Inertial Transfer: Concept and Multi-Agent Approach

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Research and development of cost saving technologies is vital to the success of NASA's strategic goal to extend human presence deeper into space and to the moon for sustainable long-term exploration and utilization. Reduction of mass has long been a method of reducing space mission costs. In this submission, Inertial Transfer, a new approach to mass transfer in space, is presented. A Multi-Agent System solution to the problem space is discussed. A scaled base-line simulator is constructed and demonstrated which will enable the development of AI capabilities necessary to perform Inertial Transfer. Finally, future work and key challenges are discussed.

-> concept, strategy, demonstration

I. Nomenclature

X = matrix containing accelerations in the global x direction
Y = matrix containing accelerations in the global y direction
$\dot{x}$ = velocity in the global x direction
$\dot{y}$ = velocity in the global x direction
x = position in the global x direction
y = position in the global x direction
c = current time step
i = matrix column index
j = matrix row index
dt = time step

II. Introduction

The Inertial Transfer Concept is a relatively new approach to increasing the efficiency of mass transfer in space. A working definition of Inertial Transfer is the act of transferring an un-tethered object through space by utilizing the objects inertia. This concept is based on the idea that the object being transferred is not capable of self-propulsion.

This concept is being developed as a method of reducing mass and task allocation time of assets in space. Exploration of cost saving technologies is crucial to the success of NASA's strategic goal to extend human presence deeper into space and to the moon for sustainable long-term exploration and utilization.

A. Background

Background information to support the consideration of this concept and add citations.

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B. Inertial Transfer Concept

The selected concept was a multi-agent system that will perform an inertial transfer cooperatively while within a fully observed information landscape. The team generated a demonstration configuration, metrology strategy, and development schedule.

This report details the 12 week project which conceptualized and constructed of an initial proof of concept demonstration for Inertial Transfer. This report and companion files contain all developed concepts and rapid prototype hardware designs for the demonstration. The team was tasked explore the problem space of Inertial Transfer which began by forming a use-case and then determining multi-agent considerations including coordination, organization, learning, decision making, and fault detection. (cite)

Information, Communication Strategies, Metrology, and Verification and Validation. The project deliverable was to provide a proof-of-concept demonstration while operating within some subset of these considerations.

1. Short-Range Transfer

Short range transfer falls within the first operational concept of inertial transfer and is the focus of the demonstration. Here, we define a short-range transfer as an inertial transfer which occurs where the dominant sphere of influence is that of a single celestial body such as in-orbit.

2. Long-Range Transfer

Long-range transfer is an inertial transfer that occurs when the system spans two or more celestial bodies' sphere of influence.

C. Transition to Remainder of Paper

(Strategy -> Demonstration) The selected use case for the term of the project can be described as a collaborative multi-agent system tasked with performing a short-range inertial transfer of an uncontrolled, untethered object while it travels through an information landscape of type one.

The final use-case can thus be described as; a collaborative multi-agent system tasked with performing a short-range inertial transfer of an uncontrolled, untethered object relying on the first concept Information Landscape.

III. Multi-Agent Strategy

The main purpose of defining a use-case was to provide a mission concept that would allow for the exploration of listed considerations without introducing undue complexity. With this in mind, the team decided upon a collaborative multi-agent system tasked with performing an inertial transfer of an uncontrolled, untethered object. It is also necessary to determine the nature of information available to the system. Two additional concepts have been defined based on scene factors affecting the transfer, specifically the number of spheres of influence as defined by astrophysics.

Key attributes of a multi-agent system to be considered include identification of expected autonomous agents, coordination, organization, learning, decision making, health management, and infrastructure.

A. Robotic Agents

There are three primary agents that perform the operations for inertial transfer (note: could be more, this section outlines minimum required) that are identified as the sending, receiving, and observer agents. The sending agent is responsible for the launching of the payload (verify terms) and to be captured by the receiving agent. Both of these agents are equipped with limited local sensors used for control.

The observer agent monitors and communicates various measures of state, progress, health, and any impediments (such as obstacles and potential collisions) of the overall mission objectives. Each agent has its own resources for power, communication, and computation. Identification of these agents also correspond to the expected tasks that each agent performs.

Metrology considerations are generalized below. The intent was to define a list of real-time data requirements which could influence the success of an inertial transfer. Each description will contain whether the consideration was satisfied by simplifying assumptions or addressed directly with in the demonstration.

Scene sensing refers to the ability to detect outside influences such as foreign objects, gravity gradients, etc. in real time. This consideration is addressed in the demonstration by the creation of the acceleration field explained in the

Package Motion Prediction section.

B. Coordination and Organization

Each agent has been identified to correspond to a particular task, not collocated with any other agent.

The base sequence of operations involve the sending agent launching the payload, monitored by the observer agent, and captured by the receiving agent. The planned modes for this operation involve any one of the following three cases for communication.

1) All agents are capable of communicating to each other and sharing all available information. This assumes no or negligible latency.
2) Only observer and receiving agent is able to communicate. Incomplete sensor information (missing sending agent sensor data and notification of launch).
3) No agent is communicating or sharing information, and receiving agent must purely be reactive if equipped with sensors to detect and react to incoming payload.
4) Unsynchronized and partial communication (assume latency, badly timed packets – bad information).

C. Infrastructure and Communication

Communication Strategy considerations are generalized below. The prevailing communication strategy will be heavily influenced by whether the sending agent and receiving agent reside on the same structure(wired communication or wireless), the required data rates, communication priorities and sequences. Regarding the demonstration, the infrastructure used was wired communication via Ethernet. ROS was used. Data rates were assumed to be sufficient for the relatively simple nature of the demonstration. Prioritization is not an issue as there will only be a single sequential task.

- Infrastructure
- Sequence
- Prioritization
- Data Rates
- Information Interpretation
- Simulation

1. Communication Modes

The first mode is categorized by the systems ability to provide uninterrupted state information, with complete overlapping data sources, of all factors which could impact the success of the inertial transfer. Inertial transfer performed under this mode will be qualitatively the least risky.

The second mode is categorized by the systems ability to provide uninterrupted state information, without complete overlapping data sources, of all factors which could impact the success of inertial transfer. The primary difference from the first mode is that there will be some volume of space within which the object will travel that will have only a single source of real time information. Inertial transfer performed under this mode coverage will be qualitatively the more risky compared to the first mode.

The third mode is categorized by the systems ability to provide interrupted state information of any single factor which could impact the success of inertial transfer. The defining trait of this concept is that there will be, at some point through-out the travel time, a loss of real time information on one or more impacting factors. Inertial transfer performed under this mode will be qualitatively the most risky.

D. Verification and Validation

The verification and validation considerations are generalized below. To ensure the predictable behavior of the full demonstration hardware, all information manipulation and interpretation algorithms should be validated and simulations should be constructed before deploying them to hardware. Validation was performed on all developed hardware and algorithms. The results are included within this report. The raw data is also contained in the companion files. Simulations were performed for all major introductions of functionality changes before hardware implementation.

1. Simulation

- used to examine candidate algorithms
  - indicate operability, readiness, and maturity (TRL)
- verify and validate functional use of multi-agent system
- potentially used in production system to estimate probabilistic outcomes
- used in modern systems (find and cite literature)

IV. Demonstration

Fig. 1 Inertial Transfer experimental setup.

Inertial transfer experiments are ongoing with the goal of establishing functional requirements of a multi-agent system capable of performing Inertial Transfer. This section documents how the experimental setup addresses the challenges presented in the Multi-Agent Strategy section.

The major actors in this demonstration are the operational scene, the sending agent, the receiving agent, and the package.

The scene is represented by the BG-X007 Galaxy Collision QuadAir. This device acts as an air bearing surface which provides a low friction 2-D simulation of free - fall / low gravity.(Insert Image).

- This is not an ideal surface and must be characterized in order to plan trajectories effectively.

A. Robotic Agents

1. Sending Agent

The sending agent is a Universal Robotics UR-10 which is an articulated 6-dof robotic arm. The UR-10 has been outfitted with a rapid-prototyped mechanism designed to impart inertia to, or launch, a disk-shaped object, referred to as a puck, which is used in this experiment as the package. The goal of the sending agent is to calculate and execute a launch plan from a desired location.

The launch mechanism (Figure X) was designed to launch a puck of approximately 0.027 kg with an exit velocity of approximately 0.3 m/s. As seen in Figure X, an electromagnet is mounted on the end of a linear actuator, and the puck carriage is connected to a rod with a spring on it. Both the actuator shaft and the rod are supported by pass-through holes in the inside wall. The linear actuator extends towards the puck carriage, at which point the electromagnet is activated, which attracts a ferrous plate mounted on the back of the puck carriage. The actuator then retracts towards the wall, pulling the puck carriage and compressing the spring. Once retracted, the electromagnet is deactivated, allowing the spring to expand and accelerate the carriage and puck. As the carriage approaches the end of the launch tunnel, the tab restricting the puck is displaced and the puck separates from the carriage. (Figure of UR10 and launcher) Local sensors are limited to UR-10 default sensors used for control and an IR emitter and IR sensor used in puck velocity measurement located at the end of the launch tunnel. Currently, this sensor is used for evaluation of launch performance and will be incorporated into the Inertial Transfer procedure in the future.

2. Receiving Agent

The receiving agent is a Universal Robotics UR-3 whose end-effector is a passive rapid-prototyped obstacle whose design is meant to provide an interception surface for the puck. Active grasping is not currently integrated with the demonstration. The goal of the Receiving Agent is to calculate an intercept point, given the Sending Agents launch plan, and move to this position.

3. Observer Agent

Current experiments do not utilize an observer agent. The states in which an Observer Agent would monitor are assumed static and/or integration of data that would be collected has not been accomplished. Explicitly, the experiments operate in a collision free environment where the health of the agents are assumed nominal.

B. Coordination and Organization

This experiment will operate under the assumptions outlined in Concept 1. The following is the experimental Inertial Transfer operation sequence;

1) A launch plan will be created by the launching agent which consists of a launch velocity and angle.
2) The launch plan will be sent to the receiving agent, an intercept position and orientation will be calculate, the a motion plan will be executed.
3) When in position, the receiving agent will indicate that it is ready to receive the package.
4) The sending agent will execute the launch plan.
5) The object will travel through space.
6) The receiving agent will intercept the package.

1. Launch Plan Generation

Generating the launch plan requires accurate information regarding the interaction between environmental influences and the package during travel. It was determined that the primary influence is a result of the table having inconsistencies in the surface slope. This provides acceleration from non-uniform distribution of pressure provided by the table and gravity. The magnitude of these forces rendered any other influences inconsequential as even conservative estimations of other influences(i.e., drag) were several orders of magnitude lower. In order to model the external influences on the package, an acceleration field of the table was mapped. The reader is referred to the appendix for a detailed analysis of the acceleration field.

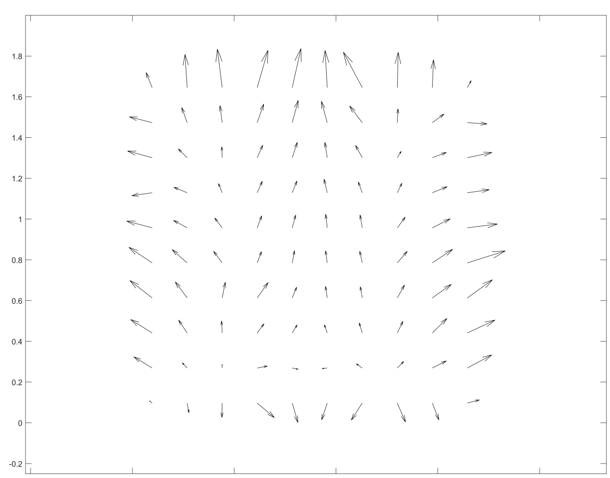

Fig. 2 Two dimensional representation of the acceleration field.

The acceleration field was mapped using a rapid-prototyped puck with a larger radius and lower mass than the traditional puck. This device was instrumented with an accelerometer and Raspberry Pi Zero. The table surface was divided into a $10x10$ matrix and the acceleration was measured within each cell. The acceleration magnitudes in the x and y directions were stored in separate $10x10$ matrices.

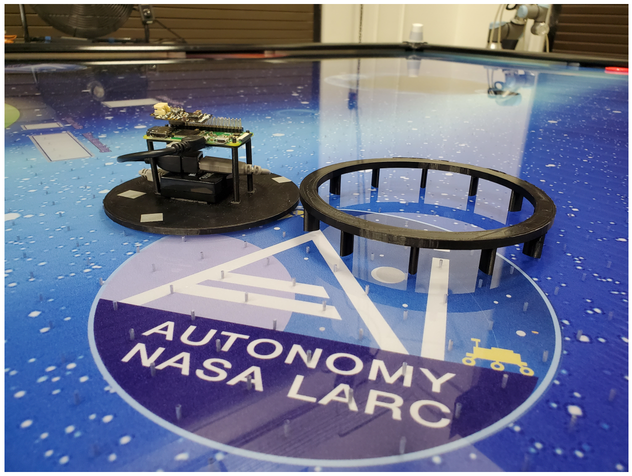

Fig. 3 Acceleration field measurement device.

Using the Acceleration Field, a model was constructed to predict the travel path of the package across the table surface.

Given:
Acceleration matrices:

$$X, Y \tag{1}$$

Initial velocity:

$$(\dot{x}_c, \dot{y}_c) \tag{2}$$

Initial position:

$$(x_c, y_c) \tag{3}$$

$$\ddot{x} = X_{ji} \tag{4}$$

$$\ddot{y} = Y_{ji} \tag{5}$$

$$\dot{x}_{c+1} = \dot{x}_c + \ddot{x}_c dt \tag{6}$$

$$\dot{y}_{c+1} = \dot{y}_c + \ddot{y}_c dt \tag{7}$$

$$x_{c+1} = x_c + \dot{x} dt \tag{8}$$

$$y_{c+1} = y_c + \dot{y} dt \tag{9}$$

Now that a path prediction can be calculated, the sending agent performs an exhaustive search by calculating all predicted paths from the desired launch location by varying launch angle(Figure x). The launch angle, which returns the smallest error between predicted path and the desired package destination,is selected.

Infrastructure and communication and verification and validation: (this section may best to be detailed in experiment as this largely is dependent on the implementation. combine with communication – add security here?) (note: some of the lists in this section are out of place and out of date)

V. Future Work

To Do.

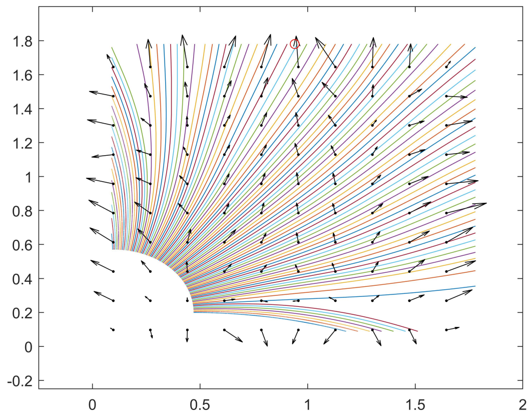

Fig. 4 Candidate Paths.

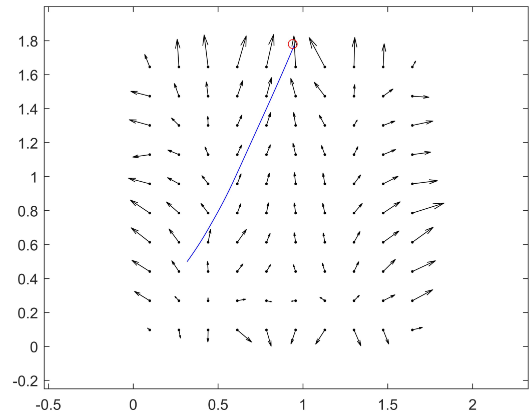

Fig. 5 Selected Path.

VI. Conclusion

The first experiment was to perform an inertial transfer sequence, as detailed in the Experimental Setup Section. The goal was to demonstrate the base line performance of the inertial transfer simulator. The initial position was defined and provided to the Sending Agent (Right of FigureX) and the desired goal was defined as the center of the opposing wall directly in front of the UR-3 (left of figure). The Sending Agent was able to successfully move to the initial position, calculate a launch angle. The Receiving Agent is informed of the current position and launch angle of the Sending Agent, at which time an intercept point and intercept angle are calculated. The Receiving Agent successfully moves to the calculated location and achieves the calculated angle. Upon receiving confirmation that the Receiving agent is in position, the Sending Agent launches the package. The package, with an exit velocity of 0.32 m/s, travels to the desired location. The average error in the packageâĂŹs location compared to the desired intercept point is 0.03 m. Given the accuracy of the final position is not commensurate with the expected accuracy of the robotic hardware involved, it should be noted that the system was operating without reactive intercept capability and a model with large discretization sizes.

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