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Integrating Model-Based Transmission Reduction into a Multi-Tier Architecture

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Abstract—A multi-tier architecture consists of numerous craft as part of the system, orbital, aerial, and surface tiers. Each tier is able to collect progressively greater levels of information. Generally, craft from lower-level tiers are deployed to a target of interest based on its identification by a higher-level craft. While the architecture promotes significant amounts of science being performed in parallel, this may overwhelm the computational and transmission capabilities of higher-tier craft and links (particularly the deep space link back to Earth). Because of this, a new paradigm in in-situ data processing is required.

Model-based transmission reduction (MBTR) is such a paradigm. Under MBTR, each node (whether a single spacecraft in orbit of the Earth or another planet or a member of a multi-tier network) is given an a priori model of the phenomenon that it is assigned to study. It performs activities to validate this model. If the model is found to be erroneous, corrective changes are identified, assessed to ensure their significance for being passed on, and prioritized for transmission. A limited amount of verification data is sent with each MBTR assertion message to allow those that might rely on the data to validate the correct operation of the spacecraft and MBTR engine onboard.

Integrating MBTR with a multi-tier framework creates an MBTR hierarchy. Higher levels of the MBTR hierarchy task lower levels with data collection and assessment tasks that are required to validate or correct elements of its model. A model of the expected conditions is sent to the lower level craft; which then engages its own MBTR engine to validate or correct the model. This may include assigning a yet lower level of craft to perform activities. When the MBTR engine at a given level receives all of its component data (whether directly collected or from delegation), it randomly chooses some to validate (by re-processing the validation data), performs analysis and sends its own results (validation and/or changes of model elements and supporting validation data) to its upstream node. This constrains data transmission to only significant (either because it includes a change or is validation data critical for assessing overall performance) information and reduces the processing requirements (by not having to process insignificant data) at higher-level nodes.

This paper presents a framework for multi-tier MBTR and two demonstration mission concepts: an Earth senor net and a mission to Mars. These multi-tier MBTR concepts are compared to a traditional mission approach.

TABLE OF CONTENTS

1. INTRODUCTION ................................................. 1

2. BACKGROUND .................................................. 2

3. INTEGRATING THE MULTI-TIER APPROACH AND MODEL-BASED TRANSMISSION REDUCTION ............... 3

4. COMMUNICATIONS PARADIGM FOR A MBTR HIERARCHY / MULTI-TIER MISSION .................. 4

5. EVALUATION OF THE MBTR HIERARCHY CONCEPT .......................................................... 5

6. DEMONSTRATION MISSION CONCEPTS ........... 5

7. CONCLUSIONS AND FUTURE WORK ............... 6

REFERENCES ............................................................................ 6

1. INTRODUCTION

Numerous applications exist that can benefit from a group of heterogeneous robots operating collaboratively. Some of these applications require that the robots collect data across a wide area of unknown status. While craft with a single movement-approach (e.g., ground-based craft) could conceivably collect the requisite data, their performance would be less than satisfactory when compared with an approach that integrated multiple craft with alternate movement characteristics. The Multi-Tier Autonomous Mission Architecture (MAMA) [1] is one approach that can facilitate this collaboration. MAMA coordinates the efforts of multiple craft across orbital, aerial, surface and other tiers. These craft exchange data and collaborate to achieve mission goals.

Craft coordination and collaboration can be task-based or goal-based. Under a task-based approach, a controller defines a desired objective (e.g., imaging a desired area) and the MAMA-member craft autonomously determine the most effective way to achieve this goal. However, in many cases, while the desired outcome is known, the exact tasks that are required to perform the outcome are not. In this case, goal-based control is implemented. With goal based control, a well-defined (generally broad) goal is provided to the collaborating craft which then take actions to assess the requirements of goal attainment and perform those actions. For example, it may be desirable to find locations containing a particular resource (either on Earth or another body), ensure that an area that troops will be traversing is free of landmines and other threats or determine the validity of a scientific principle. In these cases, significant data will be collected; however, most of it is not relevant to
controllers. In these cases, controllers are interested in an assertion – and the data to back it up.

Model-Based Transmission Reduction (MBTR) [2] is an effective way of managing inter-craft and craft-controller communications in cases where investigations or assignments are goal-driven. Under MBTR, a result and supporting data are conveyed to controllers. When MBTR is combined with a MAMA, this can be performed hierarchically: several lower-level assertions may be combined to prove or refute a higher (composite) assertion.

2. BACKGROUND

Pristine-Class Missions

Most planetary science missions have consisted of a single large spacecraft. [3, 4, 5, 6] In some cases, a sub-craft has been deployed (e.g., a lander), or two craft have worked together to achieve a goal (e.g., the GRAIL mission). However, no mission to-date has utilized a large collection of heterogeneous craft, despite the advantages that this approach may provide in certain circumstances. The trend on Mars has been towards progressively larger lander craft (e.g., the current Mars Science Laboratory is car-sized). [7] However, the growing size of these craft is pushing the boundaries of what can be easily and safely landed on the planet’s surface (given its atmospheric conditions); the Mars Science Laboratory (MSL) required an intricate set of maneuvers for this safe landing, which (while ultimately successful) increased mission risk.

Earth-orbiting missions are also comparatively large. The Hubble-sized Earth-observing spacecraft recently provided to the National Aeronautics and Space Administration (NASA) by the National Reconnaissance Office (NRO) exemplify the scale of the spacecraft that are used for these applications. [8] While these craft can provide an exquisite level of detail of a target area, they lack the ability to provide significant breadth of coverage. Acknowledging this capability shortfall, the Defense Advanced Research Projects Agency (DARPA) has undertaken to provide a quick-response capability, SeeMe, which aims to provide a short duration between capability request and delivery. [9]

Multi-Tier Approach

Fink [10, 11] and others [12, 13] suggest an approach that combines the efforts of multiple, comparatively smaller, craft with different breadth and depth of coverage capabilities. Fink’s “tier-scalable” approach implements top-down control of multiple craft, utilizing the significant computing resources located on the orbital craft, in particular, to coordinate the efforts of the lower-level craft. [1, 10, 11, 14]

A multi-tier approach, proposed in [15] and expanded upon in [1, 16] provides goal-based tasking from the higher-tier craft; however, the lower-level craft are left to determine the appropriate method for achieving the tasked goals. A computing task hand-off method allows analysis tasks that exceed the computational resources of a lower-level craft to be performed by a higher-level craft; the results of the analysis are then returned to the lower-level craft for incorporation in decision-making.

The multi-tier approach also incorporates effective ways of dealing with several specialized circumstances that require greater coordination. The first is a collaborative task (e.g., a task that requires coordinated movement in order to be successful). For example, if two robots were erecting a structure, movement-level coordination would be required to place a beam successfully into location. In this case, a script, which includes checkpoints (where the craft wait until all others required to proceed are done), is created by a group or task controller and disseminated to all participating craft.

MAMA also contemplates cases when it may be desirable to share resources between different groups within the same mission or even across missions. A craft hand-off and tasking mechanism exists for this.

Model-Based Transmission Reduction

MBTR is a multi-faceted approach to reducing the amount of data that is required via increasing the value of each byte of data. In [2], four levels of MBTR are presented: model-based data transmission, model-based data analysis, model-based result transmission and model-based findings transmission. Each subsequent level builds on the value of the lower levels to create a more value-rich data product that is transmitted.

Model-based data transmission (MBDT), demonstrated with image data in [2, 17], compares collected raw data to a model of what is expected. Discrepancies, above a threshold minimum difference value (if specified), are transmitted to Earth-based controllers to refine the original model. Discrepant data can also be priority-ordered for transmission.

Model-based data analysis (MBDA) uses context-aware assessment to prioritize data for transmission. While MBDT would choose data based on the largest discrepancy from the model (e.g., the largest color/shade different for image data), MBDA utilizes its contextual understanding of the data to determine the importance of model updates. For example, MBDA could be instructed to prioritize data that crosses a threshold (e.g., well-performing versus under-performing crops) over data that indicates a quantitatively larger discrepancy from the model.
Model-based result transmission (MBRT) enhances MBDA by formulating a prospective conclusion based on the data under assessment. Data is then prioritized based on its level of support or refutation of the conclusion under consideration (with data that provides either strong support or refutation prioritized over data that is of lesser value).

Model-based findings transmission (MBFT) is the highest-value level of MBTR. Under MBFT, the spacecraft’s onboard computing software autonomously evaluates a model of a phenomenon of interest and evaluates the observed data in light of this model. The software updates the model, based on the observed data. It then selects sample data elements to send back in conjunction with the updated model for verification purposes.

3. INTEGRATING THE MULTI-TIER APPROACH AND MODEL-BASED TRANSMISSION REDUCTION

The integration of the MBTR and MAMA architectures necessitates several changes to the basic forms of both architectures to ensure interoperability. While the architectures are comparatively synergistic, some of the control logic of the multi-tier architecture must be replaced with an MBTR-compatible approach. Similarly, the MBTR approach (based on MBFT) must be revised to trigger additional lower-tier data collection.

Changes Required to the Multi-Tier Architecture

A typical MAMA mission begins with the tasking of the orbital or system-level craft (the system-level craft is utilized to coordinate the efforts of multiple mission-specific orbital craft) with a high level objective. The orbital (or system) craft sub-divides this task into sub-tasks for one or more subordinate craft. These tasks are assigned to the sub-craft, which review the assigned tasks, possibly further sub-dividing the tasks into tasks for their subordinate craft. At each level, the craft may opt to collect data itself (for verification, etc.) before tasking its subordinates. This is where the prototypical mission concept comes from: an orbital craft takes imagery, which is used to assign targets to a UAV, which is used to deploy and task ground rovers.

The incorporation of MBTR requires that the MBTR analysis engine be running on each involved craft. Instead of just sub-dividing tasks to effect their completion, the MBTR engine sub-divides research goals into component goals. For example, the assertion that a route is safe might be subdivided into several assertions covering areas of the route – or assertions covering safety from various types of dangers. The former would be based on craft movement capabilities; the latter on craft sensing capabilities. Each craft must perform (or have performed for it, using the processing job off-tasking functionality) data analysis to determine whether it possesses sufficient data to respond to the research goal that it is pursuing. If not, it must collect or arrange for the collection of this data. If sufficient data is not obtainable, it must assert and defend this assertion.

Changes required to Model-Based Transmission Reduction

The MBTR approach will need to be modified to work in collaboration with the multi-tier architecture. MBTR, at present, presumes that it is operating on a single craft as a single process. Further, it is not resource-consumption
A typical MAMA/Multi-Tier hierarchy is shown in Figure 1. However, when operating in the resource-limited space (or remote planetary) environment, resource usage is a key consideration. This is further intensified by the fact that the MBTR process, under the multi-tier MBTR approach, may be commanding vehicular movement. Given the limited amount of fuel and risk associated with this activity, the MBTR process must make resource-conscious decisions. Specifically, it must project the possible value of the data that could be collected by a requested action and compare that to a projected cost. A heuristic is used to determine whether to command the action immediately or to store it as a candidate task to be compared with other possible data gathering activities.

An MBTR Hierarchy

Figure 2 shows the data collection process of a MBTR hierarchy. The process begins with a task assignment. The MBTR software determines the appropriate collection of craft to assign the task to. This may include the current craft (e.g., the orbital craft which may need to take a high-area-of-coverage image to begin with). After this initial data collection is conducted, one or more craft may be tasked to make (or refute) the assertions required to confirm (or refute) the high-level objective. As Figure 2 shows, a craft may task its subordinate (e.g., craft 4, in the example) to collect additional data that is required to confirm or refute the assertion.

Once the data is returned to the orbital craft, it attempts to confirm or refute the assertion. In many cases (presuming correct projection of the data required), this may be immediately possible. However, in others (as shown in the figure) additional data collection may be required. In the specific example depicted in Figure 2, craft 2 is tasked to collect additional data that is deemed necessary. The data sufficiency analysis is conducted again and, presuming sufficient data is available, the controller is notified of the identified result.

4. COMMUNICATIONS PARADIGM FOR A MBTR HIERARCHY / MULTI-TIER MISSION

Previous work [18] presented a basic inter-robot control methodology for sending tasks between robots. This approach, however, is not suitable in its current form for a combined MAMA/MBTR mission. The message format, however, was designed to be extensible. This basic four message format is expanded to provide the foundation for the MAMA/MBTR inter-craft communications.

Existing Message Format

The basic approach from [18] consists of four messages: a command message, query message, data transmittal message and an exception message. The command message is utilized to convey a tasking assignment. The query message is utilized to obtain status / health information, performance data, task progress data or stored data. The data transmittal message is used to transmit raw data between the various system nodes (craft). Finally, the exception message is used by a subordinate craft to advise its superior that an error condition has occurred or that it will (or that it appears plausible that it will) fail to meet a performance milestone.

Extended Message Format

The extension of each basic message type will now be presented. These messages are still compatible with the messaging framework discussed in [18].
**Command Message**—The command message, in the base format, is designed to assign an object of interest for assessment. This message contains an object identifier, approximate coordinates, a prioritization and a type descriptor. This message is extended via adding additional type identifiers. Instead of referring to a single object, a command message can now refer to a phenomenon. If the phenomenon is of global interest, the coordinate fields are left blank. For localized phenomenon, coordinates can be supplied. Message body space is used to describe, in a machine-readable format, the assertion that the command message confirmation or refutation of.

**Query Message**—The base query message contains a globally unique query identifier and either a task identifier or an action type identifier. The task identifier would correspond to the command’s identifier for task assignment. This message is not changed; however, additional space in the message body is used to send back the current belief values for the assertion that the robot is trying to confirm or refute.

**Data Transmittal Message**—The data transmittal message was designed to be a free-form message to accommodate numerous data types that a robot might need to send (e.g., graphics, binary sensor data, etc.). It begins with a query or task ID, corresponding to the query or task that the data relates to. For the MAMA/MBTR approach, the body of this message utilizes the MBTR model description language to describe the proposed changes to the model that the robot is proposing. Further, it forwards (in a second message) the data that is required for the superior robot to confirm or refute the assertion that it is making.

**Exception Message**—The base exception message is used to convey robotic failures and mission-performance-related exceptions. This message is used as-is, with the addition of the additional type descriptors discussed, previously, in the context of the command messages.

5. EVALUATION OF THE MBTR HIERARCHY CONCEPT

A qualitative evaluation of the MAMA/MBTR approach has been performed. The key consideration was how the combined framework performed relative to a normal MAMA mission or single-craft MBTR implementation.

Several considerations were identified; however, these could not be quantified, as they are heavily reliant on implementation-specific details. First, it is unclear as to the effect that the incorporation of the MBTR software onboard the lower-level craft would have on the performance of their onboard control software. In the worst case, the processing requirements might completely overwhelm the capabilities making the combined mission unfeasible (or requiring additional investment in hardware to make the mission possible). Also problematic is the fact that the combined approach may operate, but in an inefficient way. The real-time control needs of the robot and the long-duration processing needs of the MBTR evaluation process may be in constant conflict for the limited processing capabilities onboard the spacecraft. These scenarios will need to be tested for during the mission implementation process.

Second, it is clear that the MAMA/MBTR combined framework is not an optimal solution for all mission types. Missions that are not data-collection and processing driven would not be candidates for the combined approach. This raises an obvious question: what is the optimal approach for a mission with multiple objectives. A Mars mission, for example, might have significant data-driven aspects; however, there may be construction and other requirements. Further testing is required to see if the MBTR aspects of the combined framework can be successfully made dormant to allow performance during non-data-collection-driven mission aspects to perform at the level of the base MAMA approach.

6. DEMONSTRATION MISSION CONCEPTS

Two demonstration mission concepts are presented to aid in the understanding of the implementation of the MAMA/MBTR architecture. The first of these missions, an Earth sensornet application, would be an excellent test case for the second, a Mars survey mission. The use of MAMA for a Mars mission has been discussed previously in [16]; this is extended, herein, to incorporate the MBTR technology, making the mission more versatile, reducing mission communications requirements and increasing mission autonomy and utility.

An Earth Sensornet

An Earth sensornet application would be an excellent test case for the MAMA/MBTR architecture. The Earth sensornet (depicted in Figure 3) consists of a lead (pristine-class) orbital tier member, four smaller orbital craft (in this case 3-U CubeSats are presumed), three aerial craft (UAVs are presumed) and six ground craft. It is presumed that the ground craft start the mission in a proximal position to their corresponding aerial craft.

The CubeSat-class spacecraft, while orbital-tier members,
are not hierarchical superiors to the aerial craft. They can be used, however, to relay messages from the orbital lead satellite to the aerial and (if necessary) ground craft.

A weather phenomenon is an excellent test case for this application. In the case that a severe weather instance was detected, orbital imaging could be utilized to obtain a high-field-of-view imagery to localize the scale and location of the phenomenon. The UAVs could (assuming that their safe operation could be assured, depending on the type of the weather phenomenon) then be deployed to the region to collect additional visual sensing data. Moreover in applications where wind speed was a significant interest (e.g., a tornado or hurricane) the difference between the craft’s believed flight speed and GPS-derived movement could be utilized to characterize the winds aloft at each altitude level that the UAV could fly at for this purpose.

In the case where the UAVs could not be safely deployed, or conditions where additional on-ground data collection (e.g., damage assessment) or higher resolution data was required, the ground-based craft could be deployed to collect additional data.

**A Mars Mission**

A MAMA/MBTR Mars mission is also considered. In this application, with a smaller number of craft, two aerial craft are deployed from the orbital lead satellite (which is also the interplanetary spacecraft that carried the other six craft to Martian orbit). These aerial craft will deploy the ground rovers to the surface in the instance of their first use.

This mission contemplates two sets of complementary objectives. First, the craft will perform exploratory activities across the Martian surface. Second, a science station will be erected on the surface. The ground craft in the left group (under aerial craft 1) are larger and have additional manipulation capabilities to effect this goal. They must be deployed in close proximity to the drop point of the science station (which is deployed, similar to the MSL’s deployment method [7], directly to the surface). To ensure that the craft that will erect the structure are located by its drop location, aerial craft 1 will survey the area and locate the station before deploying the craft to the area. These craft will participate in construction activities initially (when not needed, they will perform local characterization activities). Once construction is complete, they will move progressively further from the science station to investigate phenomenon identified by the orbital lead craft and/or aerial craft 1. The science station has capabilities that any ground craft can utilize for additional sample processing (in addition to its ongoing independent activities).

**8. Conclusions and Future Work**

The aforementioned presents a vision for the combination of two previously independent research efforts. It appears that the two technologies present a significant synergy, when implemented in conjunction. This initial work has focused on the combination of the two technologies and the resolution of several areas where the two technologies implement aspects of the control and other processes in different ways. Future work will focus on its implementation in the Earth sensornet application discussed in section 6 as a precursor for the Mars application (and other possible applications).

**REFERENCES**


Biographies

Jeremy Straub is a PhD student in the Department of Computer Science at the University of North Dakota. He currently serves as the Student Program Director for the North Dakota Space Robotics Program. His research is presently focused on artificial intelligence for space applications. Before returning to pursue doctoral studies, Mr. Straub held progressively responsible positions in industry. He has over 10 years professional experience in developing and managing the development of cutting-edge commercial systems, including North America’s first commercial traffic-adaptive navigation system. Jeremy holds a BS in Information Technology, a BS in Business, a graduate certificate in Space Studies, an MBA and an MS in Computer Systems and Software Design. He is a member of the AIAA, IEEE, SPIE and SSPI.