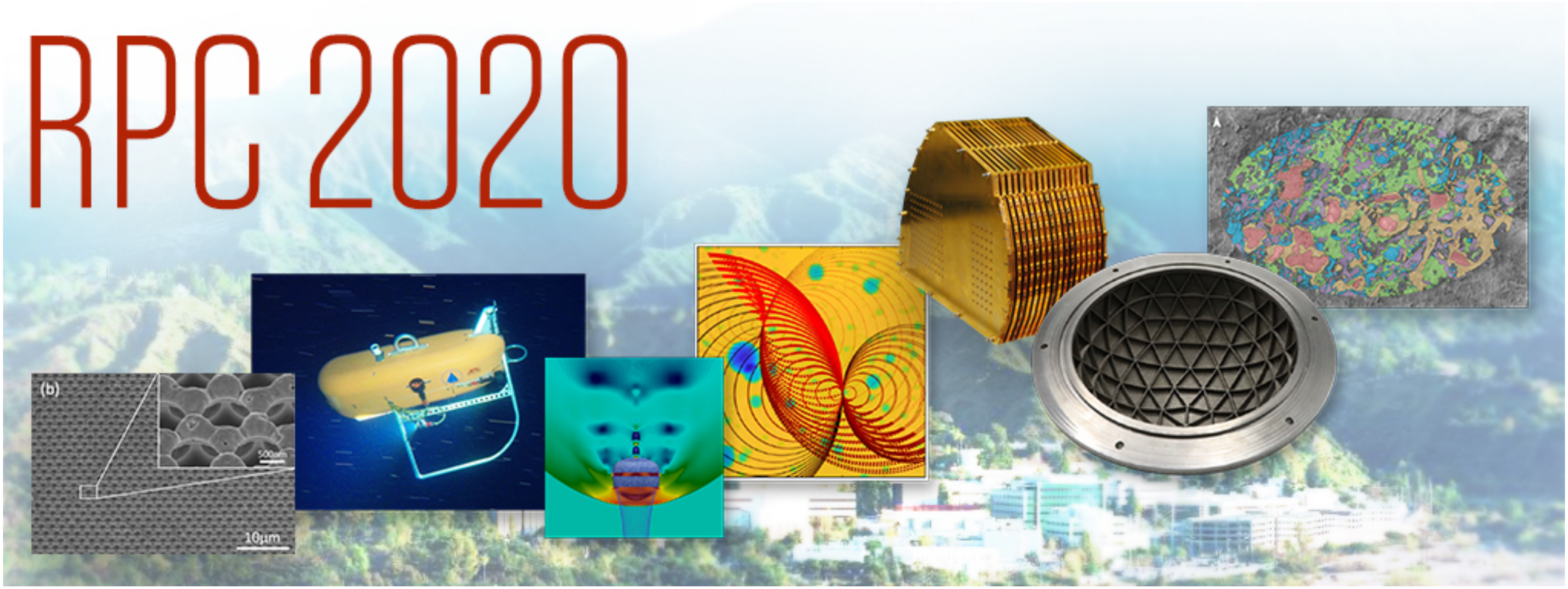

Virtual Research Presentation Conference

Online Model-Predictive Control of Underactuated Robotic Aerial Platforms

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Program: SURP

Assigned Presentation # RPC-252

Jet Propulsion Laboratory
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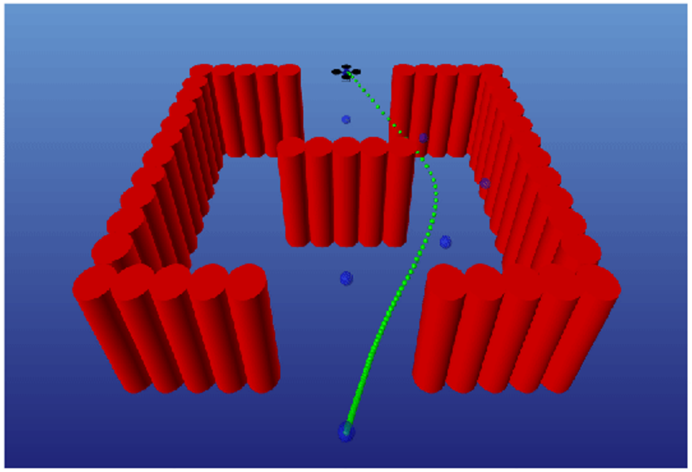
Tutorial Introduction

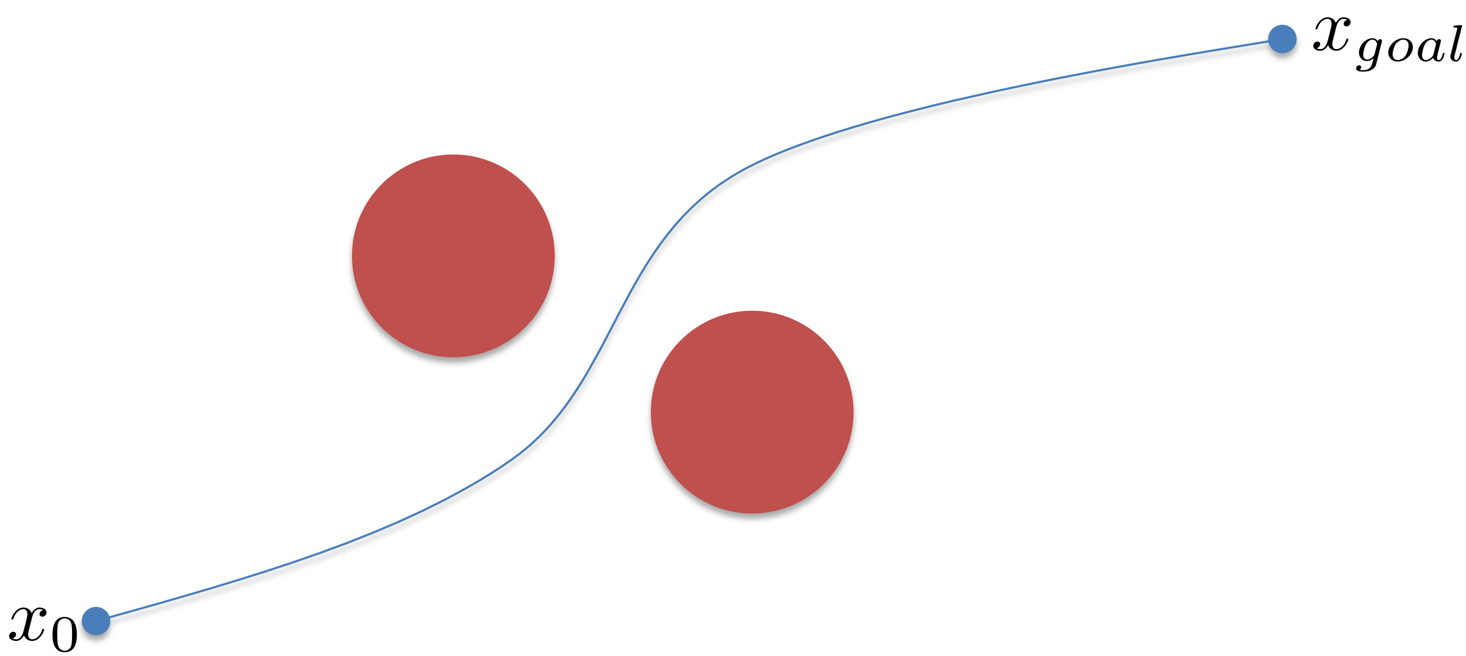
Abstract

Many free-flying robotic space mission concepts have to deal with severe power, weight, deployment, and environment constraints. These constraints can result in challenging control problems that cannot be addressed by classical linear feedback strategies. This project seeks to develop and test new high-performance optimization tools that are specifically tailored for model-predictive control of aerial vehicles and are capable of running in real time on resource-limited onboard computers. These new tools can be readily applied to many future JPL mission concepts, such as low-altitude planetary aerobot (blimp) explorers, jumping and bouncing robots (Hedgehog or Tensegrity designs), and unique rotorcraft. Optimization-based control strategies could also offer improved performance and resource utilization over classical control methods on many existing hardware platforms.



Problem Description

- Model-predictive control (MPC) is a powerful control technique used in many modern autonomous systems
- Online numerical optimization allows complex dynamics and constraints to be handled
- Current solvers are not optimized for real-time performance on resource-limited embedded computing hardware



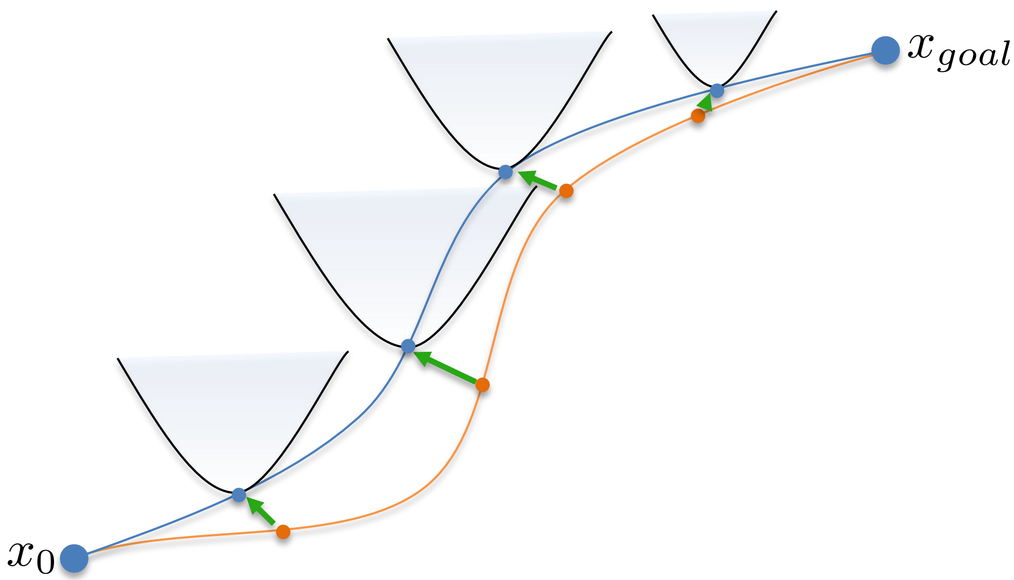
Problem Description

- Standard solvers like CVXGEN and ECOS are based on primal-dual interior point methods that can achieve high-accuracy solutions, but require solving large, sparse linear systems and are not designed to be "warm-started"
- Instead, we rely on a new solver called ALTRO that is purpose built for trajectory optimization problems
- ALTRO only requires solution of small, dense linear systems and can be warm started efficiently, making it ideal for MPC on embedded processors
- These tools can be applied to many challenging control problems of relevance to JPL, including entry guidance, powered descent, low-altitude planetary aerobot (blimp) explorers, jumping and bouncing robots (Hedgehog or Tensegrity designs), and unique rotorcraft.

Ingenuity, Credit: JPL/Caltech

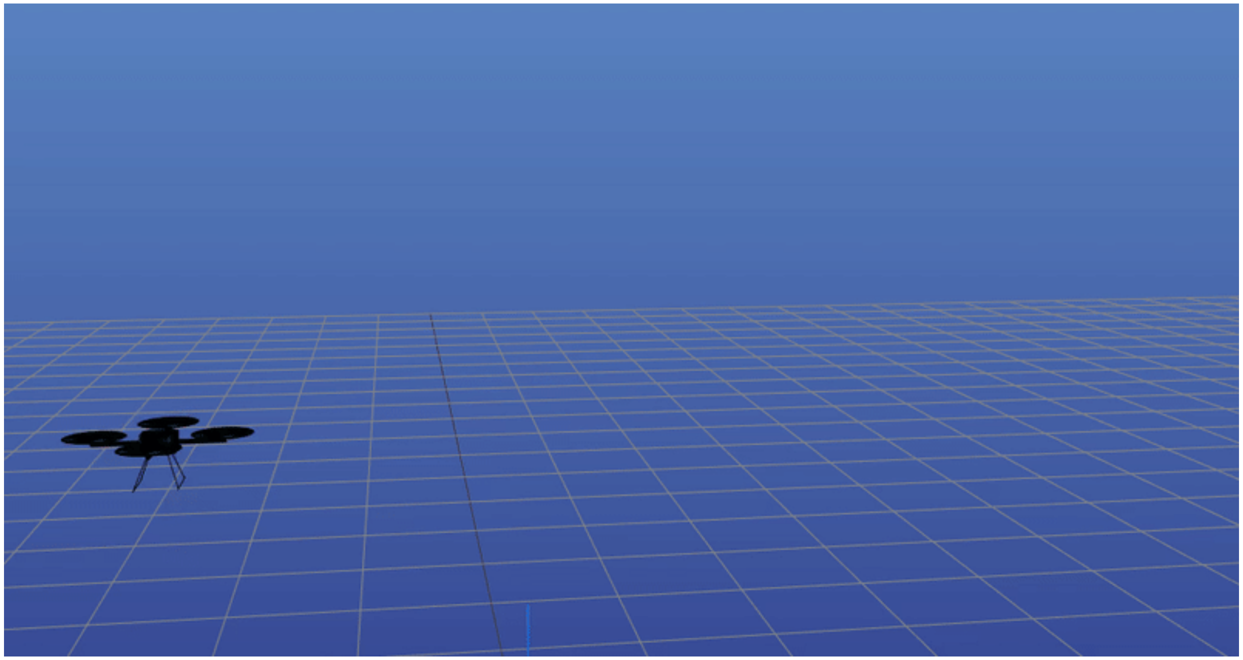
Methodology

- The ALTRO solver is based on two key ideas: iterative LQR (iLQR), the augmented Lagrangian method
- Iterative LQR solves trajectory optimization problems by sequentially approximating them as LQR problems, which can be solved quickly and reliable by solving a sequence of small problems along a trajectory.
- The augmented Lagrangian method allows ALTRO to handle constraints like torque limits and obstacle avoidance. Augmented Lagrangian methods are particularly well suited to warm starting.



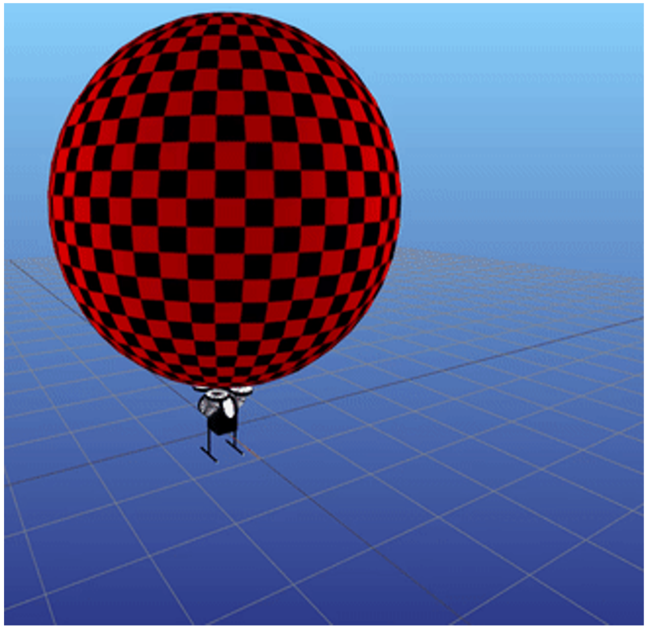
Methodology

- To better support aerial vehicle applications, we added support to ALTRO for directly optimizing quaternion states
- Quaternions allow us to handle arbitrarily large rotations without the singularity issues that plague Euler angles



Methodology

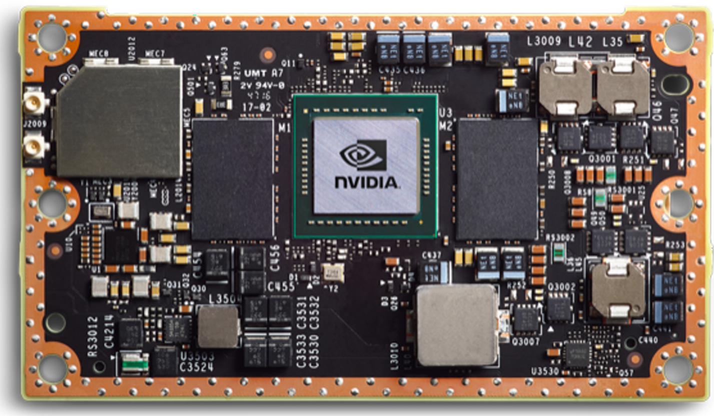
- We have implemented a full MPC-based control stack for an underactuated blimp
- The controller runs faster than real time in simulation
- Hardware experiments on blimps and quadrotors are planned over the next year



Results

This year, we have:

- Implemented a specialized high-performance MPC solver for controlling aerial vehicles
- Implemented a fast dynamics model for an underactuated blimp developed at JPL
- Run the full MPC controller on the blimp model in simulation at faster-than-real-time rates
- Achieved closed-loop solve times of 40 ms on an NVIDIA Jetson embedded computer

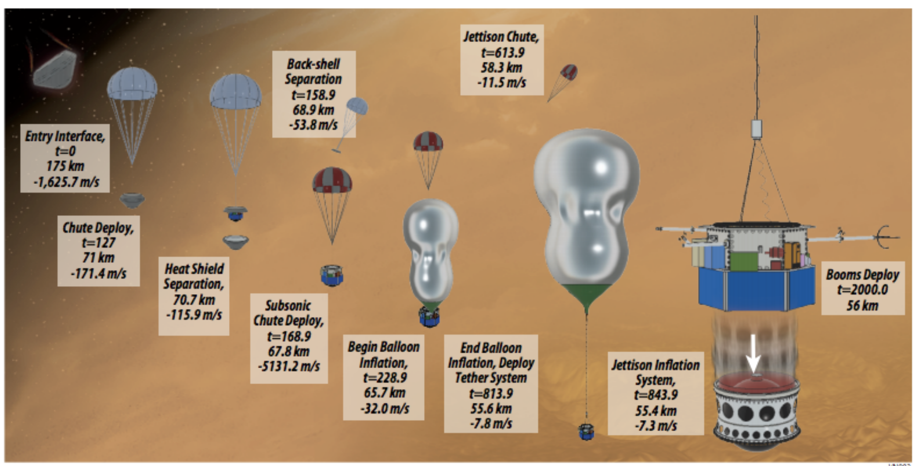


Results

Significance:

- Our customized solver often outperforms off-the-shelf solvers by an order of magnitude or more in MPC applications
- MPC can be deployed on many future JPL missions to improve performance and enable entirely new concepts

System	IPOPT	ALTRO	Relative Speedup
Cartpole	119.807 ms	4.763 ms	25x
Parallel Park	59.814 ms	1.180 ms	51x
Car w/Obstacles	179.453 ms	961.085 µs	187x
Acrobot	255.768 ms	1.035 ms	247x
Maze	6.068 s	9.003 ms	674x



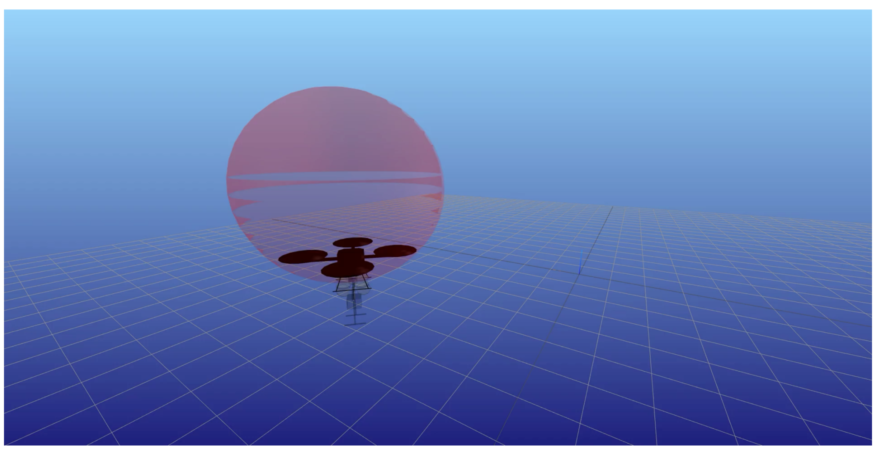
2020 Venus Flagship Mission Study
https://science.nasa.gov/science-red/s3fs-public/atoms/files/Venus%20Flagship%20Mission.pdf

Ingenuity, Credit: JPL/Caltech

Results

Next Steps:

- A full hardware-in-the-loop simulator for the blimp with MPC running on the NVIDIA Jetson and a high-fidelity simulator running on a desktop
- Run the MPC controller on a real quadrotor
- Implement "dynamic emulation" on the quadrotor to reproduce the dynamics of a blimp for controller testing
- Run the MPC controller on a real blimp



JPL blimp aerial platform

Publications and References

1) Taylor Howell, Brian Jackson, and Zachary Manchester, "ALTRO: A Fast Solver for Constrained Trajectory Optimization," *International Conference on Intelligent Robots and Systems (IROS)*, November, 2019.

2) Brian Jackson and Zachary Manchester, "Planning with Attitude," submitted to *International Conference on Robotics and Automation (ICRA)*, 2021.

3) Brian Jackson, Tarun Punnoose, Kevin Tracy, Taylor Howell, Daniel Neamati , Rianna Jitosho, and Zachary Manchester, "Fast Model-Predictive Control with the ALTRO Solver," submitted to *International Conference on Robotics and Automation (ICRA)*, 2021.