National Aeronautics and Space Administration

Scalable and Distributed Swarm Motion Planning via Integrated Optimization and Machine Learning

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Program: FY21 R&TD Topics **Strategic Focus Area: Swarms**

Objectives

The objective of this R&TD was to create a highly scalable and computationally efficient real-time motion planning tool which can be tailored to a variety of JPL missions that involve swarm of space vehicles. We aimed to advance the state-of-the-art in motion planning for multi-agent autonomous systems, by tackling the critical issue of scalability via integrated optimization and machine learning approach. Our swarm motion planner ultimately targets globally optimal motion planning of hundreds of space-vehicles within a few seconds. This represents significant improvement over the state-of-art motion planners.

Background

The state-of-the-art sampling-based motion planning approaches such as variants of the Rapidly-Exploring Random Tree scale well but do not handle high-fidelity dynamics of spacecraft. The optimization-based motion planning approaches can handle dynamics well but has poor scalability, due to physical constraints (e.g. collision avoidance) that makes the problem non-convex and NP-hard.

We propose to develop a distributed and real-time motion planning algorithmic framework and software for multi-agent dynamical systems with an unprecedented level of scalability. Motion planning and trajectory optimization are central to future NASA missions involving swarms of autonomous space vehicles. In response, we seek to fundamentally advance the existing practices for swarm motion planning, which lack scalability and are not compatible with highly distributed computational platforms. To this end, we take a hybrid machine learning and optimization theoretical approach with two objectives in mind: i) Tackling the inherent computational complexity of motion planning to reduce trajectory optimization computation time for large swarm by orders-of-magnitude, and ii) Enabling distributed decision-making by swarms of agents with very limited computational capability. Specifically, we use advances and techniques in artificial intelligence, convex optimization, and distributed control to build a swarm motion planner with immediate applications to pressing JPL's future space exploration problems.

SOA Comparison

Multi-Agent Planning SoA	mRRT*	ORCA	MILP	SCP	Parabolic	DNN	Integrated Approach
Methodology	Sampling -based	Velocity Obstacle based	Optimizat ion	Optimizati on	Optimizati on	Machine Learning	Opt + ML
Scalability	▲	✓	X	▲	▲	✓	✓
Optimality	▲	X	✓	▲	✓	▲	✓
Dynamical Feasibility	X	X	▲	✓	✓	▲	✓
Computational Efficiency	▲	✓	X	▲	▲	✓	✓

Figure 4. Comparison of our proposed approach in relation to the state-of-the-art multi-agent planning methods

Approach and Results

To achieve the computational efficiency and scalability required to enable real-time on-board swarm motion trajectory planning, we take an integrated approach that leverages upon recent advances in both optimization theory and machine learning in a synergistic manner. To this end, there are two main research thrusts each driven by optimization theory and machine learning, respectively.

Thrust (1) Massively Scalable and Distributed Optimization for Motion Planning: This thrust aims at providing orders-of-magnitude scalability improvements in solving challenging instances of swarm motion planning and control problems. We formulate the problems under study as non-convex quadratically-constrained quadratic programs (QCQPs) and adopt a multi-stage approach to find feasible and near-globally optimal solutions through simple distributed operations. The proposed framework [Figure 1,2] consists of (a) low-complexity convex relaxation, (b) feasibility enforcement via penalization, and (c) high-performance numerical search.

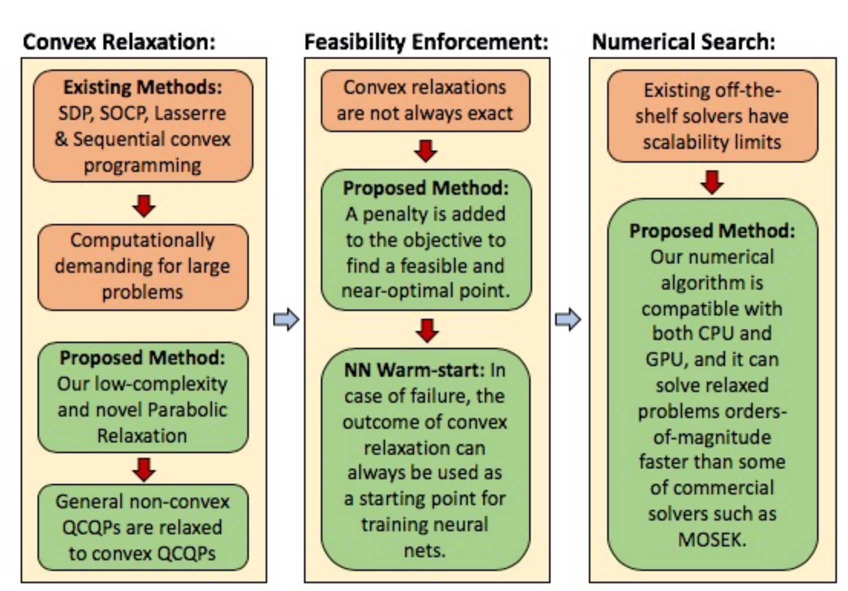

Figure 1. Proposed Optimization-theoretical Approach

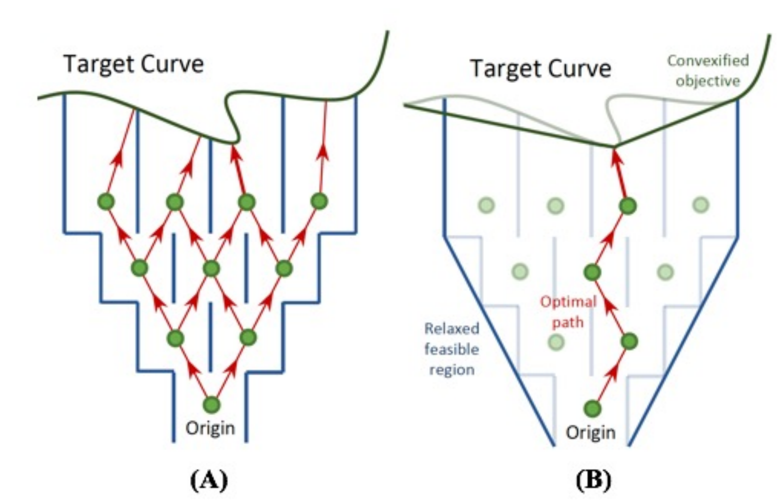

Figure 2. (A) Inherent complexity of motion planning due to non-convexity (B) Convex relaxation and feasibility enforcement to tackle the complexity

Thrust (2) Intelligent Initialization and Optimization-free Planning via Deep Learning: This thrust aims at two objectives: (a) providing high-quality initial seed for Task 1 to increase the speed of convergence, and (b) learning an optimization-free planner that can provide instant solutions via a Deep Neural Network (DNN). It is well known that the performance of optimization algorithms is highly-dependent on the initial seed. As part of Thrust 2, we equip the proposed parallelized optimization solver (Thrust 1) with a DNN that learns the high-order behavior of the cost function in the parameter space. The procedure consists of the following three phases shown in [Figure 3]:

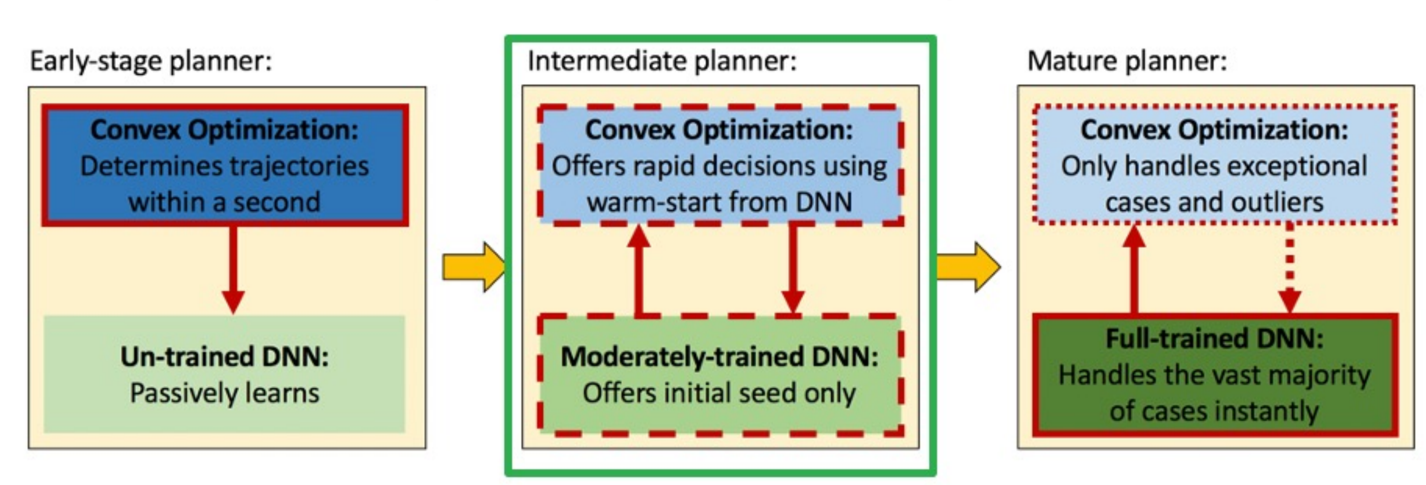

Figure 3. The Mentor/Mentee relationship between the optimization and AI technologies to be developed. Matured DNN will provide instantaneous computation-free plan for the vast majority of cases while Reliable but slower and more expensive optimization module handles exceptional cases for robustness

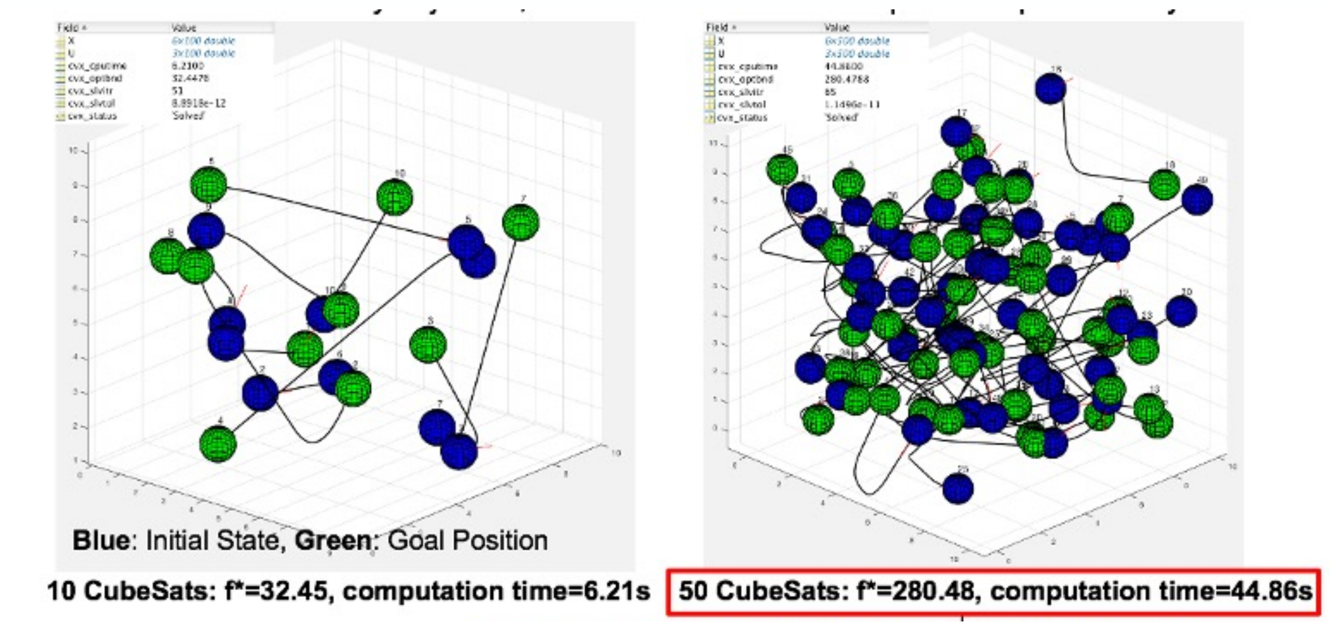

Figure 5. Simulation results showing optimal trajectories that minimizes total delta-V expenditure for reconfiguring Swarm of CubeSats (from blue to green configuration) inside extremely cluttered environment. Our developed optimization-based planner is capable of generating optimal and dynamically feasible trajectories for problem instances involving swarm that current state-of-the-art methods fail to yield solution to.

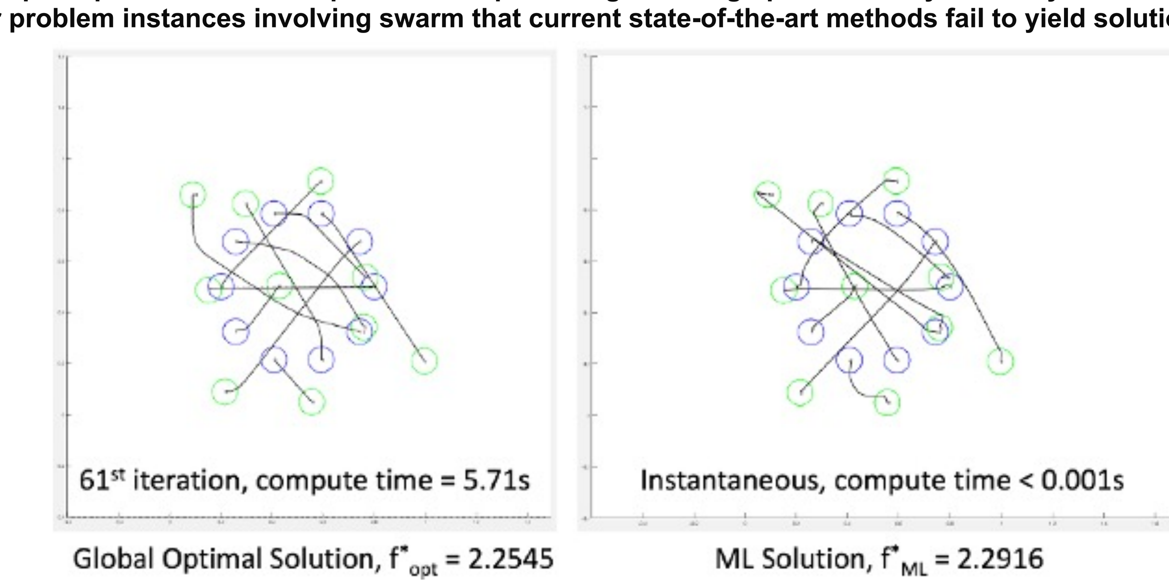

Figure 6. Optimization planner provides swarm trajectory that is globally optimal, dynamically feasible, and safety guaranteed (collision-free) but requires computational time. ML planner provides swarm trajectory that has dynamics (e.g. quantum jumps) and safety (e.g. collision) violations but is able to generate near-optimal swarm trajectory instantaneously.

Significance/Benefits to JPL and NASA

Our swarm motion planner will enable missions that require distributed and onboard trajectory planning in real-time by large fleet (~100) of autonomous space vehicles to maximize given scientific objectives. This technical capability is essential for swarm missions that cannot solely rely on the ground-in-the-loop guidance by mission operators due to the sheer number of space vehicles involved. This approach offers enhanced robustness by continuous adjustment of trajectories based solely on onboard computational resources. This capability is essential for adaptation to changing environments, science objectives, and for mitigating unforeseen obstacles. The proposed scalable swarm motion planner can be readily applied to a variety of autonomous space vehicles under consideration at JPL, acting as a core component of autonomy in future swarm missions ranging from formation flying of hundreds of SmallSats, to coordinated exploration using a large fleet of PUFFERs and Mars-Helicopters.

Publications

[1] K. Yun, C. Choi, S. Alimo, A. Davis, L. Forster, A. Rahmani, M. Adil, and R. Madani, "Multi-Agent Motion Planning using Deep Learning for Space Applications," ASCEND 2020

[2] C. Choi, M. Adil, A. Rahmani, and R. Madani, "Optimal Multi-Robot Motion Planning via Parabolic Relaxation," IEEE Robotics and Automation Letter (under review)

[3] A. Sabol, K. Yun, C. Choi, M. Adil, and R. Madani, "Machine Learning Based Relative Orbit Transfers for Swarm Spacecraft Motion Planning," IEEE Aerospace Conference 2022 (submitted)

[4] C. Choi and A. Davis, "GEOSCAN: Global Earth Observation using Swarm of Coordinated Autonomous Nanosats," IEEE Aerospace Conference 2022 (submitted)

[5] M. Adil, A. Sabol, K. Yun, C. Choi, A. Davis, S. Alimo, A. Rahmani, and R. Madani, "Scalable Swarm Trajectory Planning via Integrated Optimization and Machine Learning," (in manuscript)

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