Inertial Transfer Concept for Autonomous In-Space Assembly

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Rocket payload and fairing size have placed strict mass and volume limitations on single launch in-space structures. These limitations are what motivates In-Space Assembly (ISA) and where Inertial Transfer has potential to improve or augment ISA capabilities by utilizing an efficient multi-agent autonomous system to transport untethered payloads. Adoption of an inertial transfer approach significantly reduces system complexity, energy and time needed for assembly compared to conventional ISA capabilities, increasing the likelihood of early adoption for assembly. The Inertial Transfer concept is presented including autonomy capabilities, potential risks, and three system configurations. These configurations are based on the autonomous system's available sensor coverage that tracks the payload's state. Participating agents have well-defined roles, expectations, and assumptions in their physical organization and coordination of actions depending the mode of operation. The sensor information available to participating agents is considered as it affects the uncertainty in the estimated state and the actions required to capture the payload.

I. Nomenclature

ISA	:	In-Space Assembly
$OSAM$	:	On-orbit Servicing, Assembly, and Manufacturing

II. Introduction

Space payloads are currently volume and weight/mass constrained by today's rocket fairing size. The most powerful operational rocket, Saturn V, had a payload mass and volume capacity of 265,000 lb (120,000 kg) and 5300 ft^3 (150 m^3) respectively [1] [2], with current operational rockets designed to lift less than half that weight and approximately the same volume [3] [2]. At NASA, we plan for a future that includes large and persistent space assets in deep space, on-orbit, and on-planetary surfaces, requiring much larger rockets than what is currently available. The Space Launch System (SLS), NASA's new transport vehicle, is on target to produce a similar payload mass and an eight-fold payload volume capacity when compared to Saturn V [2], but is not designed to carry the proposed space structures in a single launch. In-Space Assembly (ISA) is a modular multi-launch approach that operates within a rocket's volume and weight/mass constraints by launching the pieces of a large structure in multiple, smaller launch vehicles and assembling them in space which allows for much larger persistent structures. More broadly, On-orbit Servicing, Assembly, and Manufacturing (OSAM) capabilities are critical to developing space architectures and systems that enable sustainability and increased performance. The foundations of on-orbit precision space systems are versatile autonomous ISA precision robots with inexpensive and low precision structural elements [4]. Several recent studies [5] [6] have identified ISA capability requirements, some of which are shown below:

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- **Modular Design**
  smaller structures designed to be connected with relative ease to create a more massive structure
- **Robotic Assembly**
  robotic agents that can join modules as well as perform various maintenance and verification operations
- **Long Reach Manipulation**
  transportation of materials, equipment, tools, etc. between staging areas to assembly areas

Developing and expanding these ISA capabilities has the potential to enhance and perhaps enable the following NASA projects: [6]

- Sun Shade
- In Situ Resource Utilization Station
- Artificial Gravity Habitation System
- Space Dock
- High Definition Space Telescope

In-space Inertial Transfer is an augmentation or alternative to traditional robotic long reach manipulation approaches, that propels objects between manipulator workspaces. When compared to other methods this approach may increase efficiency, improve performance, and alter the overall risk posture of proposed NASA ISA projects. Other methods of long reach manipulation include extended reach tensile-cable robotic arms and material-transport vehicles. Extended reach manipulator arms offer more control of the payload; however, there is a trade-off between increasing a manipulator's reach and the space needed for storage. Multiple long reach manipulators with overlapping workspaces pose planning challenges and increase risk when considering malfunctions with potential to cause damage. Material transport vehicles also face similar challenges to extended reach manipulator arms, while also having additional payload capacity and fuel limitations. In comparison to other ISA capabilities, Inertial Transfer can also scale in both transport distance and size of the assembled structure without incurring additional assembly time or power during transport.

III. Inertial Transfer Concept

Inertial Transfer is the process of transporting a payload with a launching force imparted at the start of its trajectory, followed by untethered travel through space to its destination. This technique complements OSAM operations by providing a straightforward, potentially efficient payload transportation process and encourages modular system designs. In-space modular designs facilitate the construction of larger structures by autonomous multi-agent systems capable of performing assembly operations [7]. While Inertial Transfer provides the potential to improve OSAM operations, it also introduces new risks such as damage and loss of payload.

Figure 1 depicts a sample mission that is modeled from the Robotic Assembly of Modular Space Exploration Systems (RAMSES) [7] ISA project, with an on-orbit satellite assembled using modular structural components. Modular components, or payloads, are temporarily stored on the storage module after arriving on regular cargo transports. The storage module can also serve as a staging area for payloads designated for Inertial Transfer. The sender and receiver agents, positioned on the storage module and right structural array, respectively, are the primary autonomous robotic agents that perform Inertial Transfer. The sender is responsible for establishing the payload's initial velocity and release while the receiver captures and decelerates the payload.

All agents are assumed to be online, available, and idle before starting the mission to deliver and assemble a structural module. Participating agents coordinate by communicating key status transitions, including the intent to launch, launching the payload, in-progress status, capturing the payload, and any detected failure. The sender begins the mission by acquiring a payload from the storage bay or an external space vehicle. Given the parameters and desired destination of the payload, a launch trajectory is calculated. A payload intercept position is then calculated along with the corresponding receiver pose. The sender then signals "ready to launch," to which the receiver returns an "acknowledged" message. Once this exchange is complete, the sender then verifies that the immediate area is collision-free and launches the payload toward the receiver for capture. During its travel, the payload's state, its pose and velocity, is monitored by all agents that can sense it at any given point in its trajectory. Using the available payload state information, the receiver agent estimates the point of capture and preemptively reconfigures itself. If the payload's state is incomplete or unavailable, the receiver cannot prepare and performs a capture by reacting when its local sensors detect the payload.

Lastly, the receiver signals the final capture status.

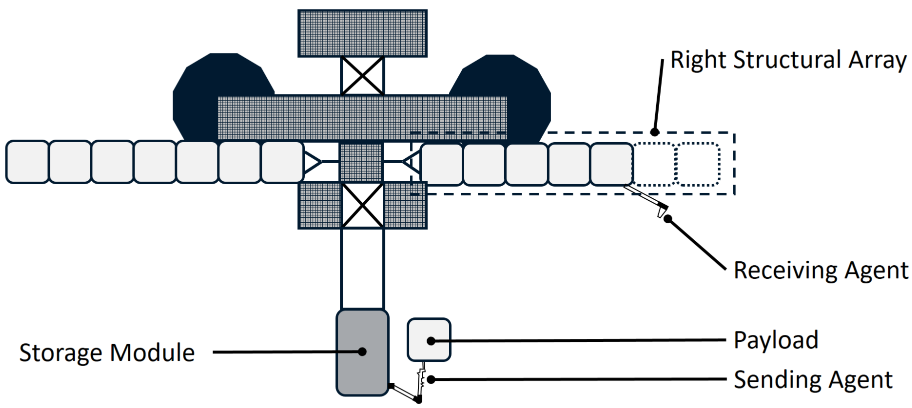

Fig. 1 Inertial Transfer Concept.

IV. Autonomous System Concept

This section details a cooperative multi-agent strategy identifying the role and expectation of heterogeneous robotic agents, organization, and coordination techniques for Inertial Transfer. The discussion addresses the complexity of the emerging concept, but does not define a holistic autonomous multi-agent system as outlined in [8].

A. Robotic Agents

A minimum of three primary agents, identified as the sender, receiver, and observer, autonomously perform the actions involved with Inertial Transfer. Each agent is assumed to have sufficient resources for power, computation, and network-based communication. The sender and receiver are the manipulator agents indicated in Figure 1. These are considered active mobile agents which are equipped with limited sensors used for feedback control and localized situational awareness.

An observer agent is introduced here whose function is specific to an autonomous implementation of Inertial Transfer. The observer is a passive agent that monitors the payload's progress using onboard sensors and communicates available information to the receiving agent in preparation for capture and to the sending agent for future planning consideration. This information includes but is not limited to measures of payload state, mission progress, and obstacles. The observer may be a mobile agent but is assumed fixed while actively observing a payload.

B. Organization and Coordination

The organization, or multi-agent topology, refers to the agents' intended placement to support the assembly. A potential configuration shown in Figure 2 has the sender on the storage bay, the receiver on the far right section of the structural array, and the observer fixed in space relative to the sending and receiving agents. Each agent has limited sensing capability around itself, identified as the coverage area.

The coordination of agents refers to the information shared between each agent and how they interact with the environment, the payload, and other agents. Agents are designed to signal key events and their local estimates of the payload's state for its flight duration and assumed to communicate with no bandwidth issues. Altering an agent's location impacts its corresponding sensor coverage area and the ability to estimate, predict, and communicate the payload's state. The following sensor coverage configurations are presented to highlight how they can significantly affect the certainty of the payload state estimation.

1. Redundant Coverage Area.

The first configuration, Figure 2, is defined by the system's ability to provide uninterrupted **redundant** payload state information for the full duration of the payload's trajectory by all participating agents. During runtime, the combined data shared between all agents can further reduce the uncertainty of the payload's state and mission progress through sensor fusion techniques. This information improves the payload's capture by accurately estimating its state to adjust the receiving agent's capture posture.

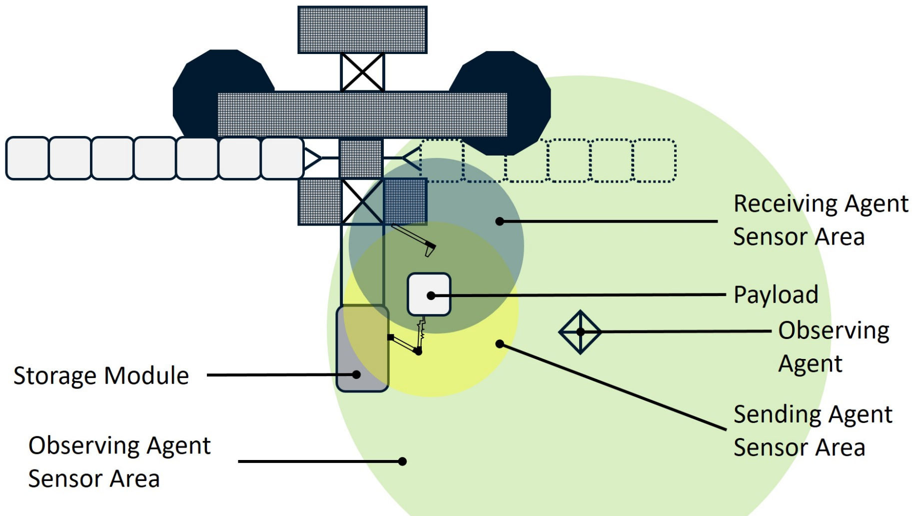

Fig. 2 Redundant Coverage Area.

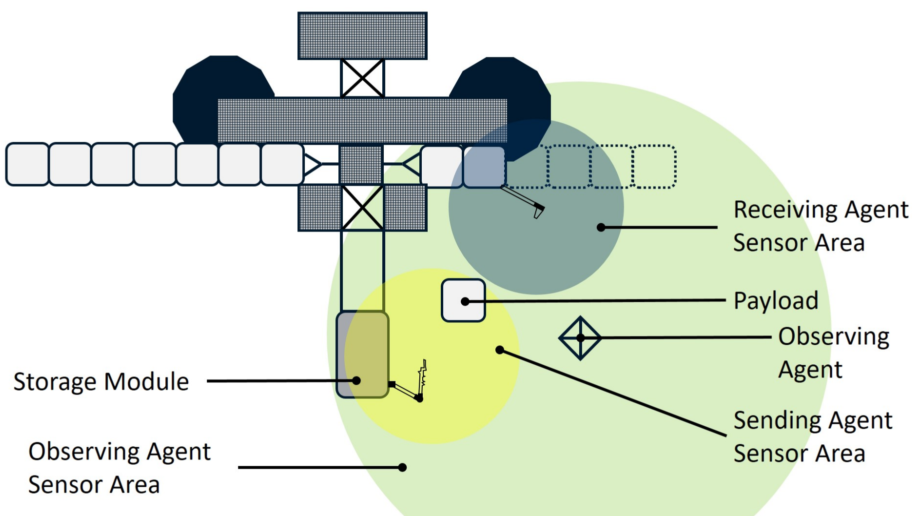

Fig. 3 Continuous Coverage Area.

2. Continuous Coverage Area.

Continuous Coverage Area, as seen in Figure 3, is defined by the system configuration's ability to provide the payload's state information by at least one agent throughout the payload's entire trajectory. The distinction between Continuous Coverage Area and Redundant Coverage area is that a portion of payload trajectory lies outside at least one sensor's coverage area. Essentially, Inertial Transfer performed with the agents in this configuration increases uncertainty in pose estimations and failure risk. While agents are aware of shared key status transitions, the increased uncertainty impacts their ability to make predictions about the payload and may require the receiver to rely more heavily on real-time reactive adjustments for capture.

3. Intermittent Coverage Area.

Lastly, a system has **intermittent** coverage, Figure 4, when agents are organized in such a way that there are gaps in sensor coverage along the payload's trajectory. As a result, uncertainty in the system's ability to estimate payload state information increases. Reliability of payload state estimates is diminished and can cause the receiver to rely entirely on local sensors reactive behaviors for payload capture.

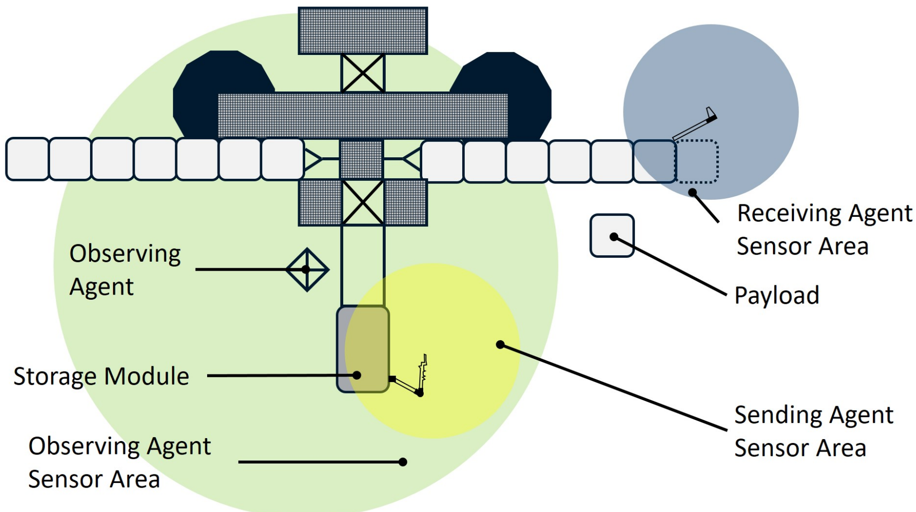

Fig. 4 Intermittent Coverage Area.

V. Conclusions and Future Work

Inertial Transfer is a concept that can enhance ISA capabilities, and more generally, OSAM, by improving material transport using a multi-agent autonomous system. In each of the three sensor configurations considered, it was shown that sensor placement and redundancy affect the system's ability to coordinate, the uncertainty, and the risk when performing Inertial Transfer. Future research aims to understand and mitigate risks and explore alternative methods for determining payload state which includes instrumenting the payload. This paper highlights the concept's potential to complement the assembly of in-space modular structures, simplify payload transport operations, and reduce cost expenditures compared to space vehicle transport.

Future studies will continue investigations of inertial transfer processes that complement or improve ISA capabilities, such as robotic assembly and long reach manipulation. Planned future work includes simulations and reduced-dimension physical testbeds. Both approaches allow for exploration of handling failed captures, payload stabilization, high-level autonomous decision-making, system health management, and estimation strategies through trade studies in a safe and controlled manner. A two-dimensional, low-friction physical testbed enables investigations of pragmatic concerns such as the effect of network latency, loss of communication, launch and capture mechanisms and control concepts, minimum uncertainty requirements for payload state, and missed capture contingency plans. Two-dimensional experiments, coupled with simulation, are an important step in the test and evaluation pipeline and provides verification and validation methods for the designed autonomous system and algorithms.

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