# Adaptive Task Reallocation for Airborne Sensor Sharing

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Abstract—Airborne sensor platforms are becoming increasingly significant for both civilian and military operations, yet at present their sensors are typically idle for much of their flight time. Opportunistic sensor sharing, e.g., via the Mission-Driven Tasking of Information Producers (MTIP) [1] can greatly improve sensor utilization, both decreasing the number of platforms needed to achieve a goal and increasing sensor efficacy. Dynamically changing environments, however, are likely to rapidly render any initial plan obsolete. In this paper, we address the challenge of adaptive reallocation of sensor sharing tasks, demonstrating how the adaptable sensor sharing of MTIP can provide significant performance improvements in a large-scale disaster response scenario, as well as identifying areas of inefficiency that are likely to benefit from further improvement.

## I. INTRODUCTION

Recent advances in automated and semi-automated flight control systems and the increase in the availability of sensors and sensor-carrying aircraft have led to a rapid increase in the use of airborne sensor platforms for information gathering by commercial, civilian, law enforcement, and military organizations. These platforms range from large to small air vehicles, fixed wing to rotary wing, and manned or unmanned, and can be fitted with a wide variety of image collecting sensors. Yet there is still much untapped potential in these platforms. In practice, airborne sensor platforms are typically launched, configured, and controlled for a singular goal or mission for a single individual or organization. As such, airborne sensors are often idle for a large portion of a mission, as the platform moves to, from, and between the particular locations that are of interest to the platform's controller.

To make use of this spare sensor capacity, we have developed *Mission-Driven Tasking of Information Producers* (MTIP) [1], a mission-driven, adaptive, and dynamic system that improves sensor utilization by opportunistically sharing airborne sensors among individuals and organizations. The net effect of the use of MTIP is to increase sensor utilization, improve the suitability of imagery collected by sensors for user needs, and to increase the amount of information needs that are satisfied by available sensors. As a result, MTIP can (a) make sensors available to organizations that lack airborne platforms, (b) reduce the number of airborne platforms needed for a given set of missions, and (c) increase mission resilience by assigning multiple platforms to perform the same task.

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To accomplish this, MTIP automatically extracts sensor tasks from user interactions with information management systems and allocates these tasks to available airborne sensor platforms. A key challenge in task allocation, however, is managing the tradeoff between leveraging pre-deployment plans and reacting to dynamic deviations that occur at runtime. Leveraging pre-deployment plans is practical and efficient, as aircraft operators are typically unlikely to deviate significantly from the flight plan that most effectively serves their mission in order to satisfy the needs of others. Put another way, if satisfying the other users' information needs were important to the owner or pilot enough to influence his or her flight plan, those needs would become part of their mission and their pre-deployment flight plan. In addition, leveraging predeployment plans has the benefit of providing ample time to compute optimal or near-optimal allocations. Subsequent deviations from such plans, however, can have a drastic impact on the service provided by a planned sensor task allocation.

We address this challenge in the design of MTIP with a task allocation strategy that considers both platform plans and dynamically observed deviations from those plans. MTIP performs task allocation using the available platforms as resources and their planned routes as constraints. Runtime monitoring of execution then triggers adaptation of task allocations in response to changes in tasks, priorities, platform routes, and availability of platform sensors, while attempting to minimize gratuitous allocation changes, in which small perturbations can cause "thrashing" between similar allocations.

This paper presents MTIP's approach to self-adaptation for task allocation and reallocation in an airborne sensor sharing system, as well as experimental validation of the benefits of self-adaptation for task reallocation in a dynamic disaster response scenario (vs. [1], which evaluates only preplanning of missions). Following a presentation of background information about MTIP in Section II, we present the MTIP approach to task allocation in Section III. Section IV explains our experimental design for evaluating MTIP's capacity for adaptation, results of which are discussed in Section V, followed by a summary and future work in Section VI.

#### II. ADAPTIVE SENSOR-SHARING VIA MTIP

MTIP, described in detail in [1], is a sensor-sharing system. It is one of many sensor-sharing systems that can be used



Fig. 1. Traditional Publish-Subscribe Information Management Systems (IMS) decouple information producers from consumers, potentially causing consumers' information needs to go unmet. MTIP uses organically-collected information from consumers (e.g., the predicates/filters controlling the information they receive from the IMS) to task information producers to collect and share information that is of interest to end-users.

for sharing airborne sensor data, many of which are also specifically focused on maintaining situational awareness in emergency or military situations (e.g., [2], [3], [4], [5], [6], [7], [8], [9]). MTIP itself is built upon one of these systems ([2]), but while these systems are good at enabling interested parties to share information, actually tasking sensors to gather that information must still be accomplished outside of the system by humans. This tends to create problems in discovery and to compete for attention with other critical tasks, contributing to sensor under-utilization.

Another closely related area is collective sensing, which has been studied for many years in a number of contexts, both for airborne and other types of platforms [10]. Collective sensing also considers multiple sensor platforms, but often those platforms are all assumed to be controlled by a single organization that can task them and often also place and move them at will (e.g., [11], [12], [13], [14]), rather than needing to adapt to the constraints imposed by an independent platform owner. Recently, smart-phones and other humancarried sensors have begun to drive interest toward opportunistic sensor systems [15], [16], [17]. These have primarily focused on diffuse tasks in which sensors are non-directional and any sensor contributes only a small portion of the sensing capability needed for a diffuse task such as pollution or noise monitoring (e.g., [18], [19], [20], [21], [22]), meaning there is typically little competition between tasks for sensor resources. MTIP, by contrast, focuses on highly directional sensors such as airborne cameras and more specific and localized tasks, in which the focus is on effective allocation of a large number of potentially competing individual tasks to individual sensors.

At a high level, the purpose of MTIP is to address a deficiency common to most publish-subscribe (pub-sub) Information Management Systems (IMS). When clients make subscriptions into pub-sub systems, they do so with a *filter* or *predicate* that limits the information they receive to that which matches their interest. However, because the purpose of pub-sub IMS is to decouple information producers from information consumers, it is often the case that information



Fig. 2. Architecture of the MTIP prototype (blue), showing flow from situation information to sensor task allocation, dispatching of tasks to a set of airborne platforms (grey), and feedback of task status and results from platforms, triggering plan adaptation.

producers will collect/provide information that is not of interest to any consumers, while remaining unaware of what information the consumers are actually interested in. MTIP addresses this by monitoring subscription predicates and other information organically provided by information consumers in the course of normal system usage. This information about use interest is then automatically transformed into tasks for information producers to collect information of interest, thus increasing the chances of meeting users' information needs, as shown in Figure 1. Specifically, the current MTIP prototype provides the following functionality:

- Automatic extraction of information needs from existing user interfaces. In addition to explicit subscriptions, MTIP is integrated with several user interfaces, including map-based interfaces such as OpenStreetMap, to extract implicit user interests from commonly performed actions. For example, MTIP identifies placement of a Point of Interest (POI), drawing of an Area of Interest (AOI), or creation of a route on a map as indicating user interest in getting imagery at the POI, within the AOI, or along the route, respectively. MTIP includes a rich set of *semantic extractors* that extract user interest from these and other commonly used interfaces, such as requests and queries.
- *Extraction of goals and tasks from information needs.* MTIP turns the information needs it has extracted into a set of goals that are desirable to achieve by sensorcarrying airborne platforms and a set of specific tasks that can be performed to achieve these goals.
- Allocation of tasks to available platforms. MTIP assigns the tasks it has derived to the set of available platforms with the objective of satisfying the largest number of goals within the constraints of the expected flight plans of the platforms.

## III. TASK ALLOCATION IN MTIP

The overall architecture of MTIP is shown in Figure 2, comprising the following components:

• A set of *Semantic Extractors* that gather implicit information on user interest (i.e., goals) from user interfaces and



Fig. 3. MTIP (re)allocation workflow: whenever any change happens to a platform, a goal, or the condition of a goal at a platform, the task allocation system is triggered to run.

activities, as well as receiving publications of platform announcements and route plans.

- A *Task Allocation* component that assigns tasks to platforms and receives and acts on platform responses and situation changes that may affect the assignment.
- A *Task Dispatcher* that sends task assignments to sensor platforms and receives back from those platforms messages accepting or rejecting tasks and providing information on the progress of tasks toward completion.
- A *Closed Loop Controller* that responds to requests for direct control of an airborne platform's sensor by a user.

This paper focuses on task allocation, the workflow for which is illustrated in Figure 3: as MTIP receives information about available resources (airborne sensor platforms) and goals, it generates a task allocation plan that is passed to the dispatcher so that it can inform the platforms that have been assigned tasks. Those platforms may choose to accept or reject tasks (either automatically or via an operator query), and also inform the dispatcher about the progress of a task, including when a task has failed or has been successfully completed. Task allocation does not distinguish any "pre-planning" phase, but rather operates continuously on the evolving situation and goals: upon any receipt of rejection, failure, or success messages, or upon receipt of new information about goals and resources (e.g., the changing location of a platform over time), the task allocation component is triggered to update its plan and any allocation changes are sent to the platforms.

To actually perform task allocation, we employ an agentbased task allocation strategy, described in detail in [1] and illustrated in Figure 4. This task allocation strategy creates agents for each of (a) the platforms, including the platform's current position and predicted projections along its preplanned route, and (b) sensor tasks, including points, routes, and areas of interest.<sup>1</sup> Each platform agent and projected agent is responsible for computing the sensor tasks that it is best equipped to perform. Combining individual agent's decisions



Fig. 4. In MTIP's agent-based task allocation, agents for current platforms (light blue) and projections (translucent blue) along the platform's anticipated trajectory communicate (purple arrows) with task agents (red) within line-of-sight and sensor range limitations to determine which tasks will be assigned to which platforms and on which segments of their anticipated route. (Figure reproduced from [1])

produces a task allocation, i.e., a mapping between resources and tasks. Note that the cardinality of resources and tasks in a task allocation is many-to-many, where a single resource agent may be assigned many tasks and a single task may be assigned to multiple resource agents.

While it is vital to provide timely and efficient task allocations, MTIP has to balance the importance of assigning tasks to the most-appropriate asset with the inefficiencies that arise from re-assignment of tasks to different platforms. Task reassignment causes additional network traffic, increased risk to the mission (that the re-assignment will fail), and additional cognitive load (e.g., to the pilot). As MTIP's agent-based allocation strategy is both extremely fast and executed by allowing agents to negotiate adjustments to their current partial state of allocation, this allows us to approach the problem of plan adjustment simply by adjusting the situation model (e.g., updating airborne platform positions, adding tasks, changing task position or priority) and allowing the agents to continue executing their decision process from a starting point of the current allocation plan, rather than restarting from scratch, which limits the expected amount of low-benefit reallocation.

#### IV. EXPERIMENTAL DESIGN

For evaluating the ability of MTIP to adapt effectively to change in realistically complex scenarios, we use a disaster response scenario based on the one previously developed in [1], which we review here. Whereas the previous tests considered only the initial planning phases of a mission, however, we now enhance the experimental scenario by having simulated platforms executing missions in real-time against the running system, with various degrees of unpredicted divergence from each platform's initial planned flight route.

## A. San Francisco Disaster Response Scenario

For a realistic scenario complexity and distribution of survey goals, we consider the disaster response scenario previously developed in [1] and reviewed in this section. The scenario begins following a major earthquake in the San Francisco Bay

<sup>&</sup>lt;sup>1</sup>At present, agents are run in a single server rather than on platforms, but the system could be decentralized by dispersing task agents to associated platforms, either localizing each to one platform that proxies its communication or mirroring on multiple platforms and synchronizing.

Infrastructure Class	# Objects	# UAVs	UAV Base (Lat/Lon)
Airports	25	2	37.625°, -122.383°
Cell phone towers	251	3	37.418°, -121.883°
Dams	152	2	37.941°, -122.261°
Fire Departments	160	3	37.779°, -122.390°
Heliports	28	1	38.466°, -121.423°
Hospitals	28	1	37.432°, -122.178°
Military Installations	8	1	37.404°, -122.028°
Power Plants	14	1	37.219°, -121.747°
Total	666	14	

Fig. 5. Summary of critical infrastructure and associated UAVs for San Francisco disaster response scenario, reproduced from [1].

area. Critical infrastructure is likely to have been damaged by the earthquake, and so UAVs are dispatched to assess damage.

In particular, we consider eight classes of critical infrastructure, obtained by restricting publicly available GIS datasets to a quadrangle of latitude 37.0° to 38.5°, longitude -123.0° to -121.0° (infrastructure classes are summarized in Figure 5). We assume a separate organization is in charge of each class of critical infrastructure, and plans to survey damage to the objects in its charge using by a set of 1-3 UAVs. All UAVs controlled by an organization start from the same location (one of its infrastructure objects), and each UAV is provided with an independently hand-planned route at a cruise altitude ranging from 500 to 1500 meters depending on terrain. The UAVs used for this scenario are Boeing ScanEagles, a frequently used small high-endurance UAV. Based on the published ScanEagle specifications, we assume platforms have a flight speed of 40 m/s and a high-resolution electro-optical sensor. We also assume that the sensor is sufficient for acquiring images for a damage assessment of sites within 20 km at a rate of three sites per minute. For purposes of these experiments, we configure MTIP to plan using projections at 5 minute intervals (which, with a three site per minute sensor implies a maximum of 15 tasks per planning location), with the planned routes averaging approximately two and half hours duration.

#### B. Simulated Mission Execution Experiments

In order to test the behavior of MTIP in a dynamically evolving mission environment, we simulated each UAV as an independent process, running in real-time with its own set of threads independent of the operation of the MTIP system. Each simulated UAV launches a server that receives and responds to task allocation messages following the MTIP protocol, with each UAV accepting all tasks that it is sent by MTIP.

Since the UAV imagers are assumed to take 20 seconds to effectively survey a site, UAV operations are simulated in 20 second steps. At each step the UAV moves 20 seconds (800 meters) along its flight path, sends its new position to MTIP (as a standard Cursor on Target (CoT) packet), and attempts to select a task site for imaging. From its list of assigned tasks, the UAV finds the set of tasks that are both close enough for imaging (less than 20 km from the UAV) and within line of sight (i.e. not blocked by terrain). If any of these task sites has not yet been imaged, one of the non-imaged task site is selected arbitrarily for imaging. Otherwise, the task site that has been imaged the fewest times is selected for additional



Fig. 6. Example of planned path vs. adaptation challenge path generated by random waypoint deletion: here the planned UAV path (light blue) to survey hospital infrastructure (red) is subjected to 50% random waypoint deletion. In this case, the route loses 5 of its 8 non-terminal waypoints, causing both of its Eastward excursions to be replaced with the truncated path segments shown in dark blue and leaving 11 of 28 survey goals without coverage.

imaging (again breaking ties arbitrarily), and if no task sites are nearby and visible then the sensor is idle for that time step.

In order both to further stress the system in our experiments and to make their running time tractable, however, we actually run most of each mission at a greatly accelerated rate. For each simulation, we first run the system for 5n seconds in real-time (where *n* is the number of infrastructure classes in the experiment) in order to allow for MTIP initialization the first round of planning and assignment dispatch. Thereafter, we shift the simulated platforms to run at a 100:1 rate, taking a 20 second simulated step every 200 milliseconds of real time.

A dynamic environment of adaptation challenges is created by random deletion of waypoints from each UAV's planned route: the route to be flown is created by taking the planned route and giving each waypoint an independent probability of being deleted d (except the first and last waypoints at the base where the UAV takes off and lands). An example of random waypoint deletion is shown in Figure 6. These deletions create a situation similar to what might happen if UAV operators are receiving emergency requests that lead them to skip planned survey sites and instead send their UAVs directly to sites that had been scheduled for later observation.

We evaluate the adaptivity of the MTIP system by means of two experiments. In the first experiment, we evaluate the impact of various levels of dynamism by varying the rate of deletion d from 0.0 to 0.7 in steps of 0.1, comparing the full scenario of eight infrastructure classes under MTIP to the situation without MTIP, in which UAVs do not share their sensors but only image their own originally assigned tasks. The second experiment evaluates the degree to which each



Fig. 7. MTIP dynamic sensor sharing allows coverage to be sustained well even when UAVs diverge greatly from their anticipated routes.



Fig. 8. Coverage of sensor tasks is significantly improved by sensor sharing even between a small number of UAVs.

available sensor increases resilience by running MTIP with fixed high rate of deletion d = 0.5 and selecting a random subset of n infrastructure classes (adding both UAVs and targets for each class), varying n incrementally from 1 to 8. We run 20 trials for each condition in each experiment.

## V. RESULTS

As anticipated, the results of these experiments show that MTIP greatly increases the resilience of sensing missions. Figure 7 shows the effect of varying the fraction of waypoints deleted on the fraction of tasks that are able to be successfully surveyed. With MTIP's dynamic sensor sharing, the fraction of tasks surveyed degrades much more slowly than when UAVs do not share their sensors. Not until more than 30% of waypoints are deleted does the fraction surveyed show any significant decrease, and even at the extreme value of 70% waypoint deletion the system is consistently able to survey around 90% of tasks. Performance is much less variable as well, another indicator of reduced fragility.

Analysis of individual tests shows that this increased resilience comes from two different sources: first, the fact that MTIP "backs up" the survey plan for each task with the spare capacity of other UAVs whenever possible, and second, the fact that the fast agent-based planning system can rapidly reallocate when unexpected UAV movements cause tasks to become unassigned or create new observation opportunities, almost as soon as those movements are observed.

The results of our second experiment show that even a small amount of sensor sharing can greatly improve resilience. Figure 8 shows that sharing between even just two sets of UAVs eliminates approximately half of the observed degradation in



Fig. 9. Adaptation can pose a significant cost on the system, as measured by the number of cancellations per task.

task completion, as well as greatly decreasing variability of performance. More sets of UAVs continue to incrementally improve the situation, up until five sets of UAVs, beyond which additional sets of UAVs do not appear to provide significant further benefit in this scenario.

Rapidly adaptation to changing circumstances, however, comes at a cost. Whenever a survey task is allocated to a UAV or cancelled on that UAV, it must be informed of the change, adding network traffic. Worse, if MTIP is in interactive mode, which queries platform operators to accept or reject each task, every new allocation produces an operator query, which can be a significant burden on the scarce resource of operator attention. Of particular concern is the possibility of adaptation resulting in a "thrashing" condition, a well-known problem of replanning (e.g., [23], [24]) in which a system shifts rapidly between plans with significantly different content but nearly equivalent utility (e.g., target coverage). Minor changes in conditions can thus cause the "best" plan to change frequently.

We quantify the adaptation cost for MTIP by measuring how frequently a survey task assignment is cancelled (which is also linked to the rate at which tasks are reassigned). To compare scenarios with different numbers of tasks, we divide the number of cancellations recorded by the number of tasks in the scenario. The cancellation rates for our two experiments are shown in Figure 9. As can be seen, cancellations are fairly frequent (though not excessively so), suggesting that there is likely to be some degree of thrashing in the reallocation process. This is further strengthened by the counterintuitive behavior of the rate of cancellation, which goes down as more waypoints are deleted and is at a maximum with only an intermediate number of infrastructure sets sharing sensors. If the primary cause of tasks being cancelled and reassigned was the divergence of UAVs from their planned routes, then we would instead expect these values to be highest in the conditions where there are the most deletion and the least platforms available for sharing. Inspection of individual runs confirms that there is thrashing taking place: notably, however, reallocations tend to be concentrated in a small number of densely concentrated task sites visible to UAVs whose sensors are saturated with tasks on that part of their path. This then explains the shape of the cancellation curves: as the number of deletions increases, UAV paths become shorter and more separated, and as the number of UAVs sharing sensors increases, the available sensor capacity eventually saturates the tasks at hand. These facts indicate that future improvements to the MTIP allocation algorithms may be able to greatly reduce the amount of reallocations and their associated costs in communication and operator attention.

#### VI. DISCUSSION

Our tests in simulation demonstrate that the MTIP airborne sensor sharing system can quickly and effectively adapt plans to changing circumstances, even for radical changes in expected paths of sensor platforms. Adaptation does come at a cost, however, which can be measured in the potentially frequent cancellations and reassignments of survey goals.

In future work, we aim to improve the performance of the MTIP allocation system by adding either hysteresis or reallocation cost to the allocation system, such that reallocation will not take place unless it makes a significant improvement, thus eliminating the observed tendency to thrashing when there are multiple near-equivalent allocations available. We also aim to transition MTIP toward deployment on various fielded airborne platforms (including validation against other types of dynamism, such as changing goals and platform loss), where its ability to improve situational awareness through sensorsharing can be put to real use and validated in the field. Finally, the MTIP approach of lightweight agent-based planning may be applicable to other complex and dynamical environments as well, such as smart transportation systems or services for mass public events, and these results may form a foundation on which to investigate such further expansions.

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