National Science Foundation

Optimization-Based Planning and Control for Assured Autonomy: Generalizing Insights from Space Missions

Award number: CPS 1931744

UNIVERSITY of WASHINGTON

Behçet Açıkmeşe, Marco Pavone, Marin Kobilarov

Stanford University

JOHNS HOPKINS UNIVERSITY

Project Objective:

Build a rigorous and reliable optimization-based framework for planning and control of autonomous systems, by leveraging invaluable insights and experience from NASA's historical flagship missions to Mars over the past 25 years. To this end, develop:

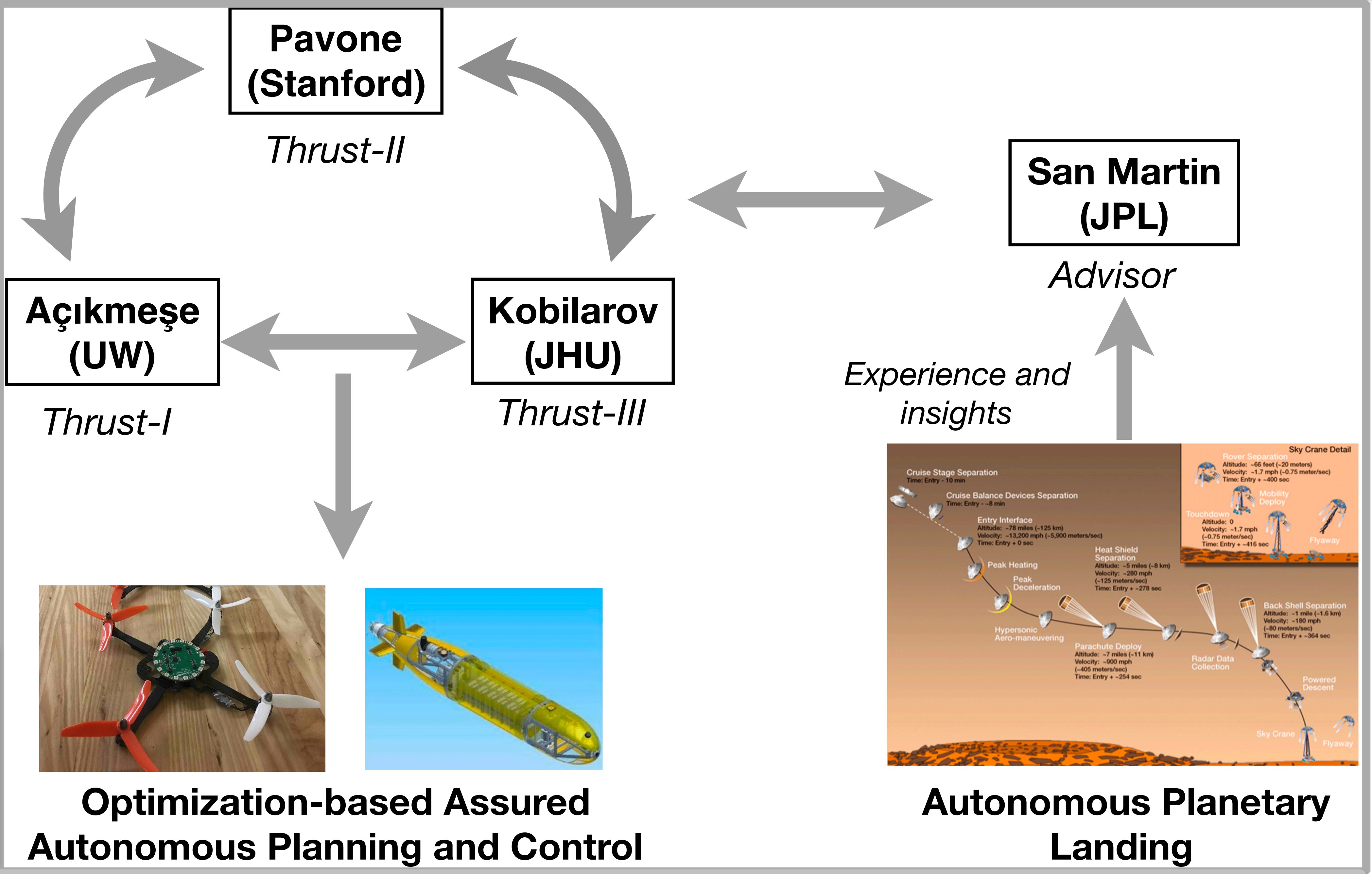
- Unified formulation of planning and control problems formalizing mission specifications, system constraints, and uncertainty
- Solution algorithms to optimize mission objectives within the specifications and constraints
- Real-time executable numerical solution algorithms that can be rigorously verified
- Real-world applications of the proposed methods/algorithms with testbed demonstrations

Key Observations:

- Missions to Mars and other planets in the last three decades have produced effective point-design solutions for motion planning and control that were successfully applied in high-risk space missions of NASA
- Optimization-based formulations of these problems capture a very general class of mission specifications, objectives, and constraints
  - with significant examples in the domain of space autonomy
  - can also incorporate the uncertainty in the autonomy problems
- Conversion of the resulting optimization problems into convex ones, ***convexification***, enables
  - development of numerically tractable solution methods
  - assurances on the obtained solutions and underlying algorithms
  - verification of the resulting software
- Development is real-world examples in testbeds is critical to closing the "scientific-loop"
  - which builds confidence for these methods and algorithms

Main Hypothesis

Optimization-based planning and control is an effective framework to formulate and solve many planning and control problems arising from autonomy.



Pavone (Stanford)

Thrust-II

Açıkmeşe (UW)

Thrust-I

Kobilarov (JHU)

Thrust-III

San Martin (JPL)

Advisor

Experience and insights

Optimization-based Assured Autonomous Planning and Control

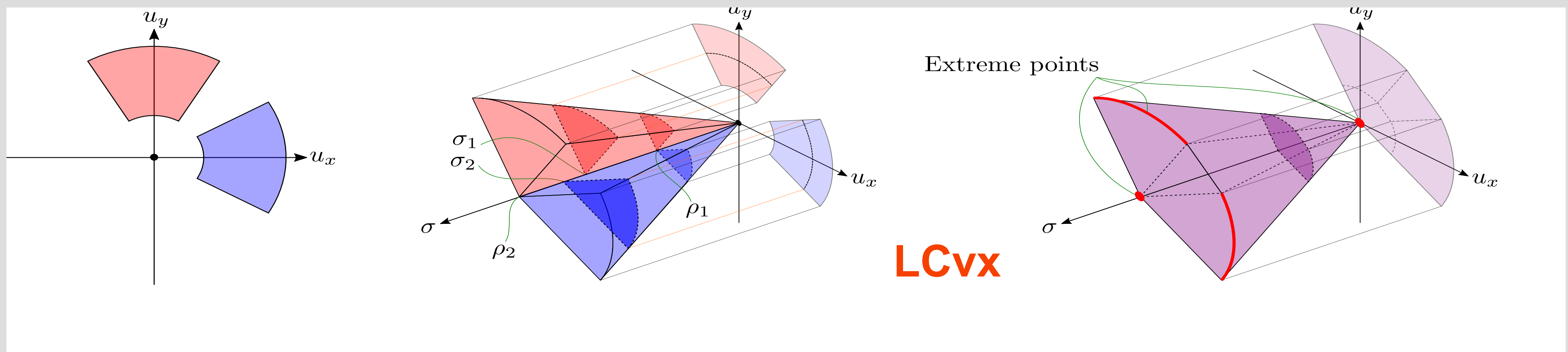
Autonomous Planetary Landing

Intellectual Merit

- Rigorous duality-based methods of convexification to convert hard planning problems into numerically tractable ones, both for offline and online computations
- Leveraging technical insights from successful NASA missions to Mars and other planets, which produced effective point-design solutions
- Unifying existing solutions and aiming to generalize our insights further to handle increasingly complex requirements of autonomous systems
- Having a strong experimental component that will enable us formulate and solve relevant motion planning and control problems in autonomous dynamical systems

Thrust-I: Convexification for Assured Nominal Motion Planning

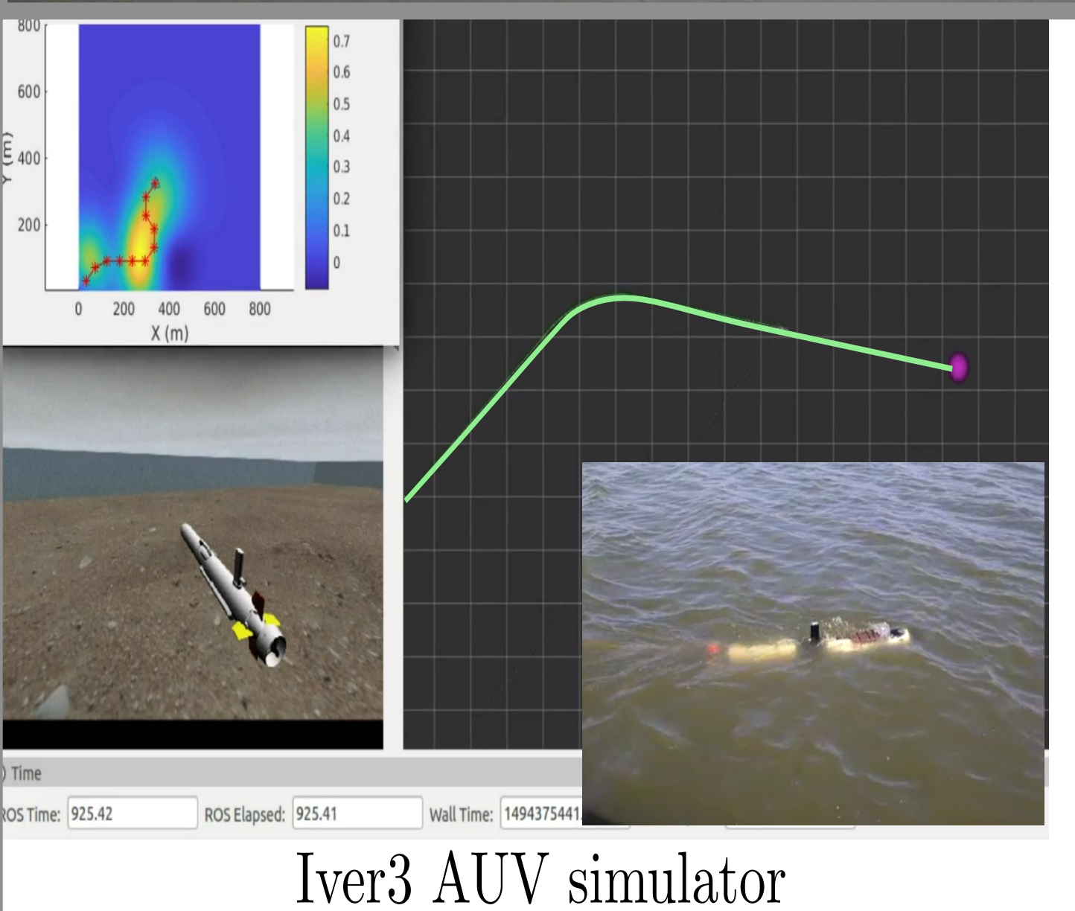
- What are the proper and relevant problem formulations?
  - models, metrics, priorities, and constraints
- What are the key insights from planetary Entry, Descent, and Landing (EDL)?
- What are the sources of non-convexity? Can they be convexified?
  - Lossless convexification (LCvx)
  - Successive convexification (SCvx)



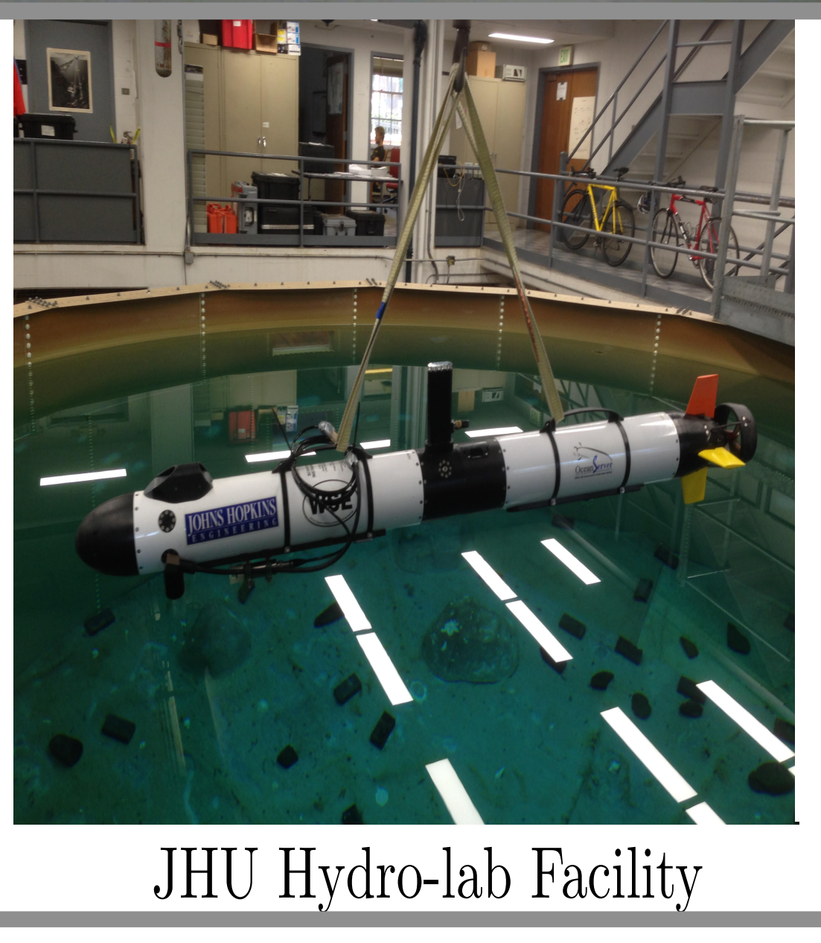
Original formulation

Convex relaxation of individual input sets

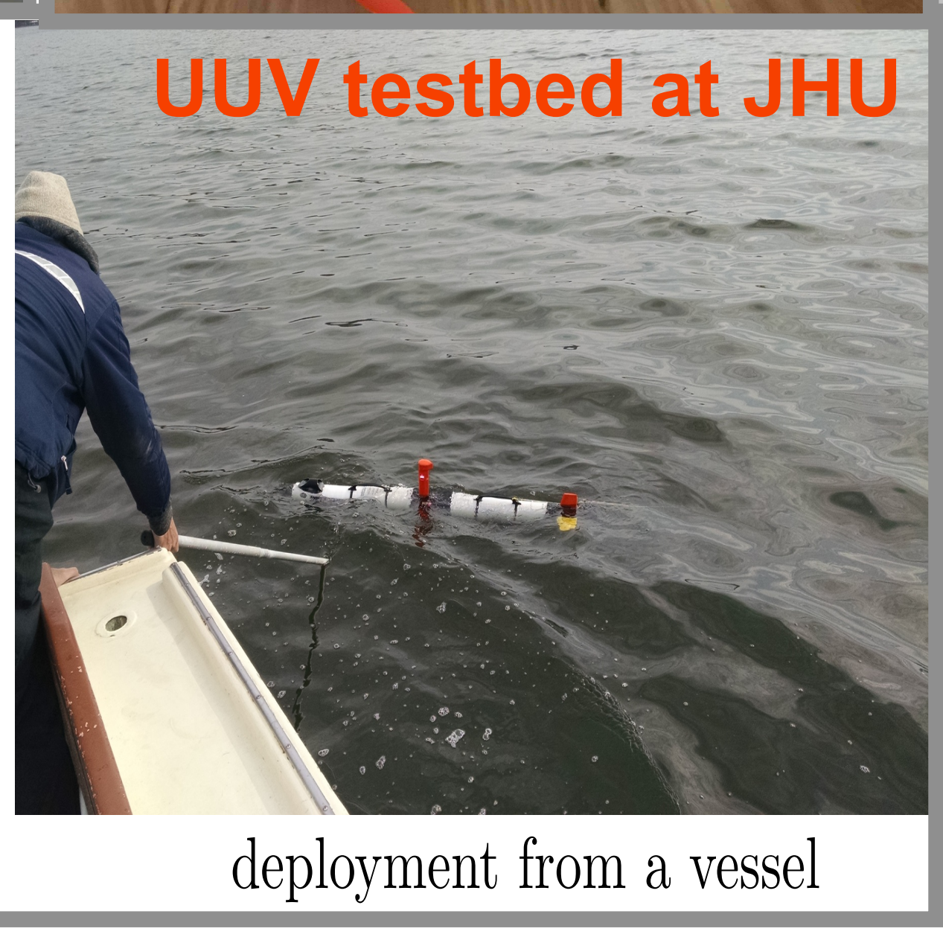
Convex hull of relaxed input sets into one convex set



Iver3 AUV simulator



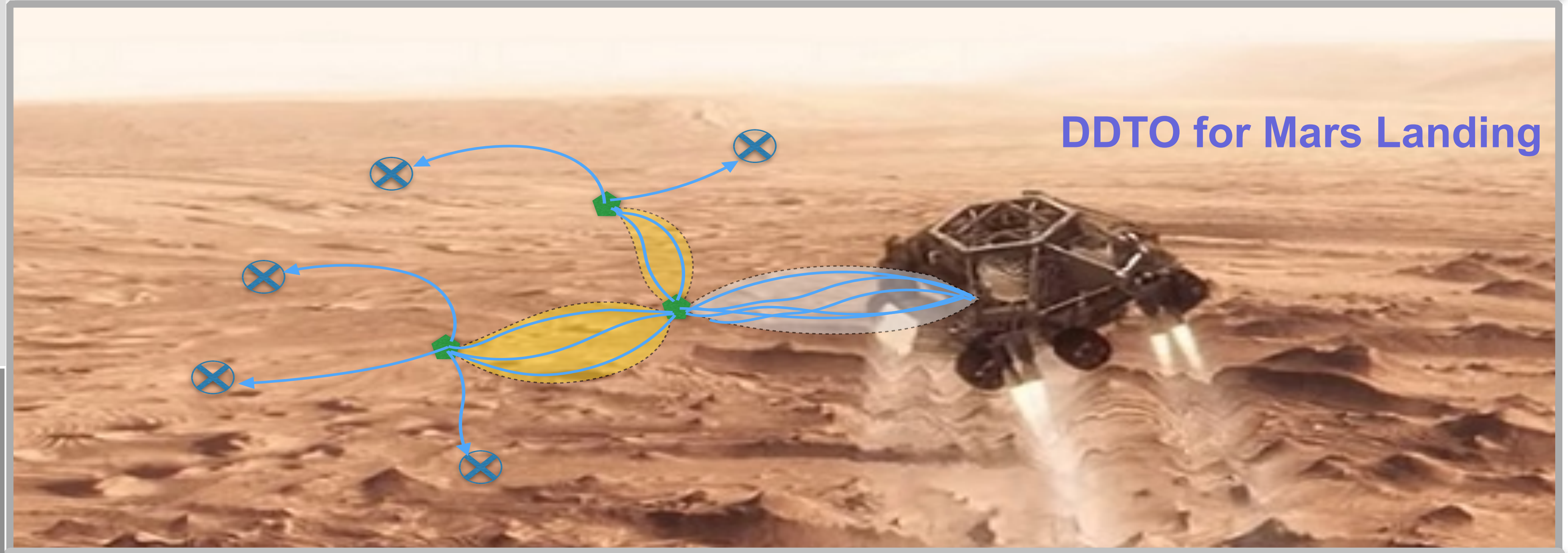
JHU Hydro-lab Facility



deployment from a vessel

Thrust-II: Resilient Motion Planning and Control for Uncertainty Handling

- How can we handle model uncertainties?
  - robust "controlled invariant funnels" for tracking via contraction theory
- How can we robustify the motion planning to uncertainties in the environment?
  - Deferred-Decision Trajectory Optimization (DDTO)
- How can we handle strong coupling between sensing and control/planning?
  - "separation principle" may fail in many scenarios with uncertainties



Thrust-III: Real-World Applications of Autonomous UAVs and UUVs

- How can we systematically validate the proposed algorithmic capabilities?
  - Formulating scenarios with relevant complexity and continuous experimentation
- Can we replicate emergency scenarios similar to those in space missions?
- How can we demonstrate uncertainty handling in test scenarios?
  - Air currents, stationary and mobile obstacles in UAVs
  - Underwater currents, boat traffic, and severly limited sensing for UUVs

Broader Impact

- Develop a framework with compelling results
  - demonstrating leaps in capabilities not incremental gains
- Providing real-world examples will produce empirical evidence of applicability
- Unique outreach opportunities due to JPL collaboration in both
  - engaging the general public via lectures in space autonomy
  - engaging practicing engineers with academic researchers