I love thinking about how robots move through complex dynamic environments, how robots perceive their dynamics, how they learn and represent the encompassing system's dynamics, and then control their own movement. This sequence of capabilities encapsulates a robot's autonomous thought process pertaining to motion and each component depends on the others. **My research emphasizes the learning or system identification portion of the autonomy pipeline** but my research group implements all autonomy aspects of path planning, perception, and control to understand the upstream and downstream impacts of system identification [1]. **While my research revolves around methodology, I am passionate about applying my methods to robots that will increase our capabilities to explore space.** Robotic technologies in space I've worked on include a high agility nanosatellite driven by control moment gyroscopes in Earth orbit, two electromagnetic docking spacecraft in Mars orbit, a network of hundreds of chip-sized satellites in an orbit, a low-jitter high-precision pointing Earth observing satellite in Earth orbit, and wheeled rovers on Lunar and Martian terrain.

Past

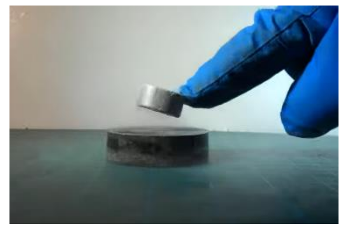

Figure 1: still frame from a video of a person poking a flu pinned magnet above a superconductor

The physics that dominate my PhD research are driven by a physical phenomenon called flux pinning, which was fascinating due to its highly nonlinear, coupled attitude and linear dynamics. A quintessential video demonstrating flux pinning instills an emotion of magic as a magnet levitates over a chilled superconductor despite being poked and prodded out of place. The magnet always comes back, as long as the superconductor's temperature remains below that material's critical temperature. At the time of my PhD, NASA's Mars Sample Return mission needed a contactless docking mechanism on an orbiter that could capture an orbiting spacecraft with some relative velocity and hold this spacecraft in place during a containment procedure. Flux pinning offered this solution and I advanced this technology from TRL 3 (designing a docking interface leveraging this physics, building 4 - 6 degree of freedom dynamic simulations of two spacecraft, analyzing theoretical system dynamics) to TRL 6 (building, flying, and analyzing microgravity flight demonstrations of this technology) [2]–[6]. The Mars Sample Return mission ultimately baselined a different technology but my job of characterizing this new technology was successful. Through this amazing endeavor, I was a NASA Space Technology Research Fellow, the chief technologist of this effort in collaboration with NASA JPL, and the Cornell-side project lead that trained over 20 Master's/undergraduate students.

Figure 2: microgravity flight experiment characterizing docking technology performance

Present

Before starting my faculty position at University of Hawaii at Manoa in January 2020, I put more research emphasis on mobility of planetary surface vehicles and terrain environments to more fully leverage my institute's predominant strength in planetary science and Hawaii's unique geographic assets, such as the planetary surface analogues on the Big Island [7]. My lab, the Robotic Space Exploration lab, aims to improve the autonomous operations of small rovers by increasing embedded real-time system identification, localization, and path planning algorithms. I am one of a handful of labs internationally that researches terramechanics in space applications and even fewer with hardware in the loop.

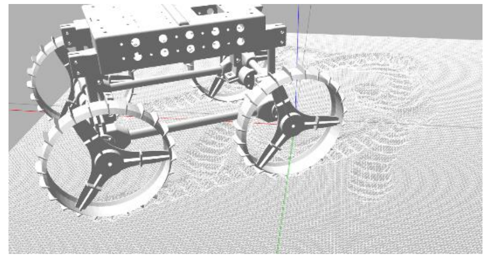
Figure 3: our in-house terramechanics simulator

Currently, NASA JPL's Mars rovers propagate rover dynamics with the simplest method possible, kinematic equations, which achieves 10% normalized root mean square error and limits the autonomous capabilities of a rover. Bailey and I have derived more accurate terramechanics equations of motions, which show highly nonlinear and discontinuous dynamics. The physical parameters that populate these complex equations represent geotechnical properties of the planetary surface that are doubly insightful for our fellow planetary scientists. Just recently, he submitted our paper relating the sensitivity of environment parameters and rover design parameters on the system dynamics state propagation to inform engineers how best to design rovers and mission operators where best to drive rovers to maximize mobility [8]. I've been leading other graduate students in training data-driven, surrogate models that may stand in for physics-derived equations to either discover underlying dynamics or to offer good enough predictions with alternative advantages, such as computation speed or model adaptability [9]. We will soon publish a survey paper describing the Pareto front of models that vary in computational intensity, prediction accuracy, and interpretability. To rapidly develop these system identification algorithms, a super-talented undergraduate student is developing a soil contact model simulation in ROS Gazebo with me to emulate high fidelity terramechanics with near real-time runtime [10]. I passionately believe in testing in real-world environments so we are currently collecting motion capture data of rovers traversing in soft soil to verify the simulator and drive our system identification algorithms.

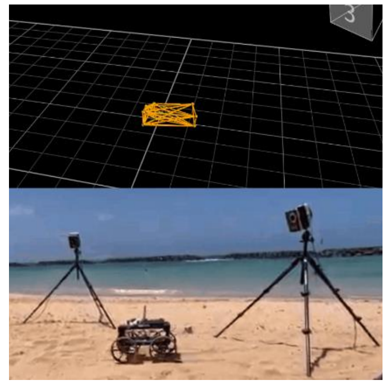
Figure 4: collecting motion capture data of rover traverse


Figure 1: spectrometer and bevameter data collection

A monumental focus of NASA and of the Hawaii Institute of Geophysics and Planetology is the identification and characterization of water-ice on our Moon's surface. I've been collaborating with planetary scientists in codifying their science objectives and instrument data into low representation states so that robots can construct models that characterize the spatial distribution of scientific states of interest, such as how much ice is where. Planetary scientists typically receive data from teleoperated missions, massage the data, and discuss potential waypoints with each other to provide to the teleoperator. My pursuit of autonomy challenges this entire workflow and has illuminated gaps in the intersection of engineering and science, where scientists have not been forced to compress their data into an independent data pipeline. My group has written several papers demonstrating autonomous path planning to maximize science information gain, leveraging active learning to sample environments more efficiently and without human intervention [11], [12]. We will soon conduct field testing with a physical science instrument and real spectrometer data processing in the loop, informed by previous work in characterizing a planetary surface analogue spectrally and geotechnically with human operators [13].

I still study satellite systems in collaboration with the Hawaii Space Flight Laboratory [14], such as optically measuring jitter to sub-arcsecond precision and identifying vibrational modal frequencies to within 5×10^{-3} Hertz. Chase and I just submitted a paper characterizing the jitter characteristics of a University of Hawaii satellite, HyTI, that showed the satellite meets mission requirements using a novel optical metrology system that our team innovated [15], [16].

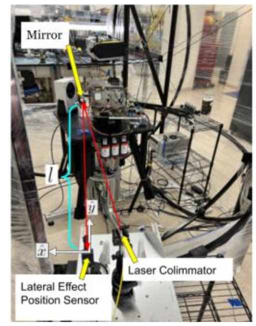

Figure 2: optical metrology system measuring jitter from HyTI

Future

In the next decade or two, we as a nation will establish humans on the moon. In the next five years, I want to build, send, and operate robots that help establish us on the moon, making lunar autonomous robotic exploration and human-robot coordinated exploration a reality.

My research in collective, multi-agent intelligence has been nurtured in several previous and pending proposals, such as the NASA Lunar Surface Technology Research proposal with University of Michigan and the NASA Planetary Science and Technology from Analog Research with MIT. Career goals include sending software or hardware solely developed by my lab to space and establishing a research institute in autonomous space robotics, specifically a NASA Space Technology Research Institute ($15M award) with to eventually convince NASA to adopt more machine learning algorithms into space missions. The aerospace community's trust in robots is at a tipping point, leaning towards an embrace of artificial intelligence but with a healthy dose of skepticism. I would like to be at the forefront of this paradigm shift, researching these topics now to enable the next generation of robotic space exploration missions.

While I will always continue working on orbital and planetary surface robots, I wish to eventually expand the environments my robots explore to include oceans and icy worlds and to expand my methods to incorporate multiple robots to explore an environment collectively [17]. I'm perpetually drawn to complex physical environments motivated by the future of space exploration, of which ocean are driven by dynamic fluids and ice by slippery contact dynamics.

Fit to University of California, San Diego

I see very obvious collaborations with the following faculty in some initial intersections: Dr. Bewley in increasing autonomous navigation of agile ocean and planetary surface vehicles, Dr. Boechler in identifying soft robot dynamics interfacing with terrain, Dr. Hwang in designing robotic sensor placement for the sake of system identification, Dr. Kramer in crafting approximate and adaptive dynamical models for space vehicles in ocean worlds, and Dr. Herbert in posing safety guarantees for autonomous planetary surface vehicles. I would like to add my own Robotic Space Exploration lab to the UCSD's facilities and resources, which would include a planetary surface vehicle (rover) design, fabrication, terramechanics and geotechnical mobility testing lab. I'd be delighted to participate in the Center for Control Systems and Dynamics at UC San Diego and California Space Grant.

Selected Publications

[1] F. Zhu, D. Jing, F. Leve, and S. Ferrari, “NN-Poly: Approximating common neural networks with Taylor polynomials to imbue dynamical system constraints,” *Front. Robot. AI*, vol. 9, p. 968305, Nov. 2022, doi: 10.3389/frobt.2022.968305.

[2] F. Zhu, L. Jones-Wilson, and M. Peck, “Capturing and Docking Spacecraft with Flux Pinned Interfaces,” presented at the International Astronautical Congress, Guadalajara, Mexico, Sep. 2016. Accessed: Feb. 04, 2018. [Online]. Available: https://iafastro.directory/iac/archive/browse/IAC-16/C1/9/32785/

[3] F. Zhu and M. Peck, “Linearized Dynamics of General Flux-Pinned Interfaces,” *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 8, pp. 1–10, Dec. 2018.

[4] F. Zhu, L. Jones-Wilson, and M. Peck, “Flux-Pinned Dynamics Model Parameterization and Sensitivity Study,” presented at the IEEE Aerospace Conference, Big Sky, Montana, 2018.

[5] F. Zhu, M. Peck, and L. Jones-Wilson, “Flight-Experiment Validation of the Dynamic Capabilities of a Flux-Pinned Interface as a Docking Mechanism,” presented at the IEEE Aerospace, Big Sky, Montana, 2019.

[6] F. Zhu, M. Peck, and L. Jones-Wilson, “Reduced Embedded Magnetic Field in Type-II Superconductor of Finite Dimension,” *IEEE Transactions on Applied Superconductivity*, pp. 1–1, 2020, doi: 10.1109/TASC.2020.2976592.

[7] F. Zhu, D. S. Elliott, Z. Yang, and H. Zheng, “Learned and Controlled Autonomous Robotic Exploration in an Extreme, Unknown Environment,” *2019 IEEE Aerospace Conference*, pp. 1–10, Mar. 2019, doi: 10.1109/AERO.2019.8741552.

[8] B. Hopkins and F. Zhu, “Parameter Sensitivity Analysis of Small Rover Dynamics,” presented at the Under review in the IEEE International Conference on Robotics and Automation,

[9] H. Mertens, “Data-Driven System Identification of a Terramechanic Model for a Rover Operating on Planetary Soil,” RWTH Aachen University, 2023.

[10] B. Witt, B. Hopkins, H. Wang, and F. Zhu, “TaRO-SCM: A Real-Time Soft-Soil Terramechanics Plugin for Gazebo,” *In preparation to IEEE Robotics and Automation Letters (RA-L).*

[11] A. Akemoto and F. Zhu, “Informative Path Planning to Explore and Map Unknown Planetary Surfaces with Gaussian Processes,” p. 12.

[12] S. Akins and F. Zhu, “Comparing Active Learning Performance Driven by Gaussian Processes or Bayesian Neural Networks for Constrained Trajectory Exploration,” in *ASCEND 2023*, in ASCEND. , American Institute of Aeronautics and Astronautics, 2023. doi: 10.2514/6.2023-4720.

[13] H. Wang, K. Arroyo-Flores, P. Espojo, and F. Zhu, “Conducting Spectra-Spatial Investigations on the Big Island of Hawaii as a Lunar Surface Analogue,” in *ASCEND 2023*, in ASCEND. , American Institute of Aeronautics and Astronautics, 2023. doi: 10.2514/6.2023-4661.

[14] M. Bottom *et al.*, “Substellar Weather Infrared Explorer (SUWIE),” vol. 54, p. 206.12, Jun. 2022.

[15] R. Wright *et al.*, “HyTI: Thermal Hyperspectral Imaging from A Cubesat Platform,” in *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, Jul. 2019, pp. 4982–4985. doi: 10.1109/IGARSS.2019.8899887.

[16] C. Urasaki and F. Zhu, “Jitter Analysis of the HyTI Satellite,” in *Under review to IEEE Aerospace Conference*,

[17] A. Akemoto and F. Zhu, “Cooperative Lunar Surface Exploration using Transfer Learning with Multi-Agent Visual Teach and Repeat,” in *2023 IEEE Aerospace Conference*, Mar. 2023, pp. 1–9. doi: 10.1109/AERO55745.2023.10115696.