Virtual Research Presentation Conference

Geometric Motion Planners for Highly-Constrained Environments

Principal Investigator: Joshua Vander Hook, 397 hook@jpl.nasa.gov

Co-Is: 347: Saptarshi Bandyopadhyay, Viet Nguyen, & William Seto;
312: Zaki Hasnain

Program: Spontaneous Concept

Acknowledgements: Ryan Harrod, Michael Trowbridge

Assigned Presentation # RPC-260

Jet Propulsion Laboratory
California Institute of Technology

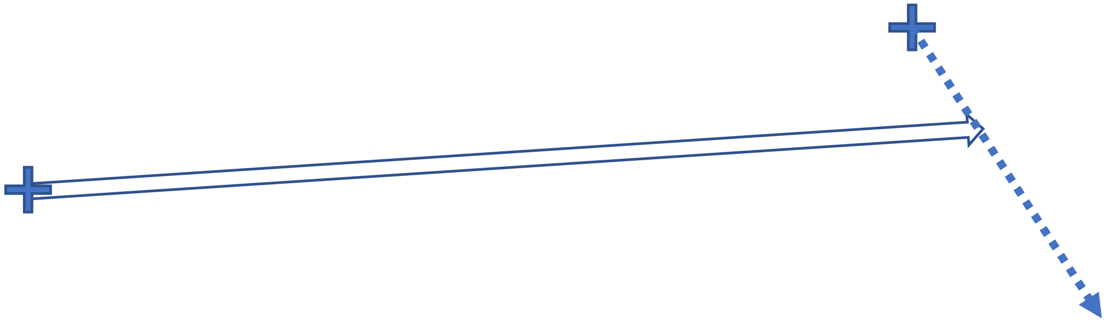
Tutorial Introduction

Abstract

A fundamental problem for **autonomous spacecraft** is **planning motion** without violating **motion constraints** imposed by mission designers or safety concerns. For example: avoiding slewing an instrument to point at the spacecraft body, or not pointing a radiator at a heat source. This is called constrained motion planning.

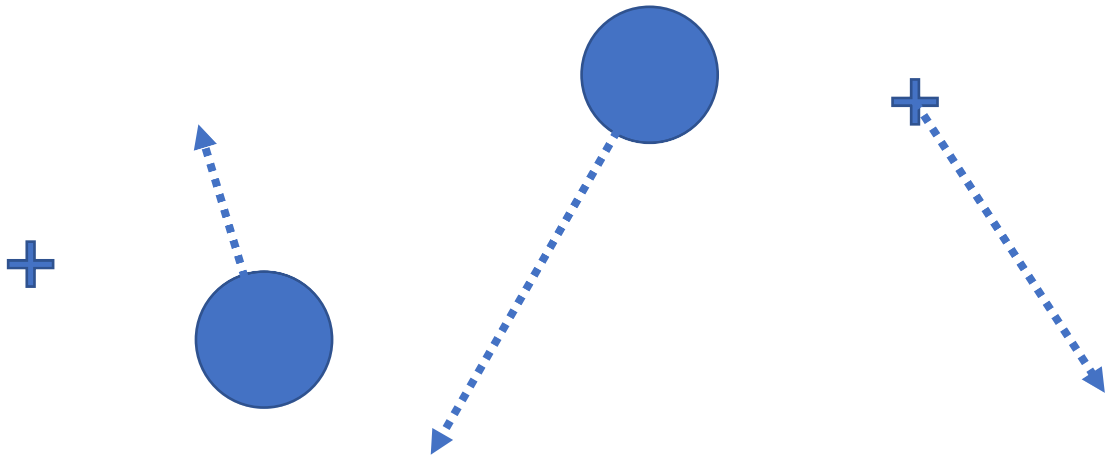
We evaluate **geometric methods** for generating **a sequence of control setpoints** for a spacecraft or robot in highly constrained environments. If an optimal controller follows these setpoints, the resulting trajectory is guaranteed to be minimal cost.

Example of trajectory optimization



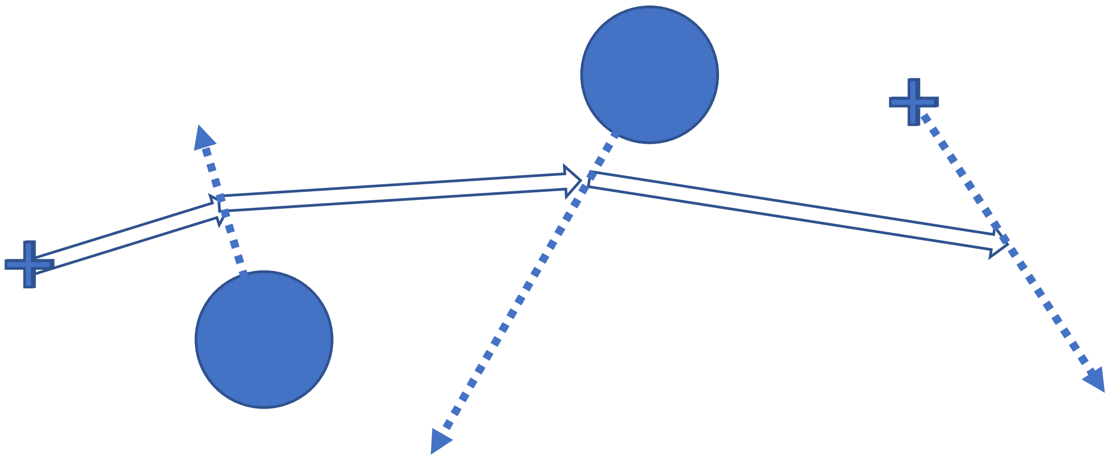
1. Current pose to moving desired pose subject to a maximum change rate!
2. Solution, constraint free, is passed to a control algorithm for path following.

Example of constrained trajectory optimization



1. Current pose to moving desired pose. Maximum change rate!
2. Solution, constraint free, cannot be followed.

Example of constrained trajectory optimization



1. Current pose to moving desired pose. Maximum change rate!
2. Solution, with safe segments, is passed to a control algorithm for path following.

Tutorial Introduction

Abstract

A fundamental problem for **autonomous spacecraft** is **planning motion** without violating **motion constraints** imposed by mission designers or safety concerns. For example: avoiding slewing an instrument to point at the spacecraft body, or not pointing a radiator at a heat source. This is called constrained motion planning.

We evaluate **geometric methods** for generating **a sequence of control setpoints** for a spacecraft or robot in highly constrained environments. If an optimal controller follows these setpoints, the resulting trajectory is guaranteed to be minimal cost.

Image by Ryan Harrod

Agility Envelope (actuators)	$f(\vec{\omega}) \leq \gamma$ $f(\dot{\vec{\omega}}) \leq \gamma$
Type I (static hard)	$\mathbf{v}(t)^T\mathbf{w} \leq \cos\theta$
Type II (static soft)	$\int_{t_a}^{t_b} \lvert\mathbf{v}(t)^T\mathbf{w}\rvert dt \leq \phi$
Type III (dynamic hard)	$\mathbf{v}(t)^T\mathbf{w}(t) \leq \cos\theta$
Type IV (mixed)	Formations/thrusters

Table by Michael Trowbridge

Tutorial Introduction

Abstract

A fundamental problem for **autonomous spacecraft** is **planning motion** without violating **motion constraints** imposed by mission designers or safety concerns. For example: avoiding slewing an instrument to point at the spacecraft body, or not pointing a radiator at a heat source. This is called constrained motion planning.

We evaluate **geometric methods** for generating **a sequence of control setpoints** for a spacecraft or robot in highly constrained environments. If an optimal controller follows these setpoints, the resulting trajectory is guaranteed to be minimal cost.

Image by Ryan Harrod

Agility Envelope (actuators)	$f(\vec{\omega}) \leq \gamma$ $f(\dot{\vec{\omega}}) \leq \gamma$
Type I (static hard)	$\mathbf{v}(t)^T\mathbf{w} \leq \cos\theta$
Type II (static soft)	$\int_{t_a}^{t_b} \lvert\mathbf{v}(t)^T\mathbf{w}\rvert dt \leq \phi$
Type III (dynamic hard)	$\mathbf{v}(t)^T\mathbf{w}(t) \leq \cos\theta$
Type IV (mixed)	Formations/thrusters

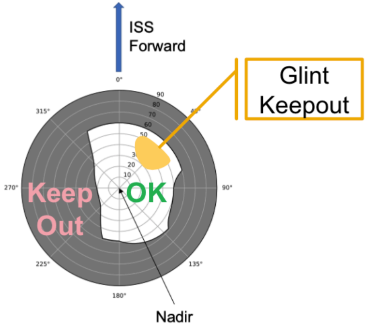
Table by Michael Trowbridge

Tutorial Introduction

Abstract

A fundamental problem for **autonomous spacecraft** is **planning motion** without violating **motion constraints** imposed by mission designers or safety concerns. For example: avoiding slewing an instrument to point at the spacecraft body, or not pointing a radiator at a heat source. This is called constrained motion planning.

We evaluate **geometric methods** for generating **a sequence of control setpoints** for a spacecraft or robot in highly constrained environments. If an optimal controller follows these setpoints, the resulting trajectory is guaranteed to be minimal cost.



Agility Envelope (actuators)	$f(\vec{\omega}) \leq \gamma$ $f(\dot{\vec{\omega}}) \leq \gamma$
Type I (static hard)	$\mathbf{v}(t)^T\mathbf{w} \leq \cos\theta$
Type II (static soft)	$\int_{t_a}^{t_b} \lvert\mathbf{v}(t)^T\mathbf{w}\rvert dt \leq \phi$
Type III (dynamic hard)	$\mathbf{v}(t)^T\mathbf{w}(t) \leq \cos\theta$
Type IV (mixed)	Formations/thrusters

Image by Ryan Harrod

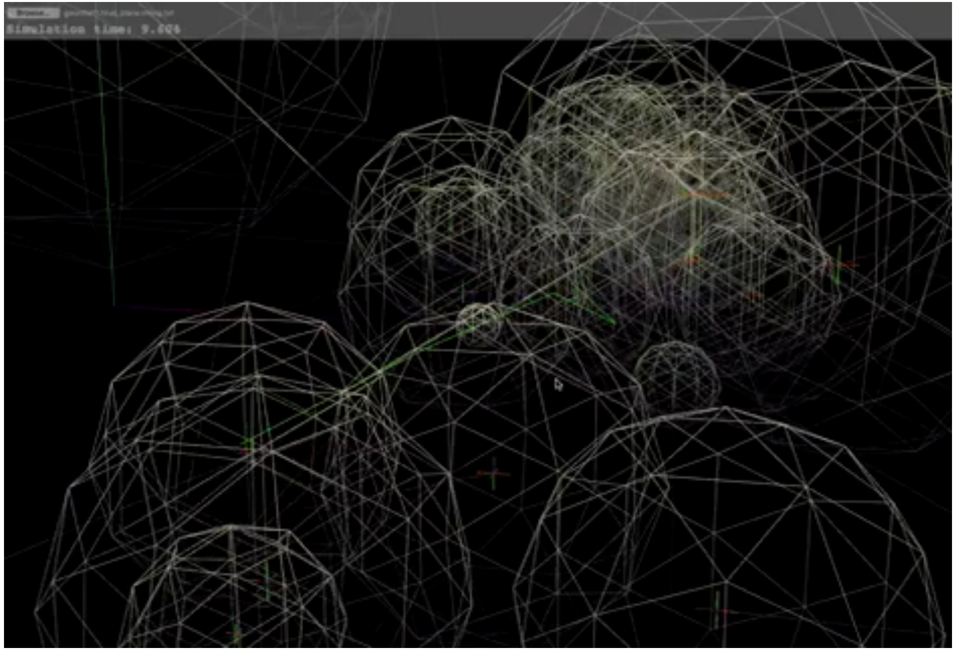
Table by Michael Trowbridge

Methodology

Formulation: We treat the problem as planning motion through a controllable space like two or 3d areas, with prohibited control areas that change with time

Innovation was to separate paths into geometric components that can be solved in closed form and to stich them back together to come up with the optimal solution

We tested the hypothesis that this method would converge faster and to better solutions by implementing the geometric algorithm and comparing directly on a challenging problem set

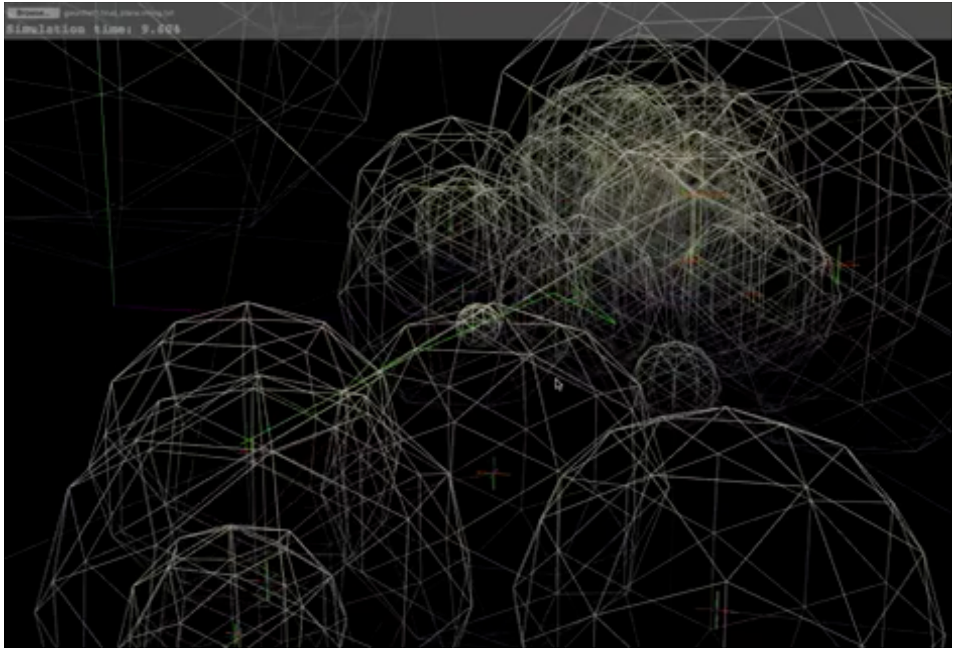


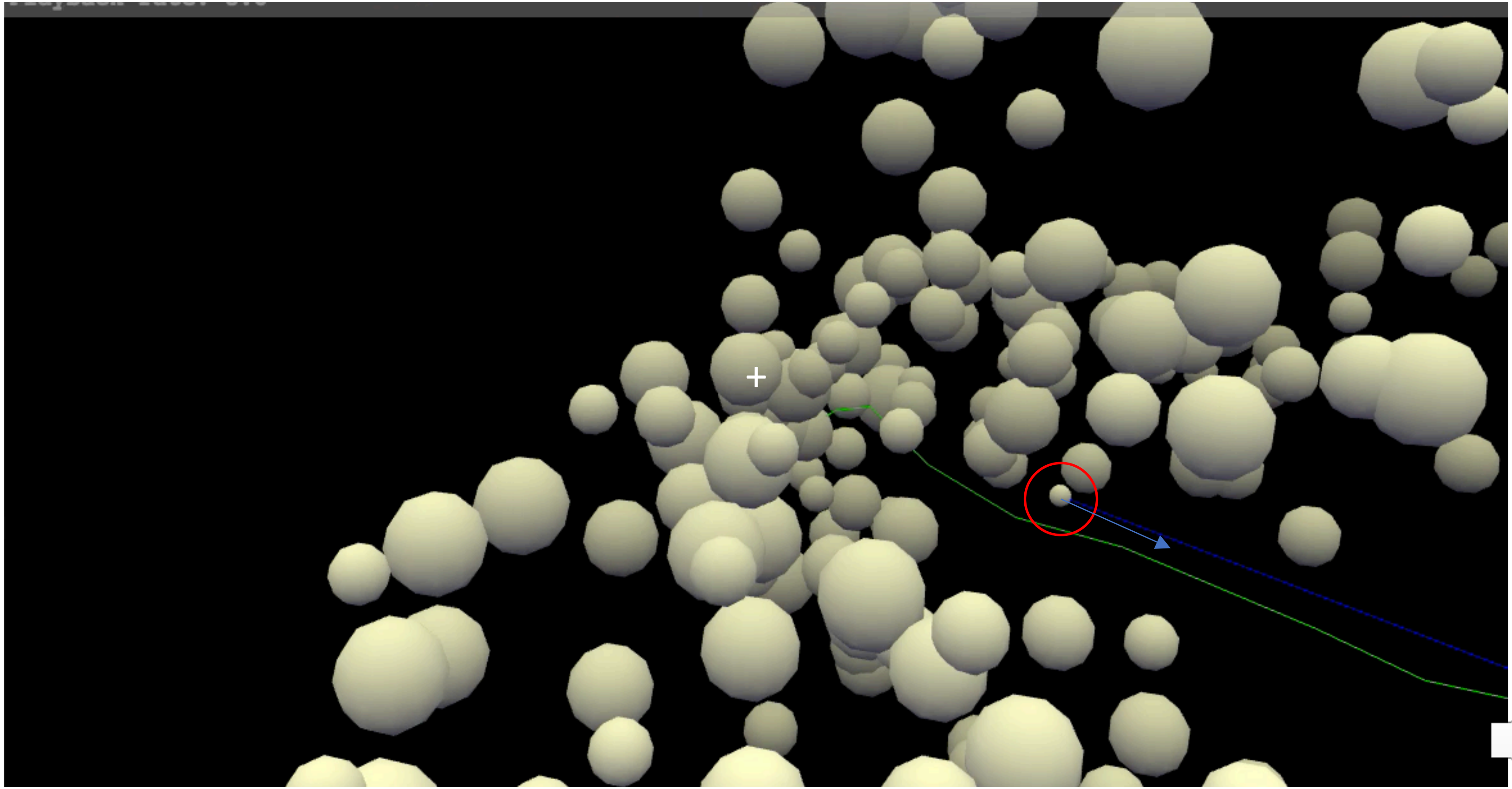
Methodology

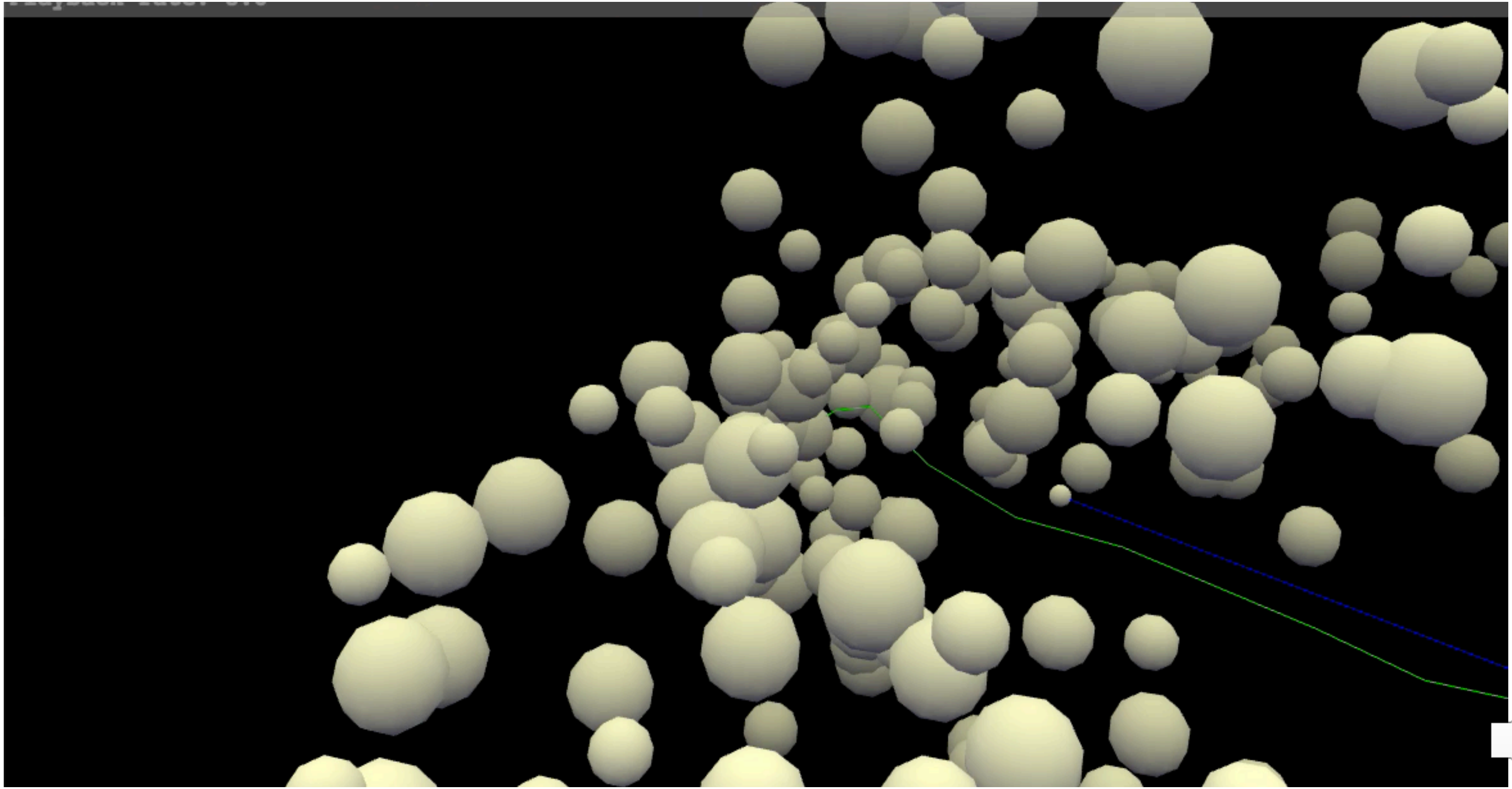
Formulation: We treat the problem as planning motion through a controllable space like two or 3d areas, with prohibited control areas that change with time

Innovation was to separate paths into geometric components that can be solved in closed form and to stich them back together to come up with the optimal solution

We tested the hypothesis that this method would converge faster and to better solutions by implementing the geometric algorithm and comparing directly on a challenging problem set







Results

a) Completed implementation of R^3 exact planner
   - a) Easily extended to higher dimensions

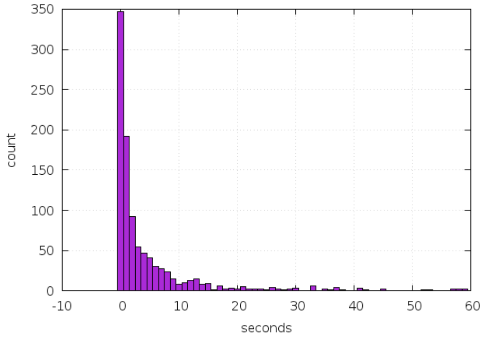
b) Filled missing gap in literature
   - a) Provably optimal solutions
   - b) Provably minimal time cost for fast convergence

c) New guarantees about cost and solution quality!
NTR 51773

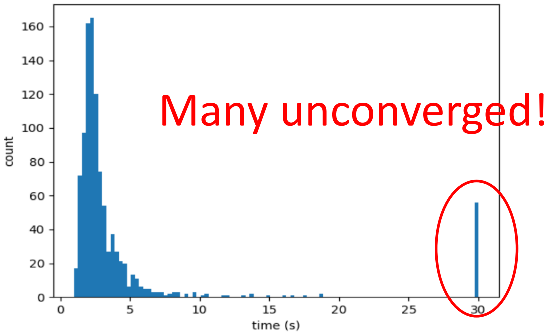
Approach	Type I	Type II	Type III	Type IV	Convergence
Geometric	JPL	☁	JPL	JPL	JPL
Potential Function	√		✔	☁	☁
Constraint Monitoring	√	√	√	√	
Randomized	√	√	√	√	
SDP	√	✖	√	√	✖ ☁

√: Kim et al. 2004 ✔ New since 2004 ✖ Flaw in proof ☁ Ambiguous: possible?

Ours (median <1)



OMPL (median 1-2s)



Results

a) Completed implementation of R^3 exact planner
   - a) Easily extended to higher dimensions

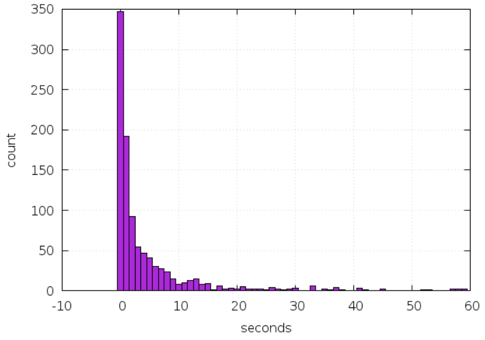
b) Filled missing gap in literature
   - a) Provably optimal solutions
   - b) Provably minimal time cost for fast convergence

c) New guarantees about cost and solution quality!
NTR 51773

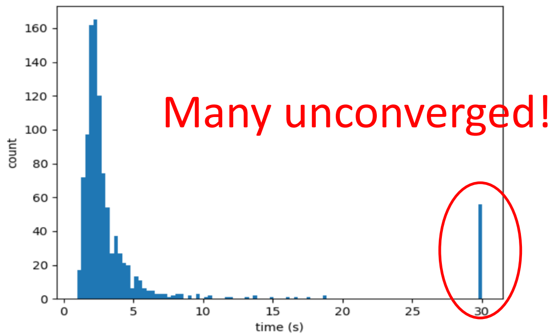
Approach	Type I	Type II	Type III	Type IV	Convergence
Geometric	JPL	☁	JPL	JPL	JPL
Potential Function	√		✓	☁	☁
Constraint Monitoring	√	√	√	√	
Randomized	√	√	√	√	
SDP	√	✗	√	√	✗ ☁

√: Kim et al. 2004 ✓ New since 2004 ✗ Flaw in proof ☁ Ambiguous: possible?

Ours (median <1)



OMPL (median 1-2s)



Recommended Next Steps

a) Study in mission context (OCO-3 or a Pre-phase A concept)

b) Extensions to objective-based planning in addition to constraints

c) Advanced concepts funding for NSPO / DARPA

Publications and References
(from AI Group Michael Trowbridge 2020)

Method	Papers	Missions
Direct waypointing (geometric)	Random: Frazzoli et al. 2001, Cheng et al. 2004 A*: Kjellberg and Lightsey, 2013	A*: Bevo-2, ARMADILLO 3U CubeSats
Constraint Monitor	Singh et al. 1997, Raymann et al. 2000	Cassini, Deep-Space 1
Potential Functions/Barrier Functions	McInnes 1994, Spindler 1998, …, Ramos and Schaub 2018	
Semidefinite Programming	Kim et al. 2004	

Principal Investigator: Joshua Vander Hook, 397 hook@jpl.nasa.gov
Co-Is: 347: Saptarshi Bandyopadhyay, Viet Nguyen, & William Seto;
312: Zaki Hasnain
Program: Spontaneous Concept
Acknowledgements: Ryan Harrod, Michael Trowbridge