Onboard Autonomous Control of Advanced Spacecraft Systems

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Advanced Spacecraft Systems Requires Onboard Autonomous Control

Comets/Asteroids

Planetary Landing

Onboard Autonomous Control

Fuel/power efficiency
Constraints
Uncertainties

Onboard real-time complex GN&C decision making

Swarms

Formation Flying

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Challenges in Advanced Spacecraft Control

- High performance control is needed for
  - Planetary pinpoint landing
  - Formation flying interferometry

- Fuel, power, or time optimality is needed for
  - Increased accuracy or payload mass for planetary landing
  - Long science observation times for formation flying observatories

- Performance must be achieved under uncertainties in
  - Spacecraft dynamics
  - Environmental disturbances
  - Sensor measurements
  - Actuators
  - Operational environment

- Spacecraft must operate under severe constraints on
  - Spacecraft dynamic states
  - Controls
  - Onboard resources
  - Mission duration
Advanced Spacecraft must be Autonomous

- Advance spacecraft must autonomously take control actions to meet these challenges
- The control computations must be performed by limited onboard computational resources
- In formation flying, these decisions must be coordinated autonomously

Increased autonomous control enables
- New and exciting science missions
- Significantly reduce operational costs and time for more traditional space missions
Convex Optimization Framework in Autonomous Spacecraft Control

GN&C problems with constraints, nonlinearities, and uncertainties

- Constrained Optimization -

Convexification

Enables

Verifiable Real-Time Convex Optimization

Rapid and robust optimal solution via IPMs

Onboard Autonomous GN&C
Convex Optimization Framework in Autonomous Spacecraft Control

GN&C problems with constraints, nonlinearities, and uncertainties

- Constrained Optimization -

Convexification

“Lossless” Convexification e.g. Planetary Landing

Enables

Verifiable Real-Time Convex Optimization

Onboard Autonomous GN&C

Rapid and robust optimal solution via IPMs
Convexity Enables Reliable Automated Solutions

Non-Convex Optimization

- Non-Convex cost
- Non-Convex constraints
- Requires expert in the loop

Convex Optimization

- Convex cost
- Convex constraints
- Guaranteed global optimum
- Polynomial-time complexity
- No human in the loop need

Sequential QP, Thrust Region methods, Simulated Annealing, Genetic Prog. ...

IPMs (Interior Point Methods)

- No guarantees of convergence or exponential complexity
- Guaranteed global optimum
- Polynomial-time complexity

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Convexity Enables Reliable Automated Solutions

Non-Convex Optimization

Convex Optimization

Convexification

Main contribution

Sequential QP, Thrust Region methods, Simulated Annealing, Genetic Prog. ...

- No guarantees of convergence or exponential complexity

Requires expert in the loop

IPMs (Interior Point Methods)

- Guaranteed global optimum
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No human in the loop need

Convex cost

Non-Convex cost

Convex constraints

Non-Convex constraints

f(x,y)

x

y

f(x,y)

x

y

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What is Convexification?
What is Convexification?

Non-convex Problem

\[ f(x,y) \]

Convex cost

Non-Convex constraints
What is Convexification?

Non-convex Problem

Convex Problem

CONVEXIFICATION

Reduction

- In general, leads to suboptimal solutions
What is Convexification?

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CONVEXIFICATION

Reduction

- In general, leads to suboptimal solutions

Relaxation

- It can lead to infeasible solutions
- If we can ensure optimal for the relaxed is feasible for the original, then we have lossless convexification

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An Important Example for Convexification: Planetary Pinpoint Landing

Entry Phase

Parachute Phase

Powered Descent (PD) Phase

Error accumulated in and entry parachute phases

5-6 km

Divert distance

Landing location

Would enable

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An Important Example for Convexification: Planetary Pinpoint Landing

Entry Phase

Parachute Phase

Powered Descent (PD) Phase

Landing error
< 1-2 km for Precision Landing
< 0.1 km for Pinpoint Landing

Would enable
- Sample return
- Access to more sites
- Human missions

Artist’s concept

MSL landing ellipse

Sample return
Access to more sites
Human missions

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Relaxed Problem and Lossless Convexification
Relaxed Problem and Lossless Convexification

Minimize fuel s.t.:
- Dynamics, initial and final conditions
- State constraints

\[
\dot{m}(t) = -\alpha \Gamma(t),
\]
\[
\|T_c(t)\| \leq \Gamma(t), \quad 0 < \rho_1 \leq \Gamma(t) \leq \rho_2
\]

Introduce slack variable
Relaxed Problem and Lossless Convexification

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Relaxed Problem and Lossless Convexification

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\]

Proofs in:
Acikmese & Ploen, JGCD 2007
Blackmore & Acikmese, JGCD 2010
Acikmese & Blackmore, Automatica, 2011

Both problems have same optimal solution!

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Algorithm-to-Flight Development Status

**2004**

- **Core idea developed**
  - Lossless convexification of the optimal control problem

**2005**

- **1st G-FOLD release**
  - 2-3 secs per trajectory computation
  - Automated use in Monte-Carlo sims
  - Successfully executed 100s of thousands of times

**2010**

- **Real-Time Version Development Started**
  - Table look-up: < 100 mili-sec
  - Custom real-time implementation: < 300 mili-sec

**2012**

- **ADAPT, Autonomous Descent/Ascent Powered flight Testbed, would demonstrate G-FOLD via a free-flyer experiment**

G-FOLD: Fuel Optimal Large Divert Guidance algorithm

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Autonomous Spacecraft Swarms

1,000s of autonomous agents for
- Ultra large distributed space apertures
  - R/F microwave array
  - Very large antennas
- Decoys at Earth orbit
- Distributed surveillance
- Distributed sensors

Control Challenges:
- Swarm deployment
- Swarm keeping/control
- Swarm guidance
- Swarm density estimation
Proximity Control for Comets and Asteroids

Robust controllers for uncertain/nonlinear systems with state and control constraints

- Successive convexification
  - solves in seconds
  - current methods in hours
- Model Predictive Control (MPC)
  - Robust to model uncertainties
  - Resolvable, continuous feasibility
  - Inherent constraint satisfaction
- LMI based feedback control synthesis for incrementally conic systems

Acikmese, Carson, & Bayard, *Int. Jnl. of Robust and Nonlinear Control*, 2010
Acikmese & Carson, ACC, 2006
Carson, Acikmese, Murray, McMynowski, IFAC, 2008
References


Thanks!

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