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An Overview of Distributed Spacecraft Autonomy at NASA Ames

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ABSTRACT

Autonomous decision-making significantly increases mission effectiveness by mitigating the effects of communication constraints, like latency and bandwidth, and mission complexity on multi-spacecraft operations. To advance the state of the art in autonomous Distributed Space Systems (DSS), the Distributed Spacecraft Autonomy (DSA) team at NASA's Ames Research Center is developing within five relevant technical areas: distributed resource and task management, reactive operations, system modeling and simulation, human-swarm interaction, and ad hoc network communications. DSA is maturing these technologies - critical for future large autonomous DSS - from concept to launch via simulation studies and orbital deployments. A 100-node heterogenous Processor-in-the-Loop (PiL) testbed aids distributed autonomy capability development and verification of multi-spacecraft missions. The DSA software payload deployed to the D-Orbit SCV-004 spacecraft demonstrates multi-agent reconfigurability and reliability as part of an ESA-sponsored in-orbit technology demonstration. Finally, DSA's primary flight mission showcases collaborative resource allocation for multipoint science data collection with four small spacecraft as a payload on NASA's Starling 1.0 satellites.

INTRODUCTION TO AUTONOMY IN DISTRIBUTED SPACE SYSTEMS

Multi-Spacecraft Systems (MSS) are systems that utilize multiple spacecraft to accomplish mission objectives. NASA's Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) Program, in their New Observing Strategy (NOS), defines Distributed Spacecraft Missions (DSM) as "a mission that involves multiple spacecraft to achieve one or more common goals".[1] To our work, MSS and DSM can be treated as equivalent. In contrast to traditional monolithic missions, where a single spacecraft incrementally achieves mission objectives, MSS/DSM both rely on a system of multiple spacecraft to accomplish mission objectives. These missions have become more prevalent due to the decreased launch costs and development costs per vehicle. MSS/DSM can involve heterogeneous spacecraft, consisting of different types, or homogeneous spacecraft, all the same type.

However, it is important to note that a MSS does not necessarily imply distribution or autonomy. The Concept of Operations (ConOps) for MSS may simply include the production of tasks and commands by ground operators, who simply command each spacecraft. Additionally, there exist MSS examples that are neither distributed nor autonomous, such as NASA's HelioSwarm mission.[2] In this mission, operators pre-compute plans for all spacecraft, which are then sent to a central hub spacecraft. The hub spacecraft relays execution plans to the individual detector spacecraft. Here, decision authority remains centralized, commanded by the ground segment and relayed to the central controller. Other examples of MSS include, but are not limited to, SpaceX Starlink,[3] Planet Labs' Flock,[4] NASA's CYGNSS mission,[5] and NASA's TROPICS mission.[6] NASA's ESTO AIST NOS defines a *constellation* as "a space mission that, beginning with its inception, is composed of two or more spacecraft that are placed into specific orbit(s) for the purpose of serving a common objective", explicitly naming CYGNSS and TROP-

ICS as examples.[1] In our work, we also consider this definition of a constellation a MSS.

When autonomy is added to a MSS, we have Autonomous Multi-Spacecraft Systems (A-MSS). An A-MSS allows one of the spacecraft within the system to assume decision authority. Adding autonomy to a MSS offers various advantages, including addressing latency, bandwidth constraints, mission complexity, and transient or temporally limited events of interest. Moreover, autonomy enables the operation of spacecraft as a collective rather than as individuals. The Reconfiguration and Orbit Maintenance Experiments Onboard (ROMEO) experiment phase of the Starling 1.0 mission[7] is one such example. The benefits of autonomy in A-MSS scale with the size of the system, emphasizing the significance of autonomy in larger A-MSS configurations.

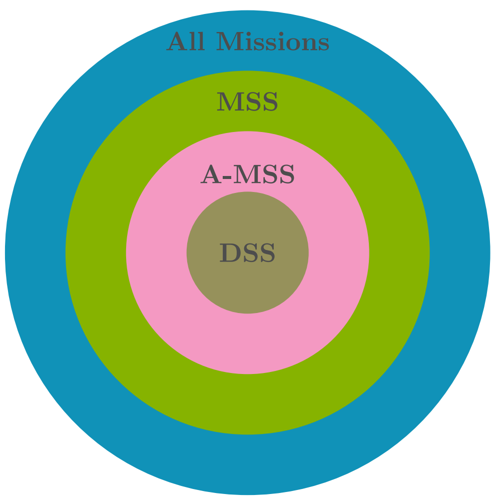

Figure 1: The relationship of satellite missions to MSS, Autonomous-MSS, and DSS. $DSS \in AMSS \in MSS \in All$

Finally, Distributed Space Systems (DSS) represent a type of A-MSS where decision authority itself is distributed across all spacecraft in the system. The ESTO AIST NOS does not make a distinction regarding decision authority when defining Intelligent and Collaborative Constellations (ICC) and SensorWebs[1] and includes generalized autonomy, problem solving, planning, and communications in both definitions. In our work, ICCs and SensorWebs could be either A-MSS or DSS depending on how decision authority is distributed. We find that the ESTO AIST NOS categorizations more than adequate to describe Earth observation systems (for example, their definitions include non-space sensors while ours do not), but find our classifications more useful when defining the scope and motivation of DSA's contributions to boarder space systems research. In particular, the distribution of decision authority in a DSS has several advantages over the centralized authority in an A-MSS, and is motivated by a number of factors (included but not limited to the following):

Definitions	
DSA	**AIST NOS**
All Missions	-
Multi-Spacecraft Missions (MSS)	Distributed Space Mission (DSM) or Constellation
Autonomous Multi-Spacecraft Mission (A-MSS)	Intelligent Collaborative Constellations (ICC) or SensorWeb
Distributed Space System (DSS)	Intelligent Collaborative Constellations (ICC) or SensorWeb

Table 1: Equivalent definitions between Ames DSA and ESTO AIST NOS

- **Fault tolerance and redundancy**: By distributing decision-making authority among multiple spacecraft, the system becomes more resilient to individual failures.
- **Improved scalability**: Distributed decision-making enables the system to scale up or down easily.
- **Increased computational capacity**: Distributing decision-making among multiple spacecraft allows for parallel processing and sharing computational load.
- **Enhanced adaptability and flexibility**: Distributed decision-making enables spacecraft to make autonomous and localized decisions based on local perception and information.
- **Efficient task allocation and coordination**: By distributing decision-making, spacecraft can autonomously allocate tasks among themselves based on their capabilities, proximity, and availability.
- **Increased robustness to communication delays and failures**: In distributed decision-making systems, spacecraft can continue operating even in scenarios where communication between nodes is intermittent or disrupted.

The Distributed Spacecraft Autonomy (DSA) project at NASA's Ames Research Center focuses on advancing autonomy in DSS through five key areas. These areas aim to enhance the state of the art in autonomy and enable more efficient and effective multi-spacecraft missions. The following subsections provide an overview of each focus area and how they contribute to the advancement of autonomy in DSS:

Resource and Task Management

The first focus area is Distributed Resource and Task Management, representing a key aspect of Autonomy in DSS. This focus area underscores the significance of autonomy in spacecraft scheduling, aiming to enable each spacecraft to generate, communicate, and execute its own schedule based on mission objectives and available data. By adopting a decentralized approach, DSS can achieve a higher level of flexibility and adaptability in managing resources and tasks.

The goal of distributed resource and task management is to empower individual spacecraft within the DSS to make autonomous decisions regarding their schedules, while still aligning with the overall mission objectives. This paradigm shift in command and control methodologies allows for a more efficient utilization of available resources, as well as the ability to respond dynamically to changing mission requirements or unexpected events. By granting spacecraft the autonomy to manage their own tasks, the DSS operates as a cohesive and integrated entity, effectively coordinating and allocating resources among the spacecraft. This capability is particularly valuable in scenarios with limited communication bandwidth or latency constraints, where a centralized scheduling approach would be impractical.

Reactive Operations

Reactive Operations is a crucial focus area within the DSA project, aiming to develop algorithms that optimize data collection strategies in real-time. These algorithms enable dynamic sensing and adjustments to operations based on evolving mission conditions. By leveraging reactive operations, a DSS can adapt to changing situations, enhance data collection efficiency, and improve overall mission performance.

The significance of reactive operations in a DSS lies in the system's ability to assume responsibilities that would traditionally require human operators. As the scale of a DSS increases, an autonomous system can react more efficiently and rapidly compared to individual human operators. This shift of responsibilities empowers the system to adapt to dynamic circumstances and optimize resource allocation, leading to improved mission outcomes and increased operational efficiency.

Modeling and Simulation

System modeling and simulation provide a means to evaluate and optimize the performance of DSS under various scenarios and operational conditions. By representing the system's behavior and interactions through models, researchers can analyze the impact of different factors and parameters on mission outcomes. Through iterative refinement, the models can be continuously improved to reflect the complexities and nuances of real-world DSS environments. This process helps identify potential bottlenecks, optimize resource allocation strategies, and enhance the overall performance and robustness of the system.

In the context of the DSA, system modeling and simulation contribute to the development and testing of autonomy in different mission contexts. For example, in the case of the DSA Starling 1.0 mission, these techniques enable researchers to assess the scalability and effectiveness of the autonomous capabilities within a smaller-scale DSS. Similarly, in the case of the Lunar Position, Navigation, and Timing (LPNT) experiment, system modeling and simulation can be leveraged to evaluate the performance and scalability of autonomy in a larger-scale DSS environment, involving a higher number of spacecraft and more complex mission objectives.

Human Swarm Interaction

Collaboration with the Starling 1.0 mission plays a significant role in the DSA project. The integration of human-swarm interaction capabilities through ground control software enables operators to command and interact with the spacecraft swarm (DSS) as a collective entity. This collaboration enhances the flexibility and adaptability of the system, as human operators can provide high-level guidance and intervene when necessary.

Network Communications

Finally, Ad hoc Network Communications is a critical component in the advancement of autonomy in DSS. DSA focuses on developing a communication infrastructure that is scalable, robust, and automatically self-configuring. By ensuring efficient and reliable communication among the distributed spacecraft, DSS missions can effectively exchange information, share situational awareness, and support collaborative decision-making. DSA has partnered with the Starling 1.0 mission and Starling has provided the capabilities listed above. DSA contributes to this focus area by building middle-ware to take advantage of the lower level network stacks Starling has provided.

Introduction Summary

Through these five key focus areas, DSA aims to push the boundaries of autonomy in DSS. By developing advanced software modules, refining operational algorithms, creating scalable models, enabling human-swarm interaction, and establishing robust communication infrastructure, DSA seeks to enhance the autonomy capabilities of distributed spacecraft systems. The ongoing Starling 1.0 mission serves as the primary demonstration platform for DSA,[8] utilizing four 6U CubeSats to showcase the advancements in autonomy and their practical application in a DSS context. Additionally, DSA's scalability study, focusing on Lunar Position, Navigation, and Timing, further explores the challenges and opportunities presented by larger-scale DSS missions, comparing simulation results with flight missions to refine and validate the autonomy techniques developed by the project. DSA also leverages containerization on the ground for modeling, simulation, validation, & verification, as well as on-orbit for trusted autonomy segmentation through the D-Orbit and OSE-SAT missions.

DSA AND STARLING 1.0

The collaboration between the DSA and Starling 1.0 is helping advance autonomy for distributed space systems. Autonomy plays a crucial role in multi-spacecraft missions, enabling spacecraft to make decisions independently, rather than relying solely on ground control. This capability is particularly important for future deep-space missions involving multiple spacecraft, where the communication delays and limited data transmission capacity make traditional command and control approaches impractical.

The Starling 1.0 flight demonstration component of DSA centers around a GPS Channel Selection Experiment, described in detail in prior papers[9] and subsection 2.1. This experiment utilizes a dual-band GPS receiver to measure the total electron content (TEC) of the plasma between the spacecraft and GPS satellites. By analyzing these measurements, the experiment aims to capture various phenomena in the ionosphere, such as the Equatorial Ionization Anomaly and the Polar Patches.[10][11] The DSA system leverages emergent capabilities, namely "shared sampling" and "simultaneous sampling" to optimize the selection of GPS channels across the spacecraft swarm. These approaches enable the efficient allocation of channels for explorative and exploitative observations, maximizing the scientific value of the collected data.

In the flight demonstration, each spacecraft within the Starling 1.0 system will downlink the complete GPS dataset, regardless of the channel selection. The ground data system will then analyze the data, comparing the actual channel allocations made by the DSA algorithms against an optimal partition. The performance of the algorithms will be evaluated based on the degree of match with the optimal channel allocations and the speed at which the DSA system reconfigures in response to changes in the observed features. This experiment was selected as the primary demonstration due to its ability to showcase autonomous reconfiguration in response to natural phenomena without significant integration efforts or modifications to the spacecraft hardware. This demonstration spans the full range of DSA focus areas listed in the introduction.

GPS Channel Selection Experiment

The GPS Channel Selection Experiment focuses on using a dual-band GPS receiver to estimate the plasma density in the ionosphere. By measuring the relative group delay between signals broadcast at different frequencies by GPS satellites, the experiment can capture a wide range of ionospheric phenomena. Two specific phenomena of interest, the Equatorial Ionization Anomaly and the polar patch, act as the features to be observed during the experiment. The experiment employs explorative channel selections when the phenomena being observed are large and homogeneous, and exploitative channel selections when the phenomena are spatially constrained and short-lived.

Figure 2 provides a simplified representation of a channel assignment scenario within the DSS, where multiple spacecraft receive signals from GPS satellites. The experiment involves constraining the number of channels each spacecraft can observe, requiring the DSA system to coordinate channel assignments across the swarm using shared sampling. In the case of spatially-constrained phenomena, simultaneous sampling allows multiple spacecraft to observe the

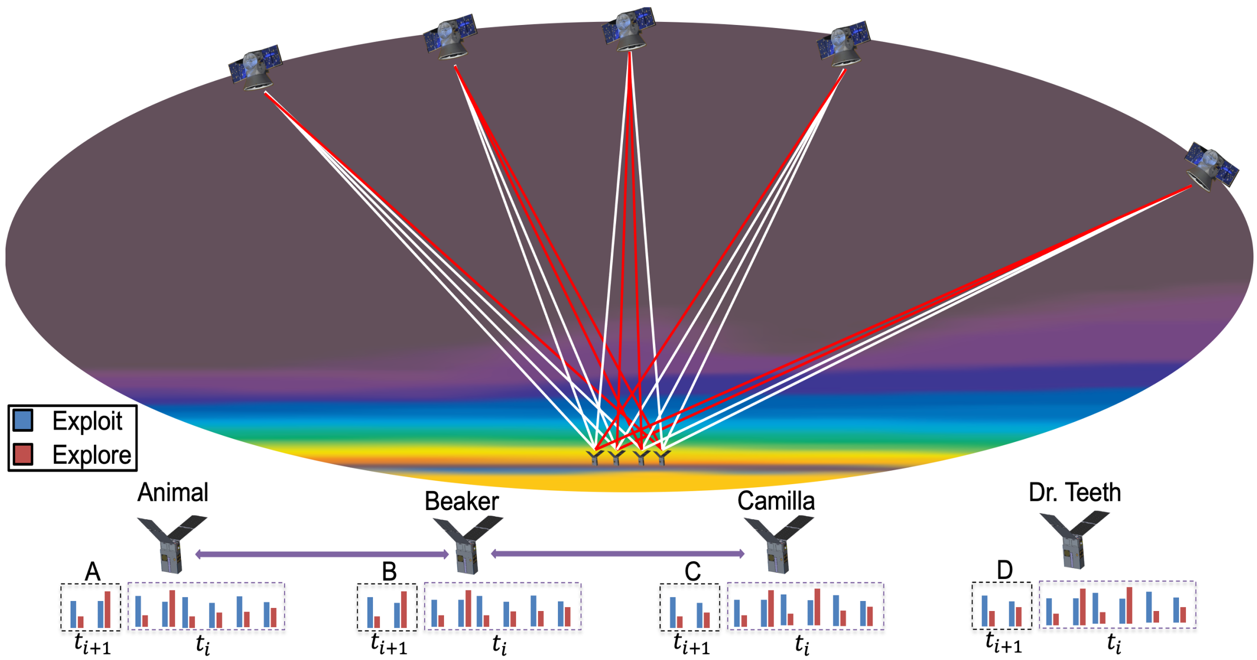

Figure 2: DSA Software performing autonomous GPS channel selection for TEC calculation. A time series below spacecraft A, B, C, and D represents the history of explore and exploit values used by the DSA software to autonomously select GPS channels; red and white lines of sight represented the variation in selected channels.

features of interest from different vantage points. The performance of the algorithms used in the experiment will be evaluated based on their ability to match the optimal channel allocations and their responsiveness to changes in observed features.

Flight Software

The DSA Flight Software utilizes the Core Flight System (cFS) as the framework for each satellite's flight software. This choice ensures compatibility with the Starling-1 flight mission software. For communication middleware, RTI's Connext DDS Micro was chosen due to its ability to handle packet-based communication, scalability, and established flight heritage. The DSA flight mission software consists of three apps within the Core Flight System framework: the Comm App, TEC App, and Autonomy App. The Comm App acts as a wrapper for RTI's Connext DDS Micro, enabling message routing over the Ad-Hoc Network of Starling 1.0; The TEC App processes GPS receiver data and provides inputs to the Autonomy App, which generates a plan for monitoring GPS channels based on inputs from the local TEC App and other satellites.

The flight dataflow diagram (see figure 3) illustrates the flow of data from raw GPS instrument data to channel selections through the three cFS apps. The Comm App facilitates communication between the local autonomy software and other spacecraft, while the TEC App calculates relevant information from raw GPS range data. The Autonomy App utilizes a Mixed Integer Linear Programming (MILP) solver to find optimal channel allocations by combining rewards from the TEC App and other spacecraft. Additional details regarding these application implementations can be found in prior papers[9,12,13] published by the DSA group.

The MILP solver was selected to produce channel allocations from a set of satellites in view. MILP offers scalability, fault response capabilities, and seamless integration with the flight software. Other options considered include Hierarchical Task Networks, Temporal Constraint Networks, Markov Decision Processes (Fully and Partially Observable), and Constraint Programming. However, MILP exhibited the necessary features, making it the preferred choice for the DSA mission.

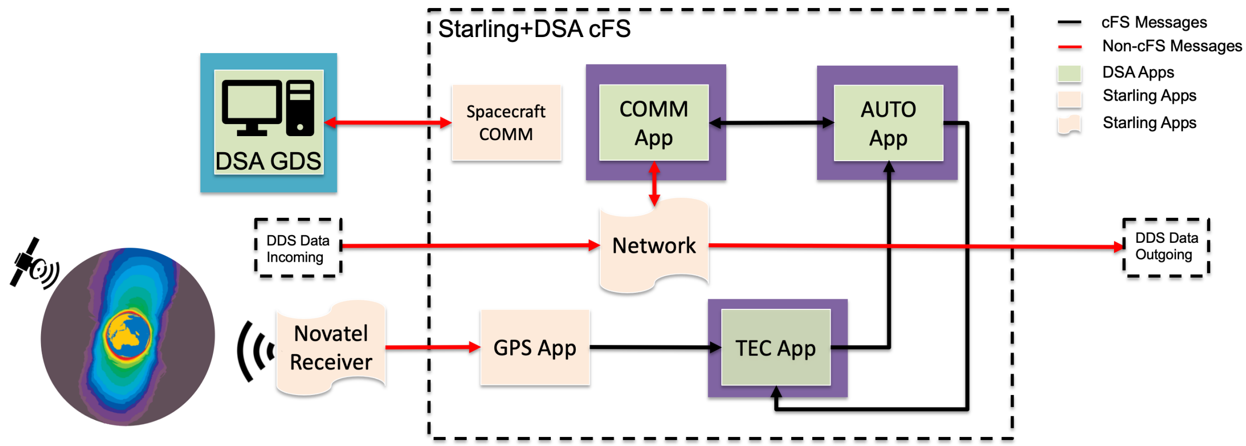

Figure 3: A simplified diagram of the 3 DSA applications operating within the Starling flight software environment, receiving GPS data, and communicating with the DSA Ground Data System (GDS), and utilizing the DDS network.

DSA AND LUNAR POSITIONING NAVIGATION AND TIMING

Upcoming decades will see a substantial increase in Lunar missions supporting and inspired by NASA's Artemis Program, including low-cost missions transported through NASA's Commercial Lunar Payload Services (CLPS) program. While Lunar missions need Position, Navigation and Timing (PNT) capabilities to ensure safe operations and meet their science objectives, the Moon does not currently have a dedicated system akin to Earth's GPS to provide localization services. Capitalizing on upcoming orbital small-sat Lunar science and exploration orbiters could provide PNT services to these low-cost, surface asset Lunar missions. Examples of such small-sat science missions include Lunar Flashlight,[14] Lunar IceCube[15] and Luna H-Map.[16] Other NASA missions have begun to investigate the necessary technologies for a LPNT network, such as NASA's LunaNet.[17] These upcoming small-sat Lunar assets could be used to create an *ad-hoc, non-dedicated* PNT network capable of providing PNT services on-demand. This approach minimizes the resource usage of antennas while still providing high-quality PNT services to these low-cost, surface asset Lunar missions.

In order to minimize operating costs, this constellation should be as autonomous as possible, i.e. localization and PNT service provision should be done with as little interaction with Earth-based mission control as possible. Implementing even a partially de-centralized LPNT system requires solving a difficult multi-agent systems problem. Communication between satellites is not necessarily pervasive; the orbits of the scientific missions permit some pairs of spacecraft to communicate directly either periodically, or not at all. Information exchange, therefore, must rely on establishing relays. Spacecraft whose primary mission is science will perform other tasks, or have constraints on how often they can perform LPNT-related duties. Orbital uncertainties lead to uncertainty in the ability to communicate at any specific time. Finally, limited time and resources require satellites to schedule communication activities to provide the best possible quality of PNT service; how to do so in a de-centralized manner, given all of the above assumptions, is a difficult challenge.

The previously presented Lunar Autonomous PNT System (LAPS)[18] demonstrated the feasibility of orbital asset localization among ad-hoc Lunar small-sat constellations using a Decentralized Extended Kalman filter (DEKF). The DEKF uses pseudoranges[1] to, and relative velocities between, visible satellites as sensor values, or measurements. DEKF update steps require measurements, which in turn require in-space links (ISLs) using the radios to perform two-way ranging operations with each other. Each such operation requires two spacecraft to communicate simultaneously. Continual updates require frequent communication between members of the constellation, which in turn, may not be feasible or allowed by the science missions. Providing service must use as few resource as possible, and may be precluded by high priority science or direct to earth transmission. The spacecraft antenna design profoundly influences the acquisition of measurements

[1] Approximation of the true range.

for the DEKF update step. Directional antennas constrain both communications and two-way ranging operations, both due to antenna pointing and antenna slew and signal acquisition times. Furthermore, in a distributed multi-agent system, *both* satellites must schedule their actions to take place at the same time, otherwise the actions will not succeed.

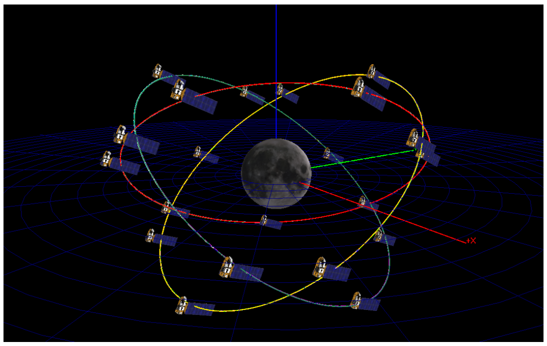

Figure 4: High-Altitude, 21 satellite 'Frozen Orbit' Constellation. The Frozen orbit constellation provides 24/7 global coverage but is an orbit that has never been flown at the Moon.

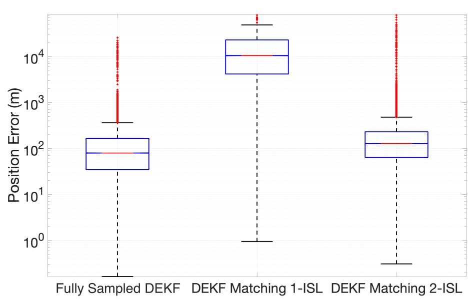

Figure 5: Comparison between matching ISL performance.

LPNT offers DSA a problem of scale to advance the TRL of autonomy technologies. While an LPNT constellation of 100 non-dedicated nodes may be infeasible in the short term, it provides a difficult test-case to drive autonomy at scale, and nevertheless can be simulated in a medium-fidelity environment. The DSA-LPNT effort is described in Frank et al[19] and included:

- Reactive Operations: instead of humans predetermining and uplinking the communication schedule, DSA-LPNT automatically determines the ISLs to perform, and performs them.
- Resource and Task Management: DSA-LPNT poses and solves the problem of determining which ISLs to perform on-board the spacecraft in the constellation, taking into account both changing spacecraft visibility and the need to perform the best measurements to update the DEKF.
- Modeling and Simulation: GMAT for orbits, Matlab for prototyping the DEKF and matching implementation, Multi-PIL for porting all Matlab prototyped algorithms to CFS and demonstrating the algorithms work on flight-like hardware.

We evaluate our approach on a hypothetical *Frozen*[2] *orbit* constellation, which consists of 25 satellites at an altitude of 5500 km evenly spaced around 3 circular, 40° inclination orbital planes, as seen in Figure 4. Assuming all assets are always available, this constellation is designed to represent a constellation that provides global, continuous PNT coverage to all locations on the Lunar surface including the low-latitude polar regions.[20] While frozen orbits have never been demonstrated at the Moon, this constellation provides a good test case for our approach. Our approach performs well compared to an idealized approach from Hagenau et al.[18]

DSA AND DISSTRACK

Validation and Verification (V&V) of DSS requires characterization of emergent system properties that are only observable at scale. To accelerate development and V&V, DSA has developed tooling for the simulation of DSS missions at two different scales and levels of fidelity: containerization and hardware-in-the-loop. Initially, the project developed containerization methods of simulating small DSS on developer laptops with network condition emulation (reachability, delay, loss, jitter, etc.) to support the development of the Starling 1.0 DSA payload.[13] To improve the scale and fidelity of the simulation, the *Distributed Intelligent Spacecraft Simulation Test RACK* (DISSTRACK) with 100 Processor-in-the-Loop nodes and test infrastructure in a single server rack was created to support LPNT development.[21] The evolution from the four-node containerized simulation to the 100-node hardware simulator is shown in Fig. 6.

[2] Low or no propellant needed.
[2] From,[21] with permission

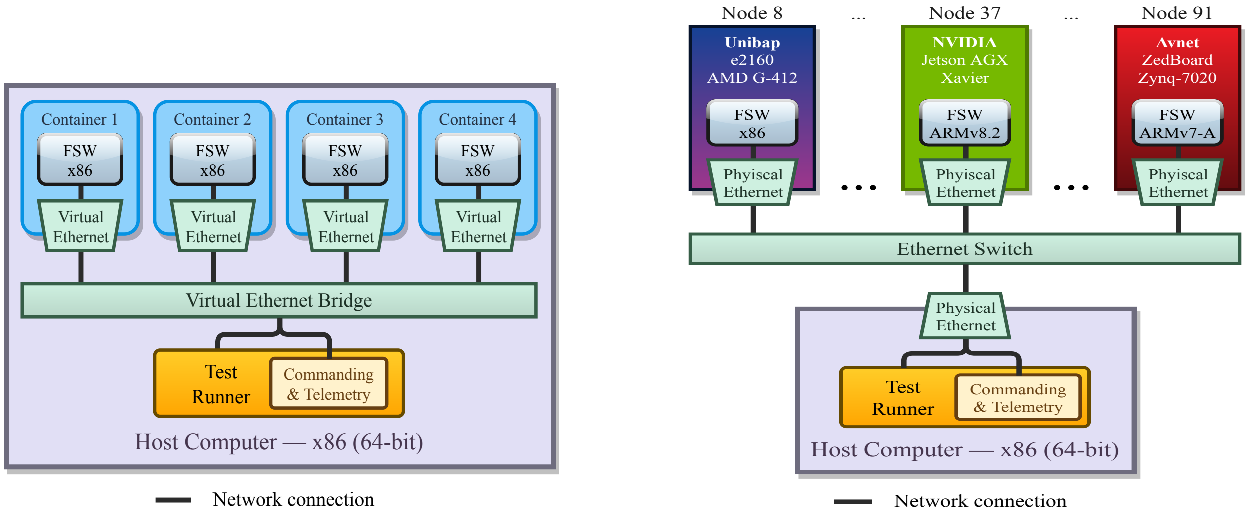

Figure 6: Comparison of character-based and hardware-in-the-loop DSS simulators

DSA AND D-ORBIT

The D-Orbit Wild Ride ION mission launched in June of 2021 carrying a Unibap iX5-100 to validate and demonstrate the SpaceCloud framework in orbit. Leveraging DSA's experience with containerization and the Unibap platform gained on the DISSTRACK simulator, DSA software was configured to demonstrate a trusted autonomous agent deriving safe inputs from experimental processing containers of varying levels of trust. All containers were executed in the SpaceCloud framework and ran NASA's *Core Flight System* cFS[3], communicating between containers with the DSA communications stack built on the open *Data Distribution Service* DDS[4] standard. The DSA autonomy agent successfully collated the results of the experimental data processing containers and detected faulty responses before providing the primary flight controller with only correctly processed results.

DSA AND OSE-SAT

Building on the success of the D-Orbit flight, DSA is preparing a new software payload for an upcoming SpaceCloud-enabled flight, demonstrating an expansion of the hybrid trust architecture used on the D-Orbit mission to incorporate more capable and flexible experimental containers. The *Opportunistic Software Experiments for Space Autonomy Testbeds* (OSE-SAT) mission maintains a traditional cFS primary flight controller but now incorporates artificial intelligence via NASA's *Plan Execution Interchange Language*[5] (PLEXIL) and Space ROS[22] experimental containers for on-orbit payload processing and dynamic retasking. Equipping the autonomy agent with a runtime verification monitor, DSA will demonstrate an effective firewall between power and flexible, yet difficult to verify, experimental containers and the strongly trusted primary flight controller reusing heritage DSA autonomy components in a traditional flight software architecture. With OSE-SAT, DSA continues to fly missions pushing the state-of-the-art for Distributed Space Systems while building upon previous mission support tooling to reduce the required development effort.

FUTURE DISTRIBUTED SPACECRAFT AUTONOMY

The DSA project represents a significant step forward in the field of distributed spacecraft autonomy, as it tackles key technical challenges and paves the way for more efficient and robust space missions. By enabling spacecraft to make autonomous decisions, collaborate, and adapt to changing conditions, the project aims to enhance the effectiveness and productivity of future space exploration and scientific endeavors. However, future Autonomy DSS will require further advances beyond what DSA has accomplished to date.

Future DSS require advances in subject areas DSA does not focus on. Such areas include, but are not limited to: advances in time delay networking, interoperability with existing or planned space networks

[3] https://cfs.gsfc.nasa.gov
[4] https://www.omg.org/omg-dds-portal/
[5] https://plexil-group.github.io/plexil_docs/

or high-bandwidth in-space links. Critically: DSA is only flight-testing DSS within LEO. While plans for practical space networks in Lunar and Martian orbit are highly desirable, how DSS will utilize such networks is still to be determined. DSA is developing both technologies for future DSS and methodologies for future technology infusion by supporting the DSA COMM application across mission architectures[6]. DSA is anticipating the need to test future DSS concepts and is working to build sustainable tools at NASA Ames to aid in their development and testing. The DISSTRACK allows for DSS software tests and experiments to scale from 2 to 100 nodes, while our D-Orbit and OSE-SAT testbeds have allowed us to quickly deploy software experiments on orbit.

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