Integrated Communication and Controls for Coordinated Swarms of Small Spacecraft

Colorado School of Mines: Jonathan Diller, **Qi Han,** Chris Dreyer
JPL: Saptarshi Bandopadhyay, Pamela Clark, Jean-Pierre de la Croix, Amir Rahmani, Federico Rossi

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Current Practice

- Use of single platform
- Use of multiple platforms
  - Issue commands to control each individual spacecraft from the earth
  - Data gathered by each spacecraft is transmitted to the Earth separately

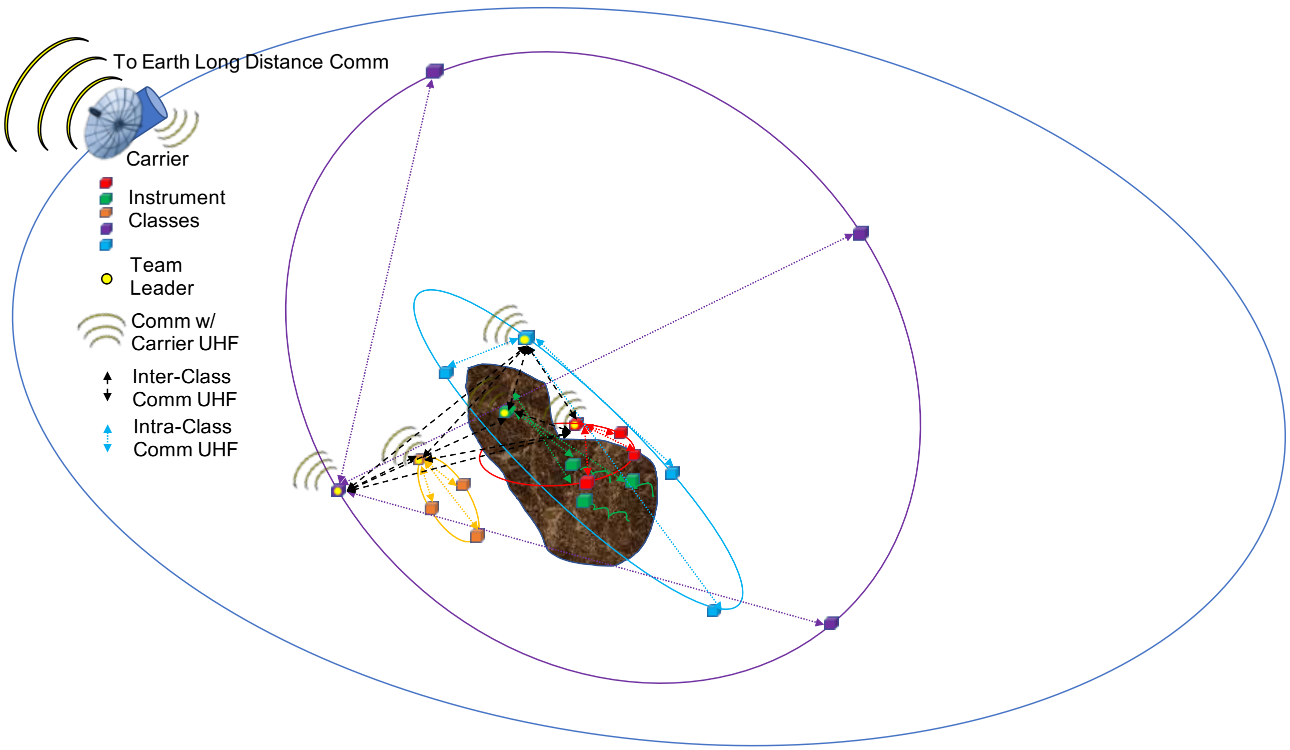
Limitations in Current Practice

- Use of single platform
  - Non-optimal data gathering conditions
  - Requiring longer duration for data collection
  - e.g. up to a third of the time wasted in NEAR mission
- Use of multiple platforms
  - Expensive, slow, unreliable

Challenges

- Intermittent network connectivity
- Stringent bandwidth constraints
- Diverse quality of data and quality of service requirements

Our System Architecture: Distributed Spacecraft Networks



- Swarm of small spacecraft
- A carrier: relay data to Earth

Our Approach

- Enable swarms of small spacecraft with integrated communication and control
  - Network-aware coordination of spacecraft orbits
  - Monitoring of distributed spacecraft network conditions
  - Mobile ad-hoc routing for data collection

Communication-aware Orbit Planning: Problem

- Objective: plan orbits to maximize quantity of data collected
- Constraints: Instrument requirements, communication bandwidth, on-board storage

Communication-aware Orbit Planning: Solution

- Used network-flow graph to model data flow
- Solved using mixed-integer linear programming (MILP)
- Found that Linear Relaxation approximates solution well and provides analytical insights

Communication-aware Orbit Planning: Evaluation

- Simulated in MatLab using IBM's CPLEX Optimizer with JPL's Small Body Dynamics Toolkit (SBDT)
- Evaluated with 7 spacecraft orbiting 433 Eros
- Compared with baseline: Monte Carlo approach to optimize quality of data without communication constraints

Communication-aware Orbit Planning: Results

- Comparison of communication-aware and communication-agnostic orbit optimization
  - 10% increase in data collected
  - 30% increase in data quality

	Comm-aware	Comm-agnostic
Reward	679.15	618.32
Number of regions observed	288	295
by cameras	45	2
by imaging spectrometers	16	151
by X-Ray spectrometer	95	81
by altimeter	132	61
Avg. observability	0.14	0.107
by cameras	0.0083	0.0057
by imaging spectrometers	0.014	0.0107
by X-Ray spectrometer	0.34	0.34
by altimeter	0.053	0.062

Network Monitoring

- When a spacecraft moves
  - Neighbors change
  - Dynamic network topology
- Need to monitor dynamic network status
- Metrics include:
  - Pairwise performance parameters: received signal strength indicator (RSSI), percentage of dropped packets, data rate, last time of spacecraft repositioning, angle of arrival, or flux of traffic
  - Node-specific parameters: battery strength indicators, average data rate, and average RSSI

Mobile Ad-hoc Routing

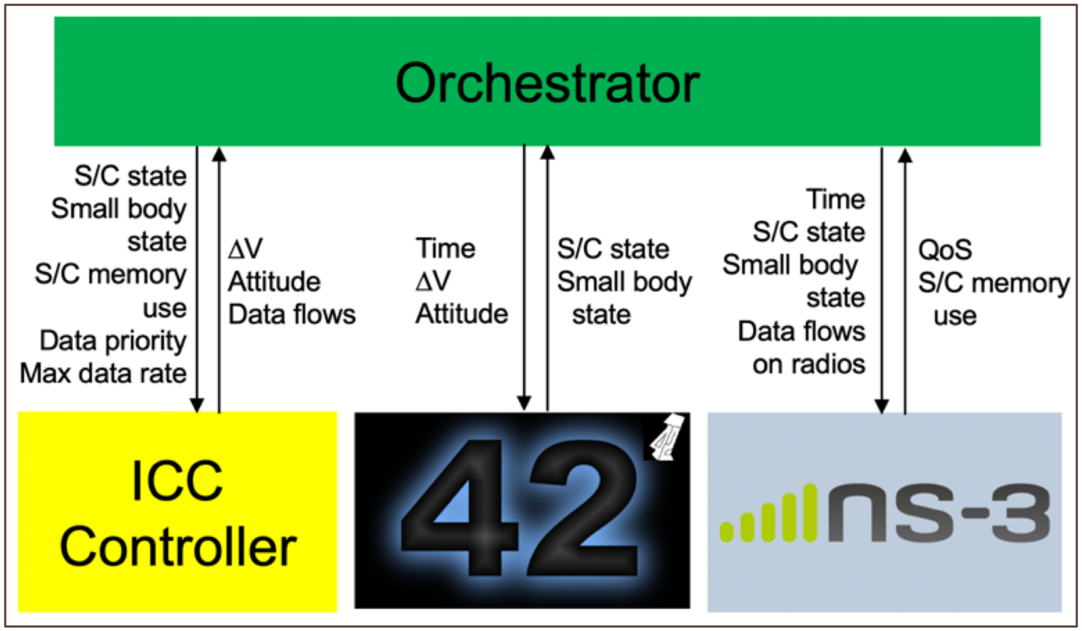
- Mobile Ad-hoc Routing (MANET) protocols are routing protocols for self-organizing mobile networks
- Works by forwarding route discovery messages throughout network
- Two main approaches:
  - Proactive: Always maintain routing information
  - Reactive: Only update routes when needed

Mobile Ad-hoc Routing

- Ad-hoc On Demand Distance Vector (AODV) [1]: MANET routing protocol
- AODV maintains routing table, updates on-demand
  - Forwards route discovery messages when needed
  - Based on number of hops

[1] C.E. Perkins ; E.M. Royer, "Ad-hoc On-Demand Distance Vector Routing" in ACM Workshop on Mobile Computing Systems and Applications (WMCSA), February 1999

Development of Integrated Simulation



Integrated Simulation Setup

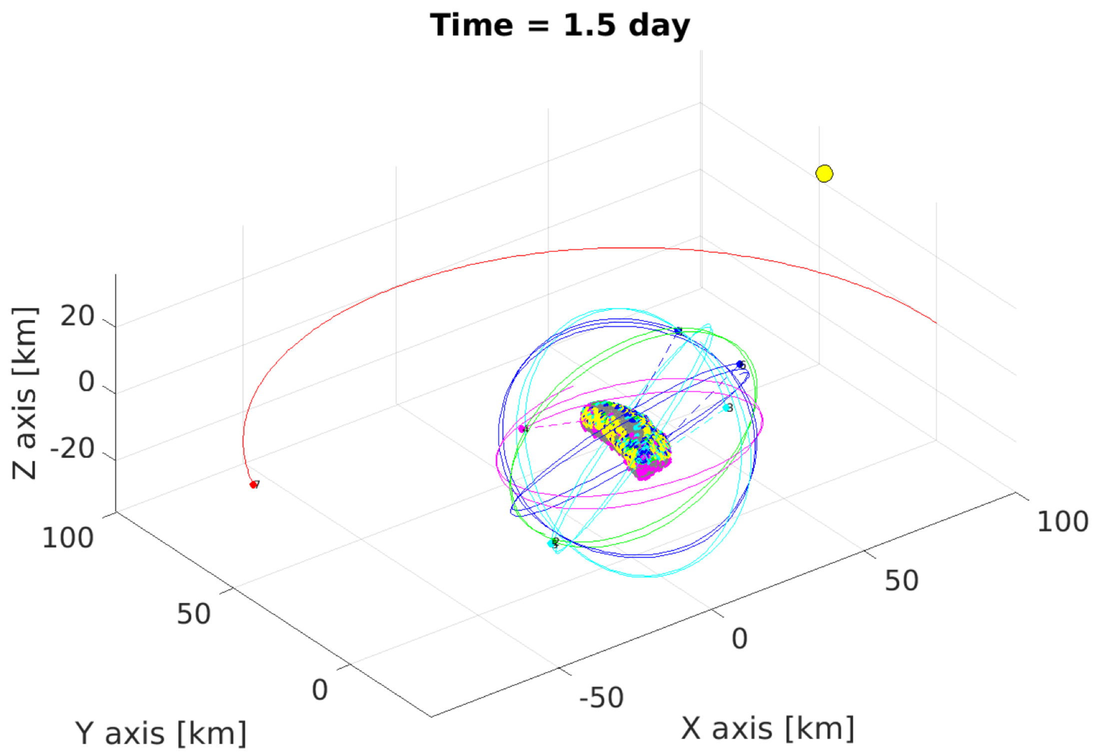
- Generated orbits using Monte Carlo orbit generator to maximize data collection with homogenous sensors
- 7 spacecraft
- Physical layer: IEEE 802.11n Wi-Fi
- Network status monitored:
  - Total data returned to carrier
  - Packet loss

Two Approaches Compared

- multi-hop ad-hoc network: UDP + AODV + Receiver-Based AutoRate (RBAR) MAC protocol [2]
  - Uses RTS/CTS messages to avoid network congestion and adaptive data rates
- single-hop network: TCP + Single-hop routing + CSMA MAC protocol
  - Probes network to determine optimal support data rate

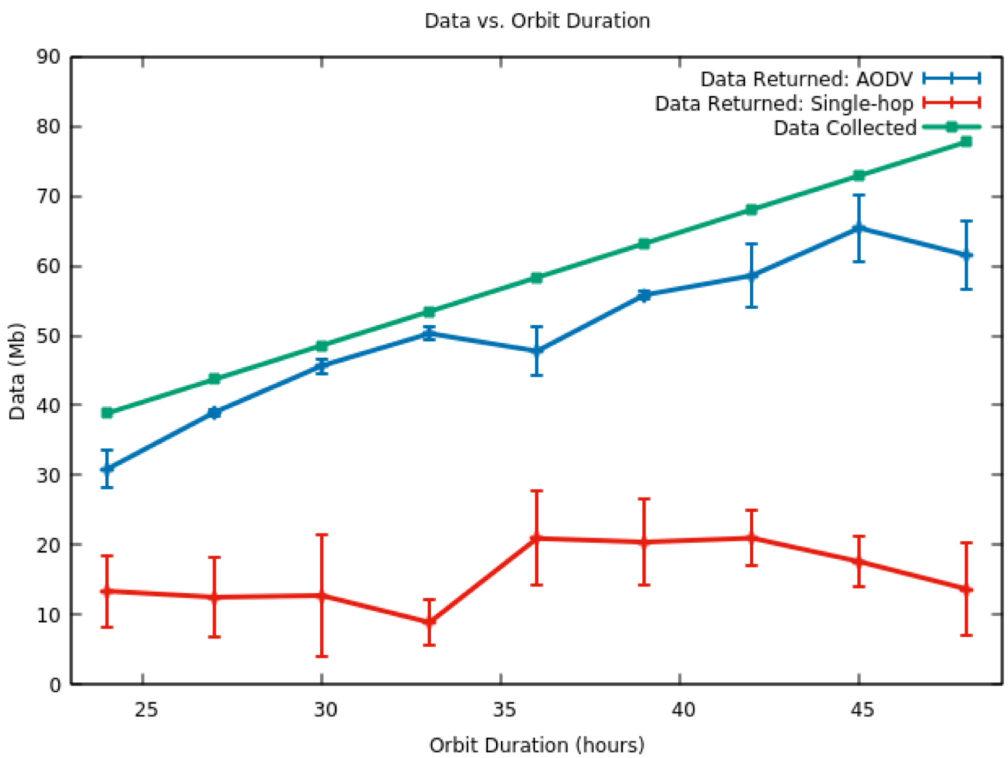
[2] Holland, Gavin, Nitin Vaidya, and Paramvir Bahl. "A rate-adaptive MAC protocol for multi-hop wireless networks." In Proceedings of the 7th annual international conference on Mobile computing and networking, 2001

Sample Planned Orbits



Data collected over varying orbit durations

- Tested with 6 hours of storage capacity
- Average increase in data collected: 240.21%
- Average data lost with AODV: 13.12%
- Average data lost with Single-hop: 72.54%



Future Work

Publications

1) Gerald Henderson, Qi Han, Distributed Learning Automata based Data Dissemination in Swarm Robotic Systems, Master's Thesis, Colorado School of Mines, August 2018
2) Josh Rands, Regression-based Network Monitoring in Swarm Robotic Systems, Undergraduate Research Honors' Thesis, Colorado School of Mines, May 2019
3) Gerald Henderson, Qi Han, Distributed Learning Automata based Data Dissemination in Networked Robotic Systems International Conference on Mobile Computing, Applications, and Service (MobiCASE), June 2019. Best Paper Award.
4) Josh Rands, Qi Han, Regression-based Network Monitoring in Swarm Robotic Systems, Proceedings of International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Mobiquitous), November 2019
5) Sam Friedman, Qi Han, Request and Share then Assign (RASTA): Task Assignment for Networked Multi-Robot Teams, Proceedings of IEEE International Conference on Mobile Ad-hoc and Smart Systems(MASS), December 2020
6) Federico Rossi, Saptarshi Bandyopadhyay, Mark Mote, Jean-Pierre de la Croix, Amir Rahmani, "Communication-Aware Orbit Design for Small Spacecraft Swarms Around Small Bodies", 2020 AAS/AIAA Astrodynamics Specialist Conference, AAS 20-603.
7) Optimization code is finalized and released as open source https://github.com/nasa/icc
8) Integration of 42-NS3 high fidelity simulation platform; available at open source project https://github.com/AeroNexus/42

Questions?

- Contact person: Qi Han, qhan@mines.edu
- The presented material has been internally reviewed by the Colorado School of Mines' Research Compliance Officer and Associate General Council.