IAF SPACE SYSTEMS SYMPOSIUM (D1)
Space Systems Architectures (2)

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SPACE VEHICLE SWARM EXPLORATION MISSIONS: A STUDY OF KEY ENABLING TECHNOLOGIES AND GAPS

Abstract

Teams and swarms of autonomous robots and spacecraft have the potential to change the way future space exploration missions will be undertaken. A swarm of space vehicles is a collection of often smaller and simpler, autonomous vehicles that coordinate in a decentralized manner to achieve a common goal.

Present day monolithic systems (e.g. single spacecraft or rovers) could be replaced or complemented by a swarm of smaller, interconnected and coordinating assets. These swarms can increase science return by cooperatively exploring an area of interest (rovers) or make distributed measurements at sights of interest cued by a leading spacecraft (SmallSats). Spacecraft swarms can yield reduced cost and greater risk tolerance by using larger number of simpler and cheaper assets. Launch cost can also be reduced by launching assets gradually and as secondary payloads. Despite these advantages, multi-agent space exploration missions have not yet been undertaken. The main focus of this paper is to understand the key technologies that enable space exploration using teams and swarms and identify the technology gaps that have prevented mission designers from considering such systems for space exploration missions.

Specifically, the contribution of this paper is threefold:

1. We propose a comprehensive taxonomy of proposed applications of multi-agent systems in space and planetary-surface domains. We also include terrestrial application to capture state-of-the-art enabling technologies for such systems. Our proposed taxonomy is:

- Space Domain: Satellite Navigation, Earth Observation, Gravity Measurement, Distributed Aperture Telescopes, Distributed Fractionated Spacecraft, In-orbit Assembly and Servicing, Solar Observation, Planetary Exploration and Mapping, Distributed Communication Array, Interplanetary Missions;
- Planetary Domain: Exploration, Mapping and Sampling, Cooperative Construction, Communication Infrastructure, Cooperative Computation; and,
- Earth Domain: Exploration, Mapping and Sampling, Cooperative Lifting, Construction and Assembly, Communication Infrastructure, Disaster Recovery/Search and Rescue, Reconnaissance, Patrolling and Tracking, Urban Transportation/Delivery Systems, Entertainment.

2. We leverage the taxonomy to identify and classify the key enabling technologies that will enable such applications, as well as their current technology maturity levels. These technologies include: Absolute Pose Estimation (metrology), Relative Pose Estimation (metrology), Time Synchronization, Formation Keeping, Distributed Inter-Vehicle Communication, Modular Space Systems, Cooperative Manipulation, Distributed Estimation and Cooperative Mapping, Cooperative Motion Planning, Cooperative Task Recognition and Task Allocation, and Human-Space System Interface.

3. We identify the technology gaps that are hindering acceptance of multi-agent systems into mainstream space exploration missions, and outline critical directions for future research and technology development.