source package to show that this software enables new scientific payloads. With sufficient funding in the future, I would develop an example CubeSat as a flight software technology demonstration in orbit.

Intellectual Merit

Large satellite constellations and new small drone technologies are becoming more prevalent. As the field evolves, it is burdened with three difficulties: 1. existing time-varying nonlinear constraints and dynamics that cannot be captured in a standard on-board model, 2. congestion between agents and uncertainties in relative states, and 3. changing legislated air and space traffic policies. To ensure safe systems that comply with aerospace traffic regulations, there is a need for this new class of mixed model and learning based controllers that are stable and robust. This proposed computationally intensive research addresses this gap in the field and leverages advances in on-board computational resources to provide combined learning and model-based motion planning solutions for low-thrust platforms.

Broader Impacts

In addition to its intellectual merit, the theoretical contributions of this research have broader impacts in robotics applications with limited control authority and evolving environments. Outside of engineering, this project is critical for producing cost-effective, scalable, and reliable spacecraft and drone solutions for internet access in rural areas, real-time weather forecasting, and natural disaster monitoring. Particularly in space engineering, instrumentation must meet high Technology Readiness Levels (TRL), numbered from 1 (basic research) to 10 (flight-proven) [6]. Progressing from TRL 5 to 8 requires demonstration in the relevant space environment, which is risky and cost prohibitive. While CubeSat technologies are lower-cost solutions and CubeSat hardware can be purchased or extended from open-source PyCubed platforms, scientists and instruments engineers should not have to be robotics experts to implement the necessary motion planning algorithms on CubeSat flight software. The proposed research meets this gap in CubeSat technologies. This project will provide scientists and engineers with a user-friendly, high-fidelity, open-source package for aerospace flight software that can decrease mission cost and risk while allowing scientists and engineers to focus on their remote sensing scientific payloads or communications systems instead of the flight software.

References.

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