A Cooperative UAV/UGV Platform for Wildfire Detection and Fighting

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***Abstract*—Unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) have received much attention in the research and development community due to their strong potential in certain high-risk missions. In applications that involve multiple vehicles, the inter-vehicle communication and cooperation becomes a critical challenge to a successful mission. An effective co-operative control framework is required to co-ordinate the system-level decision making process and information flow among the multiple agents such that the collective mission is optimally achieved. In this paper, a co-operative control framework for a hierarchical UAV/UGV platform is proposed. A top-level mobile mission controller provides effective mission planning and system-level decision making such that mission completion time and resource expenditure are optimized. The mobile mission controller can monitor the dynamic environment with its own sensing capabilities and co-ordinate UAVs/UGVs in their actions. This paper discusses the potential application of the proposed hierarchical vehicle platform to high-risk missions, specifically in the context of wildfire fighting. The task generation and allocation problems and proposed approaches are presented under the given control framework.**

I. Introduction

Research in unmanned vehicle systems has been given special attention due to a wide range of applications in both military and civilian settings. Unmanned vehicle systems are suitable for performing tasks that pose high risks to human operators, such as search and rescue, reconnaissance and strike, surveillance and monitoring in danger-prone or inaccessible terrain. Various algorithms and vehicle prototypes have been developed to address the autonomy of unmanned vehicles, ranging from low-level autonomous flight control, environment perception, localisation,to high-level path planning and navigation [1]. Equally important is the need to develop multi-vehicle systems with a corresponding co-operative control framework to co-ordinate the system-level decision making process and to specify the interaction among the individual vehicles to ensure the consistency of their activities while optimizing the collective mission in some sense.

Each vehicle platform and its applications pose different challenges that motivate the development of specialized control architecture and algorithms. For instance, a distributed control scheme applies well to a system of homogeneous vehicles that have the same processing, sensing and maneuvering capabilities, whereas a centralized or hierarchical control scheme is presented for heterogeneous platforms that involve aerial and ground vehicles of different capabilities. Various homogeneous and heterogeneous multi-vehicle platforms have been investigated for specific applications, with focus on formation flight control, hierarchical control architecture for co-ordinated team efforts in pursuit evasion games, centralized control framework for high-level mission planning and task allocation, and distributed framework for trajectory design [2], [3], [4].

The general direction of research in multi-vehicle platforms involving both aerial and ground vehicles is to increase situational awareness through co-operative sensing and maintaining communication connectivity. Chaimowicz et al. investigates methods of sensor data fusion provided by airships, UAVs and UGVs to increase situational awareness in the deployment of air-ground vehicles in urban environments [5]. How et al. considers the coupled problem of task assignment and trajectory design for a team of heterogeneous vehicles involving a blimp and rovers using the mixed-integer linear programming method [6], [7]. Similarly, the role of the blimp is to perform reconnaissance and classification tasks and to map an uncertain environment for the rovers. The COMETS project aims at developing co-ordination algorithms for co-operative fire detection and monitoring using a fleet of heterogeneous UAVs consisting of one airship and two helicopters, each equipped with either a visual or infrared camera. The focus is on developing computer vision techniques to detect and extract fire features from visual and infrared images, and construct a geolocated fire model. Data fusion techniques were also developed to measure the states of detected fire alarms and their uncertainties. However, the focus was on co-operative perception techniques, and not on co-operative control of UAVs for effective coverage. The COMETs platform considers an hierarchical decision-making framework for mission planning and task allocation, where each UAV has different levels of decisional capabilities. In this framework, interactions between UAVs occur along the different layers, and integrates centralized and distributed decision-making schemes [8].

This paper presents a 3-layered vehicle platform involving a mobile mission controller, unmanned aerial and ground vehicles. This particular heterogeneous vehicle platform requires its own co-ordination and control framework to optimally design mission plans, allocate tasks and co-ordinate the activities of each vehicle in a consistent and effective manner. The co-operative control framework is presented in the context of wildfire fighting applications. In section 2, the co-ordination and decision-making scheme is presented for the

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3-layered hierarchical vehicle platform. Section 3 discusses the potential application of the 3-layered vehicle platform in wildfire fighting. Section 4 presents the problems being investigated and proposed approaches. Section 5 presents the simulation platform being developed to demonstrate and validate the proposed co-operative control framework. Finally, section 6 concludes the paper.

II. Hierarchical structure

The hierarchical vehicle platform consists of an airship in the top-most level, and a team of co-operative UAVs and UGVs. In this set-up, a centralized and hierarchical framework is defined, where vehicles in the same layer have the same level of decisional autonomy. Full decisional autonomy comprises of the capabilities to supervise and co-ordinate the activities of other vehicles, to perform mission planning and task allocation or re-assignment. The airship acts as a mobile mission controller and has full decisional autonomy. All interaction and communication occurs vertically, between the airship and UAVs or UGVs. Depending on the application, a distributed scheme can also occur in the same layer, hence UAVs can interact among themselves or similarly for the UGVs to further decompose and co-ordinate the group tasks assigned to them by the mission controller. On the other hand, a vehicle with full operational autonomy can generate and track trajectories given a set of waypoints autonomously. All vehicles in the current set-up are assumed to have full operational autonomy. As illustrated in figure 1, the airship as a mission controller can define generic mission plans using environment and vehicle models. With sensing capabilities, the airship can also monitor the dynamic environment and supervises the activities of the UAVs/UGVs. Refined mission plans can be generated which incorporate world and vehicle state estimates from sensed data. The airship then decomposes the refined mission plans into executable tasks for UAVs and UGVs. The tasks can be assigned to each vehicle individually, or to a group of vehicles which then co-ordinate among themselves in some distributed scheme. Table 1 summarizes the decisional and operational capabilities of each vehicle.

Decisional autonomy	*Airship*	*UAVs*	*UGVs*
Supervision and co-ordination	X		
High-level mission planning	X		
Task generation	X		
Task allocation	X		
Trajectory design	X	X	X
Operational autonomy			
Navigation and localisation	X	X	X
Stability and tracking control	X	X	X

TABLE I
VEHICLE DECISIONAL AND OPERATIONAL CAPABILITIES

Under this hierarchical co-ordination framework, the 3-layered vehicle platform can act as an autonomous entity,

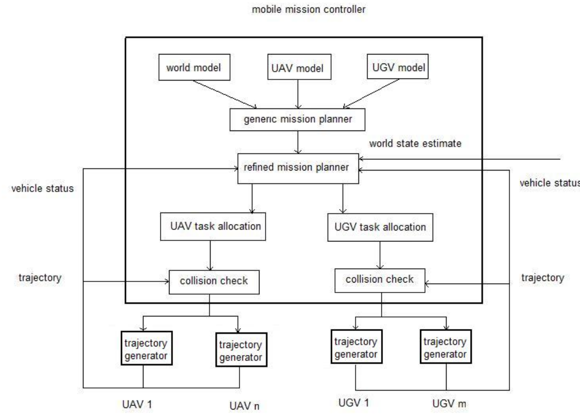

Fig. 1. Hierarchical Structure

and thus is suitable to missions where prompt detection and responses to the dynamic changes in the environment are required. In particular, the proposed vehicle platform is especially suitable to wildfire fighting because the mobile mission controller can monitor the dynamic evolution of fire, and co-ordinate UAVs/UGVs in the containment effort in near real time.

III. Application to wildfire fighting

Upon detection of a fire, the vehicle platform is deployed to the site of action. The airship acts as a top-level mission controller, it monitors the fire evolution, and co-ordinates UAVs/UGVs in fire suppression. Two fire suppression strategies are proposed: direct attack and containment. In the direct attack, UAVs are deployed by the airship to cover the active fire front in some optimal sense to put out the fire. In the containment, UGVs are also deployed by the airship to establish and maintain a safety zone, preventing fire growth beyond the established boundary. The roles of each vehicle in wildfire fighting are summarized as follows. The airship as a mission controller generates an elliptical growth model of the wildfire front based on measurements of the fire spread rates and wind velocity [9]. It generates a generic mission plan using the wildfire, UAV and UGV dynamic models. The generic mission plan consists of a set of waypoints assigned to each UAV for direct suppression of the active fireline. By monitoring the dynamic fire evolution and performance of the UAVs, that is in using some feedback control strategy, the airship refines and updates the mission plan and re-assigns the UAVs accordingly. Given a set of waypoints, each UAV computes the order to visit the waypoints in the shortest time, autonomously navigates to the waypoints and drops water there while avoiding inter-UAV collision. Similarly, each UGV autonomously navigates to the assigned waypoint while avoiding obstacle and inter-UGV collision. Upon arrival at the assigned waypoint, it monitors the area facing the direction of fire propagation. If the fire front spreads to the assigned area, it sprays water to suppress further growth beyond the established safety zone boundary.

IV. Co-ordination problems

Under the given framework, the role of the mission controller is to monitor the dynamic environment, formulate high-level mission plans, allocate tasks to the vehicles such that the mission is completed optimally in some sense. In the context of wildfire fighting, the performance objectives are to minimize the mission completion time, the mission being completed when the fire is successfully contained, with minimal resource expenditure. The co-ordination problem is decomposed into two sub-problems: task generation and task allocation.

A. Task Generation

The UAV task is to visit the assigned waypoints and drop water there. Each UAV is assumed to be able to visit n_{max} waypoints, due to water tank capacity, and can put out a burning circular area of a certain radius. The problem is to generate the waypoints in a way that can optimally slow down the fire front evolution and effectively contain the fire altogether. A dynamic growth model of forest fire fronts is available in the literature [9]. The currently investigated method is to model the effect of burnt-out zone on the shape and rate of spread of the fire front. Once the effect of the water-dropping action of the UAVs on the dynamic evolution of the fire is modelled, the task generation problem can be formulated as a control problem. The proposed approach is currently being investigated.

B. Task Allocation

The task allocation problem is formulated as a pure integer linear mathematical program [10]. Given m tasks, n agents, the objective is to assign tasks to each agent such that all tasks are completed in minimal time under certain constraints. In the given context, let task i be the action of visiting waypoint i, and agent j be UAV j. Let x_{ij} be the assignment variable, where x_{ij} is 1 if agent j is assigned task i, 0 otherwise. Finally, let p_{ij} be the cost of assigning task i to agent j, in the present work, p_{ij} is chosen to be the shortest path length from UAV j to waypoint i.

In the context of wildfire fighting, the objective is to distribute the waypoints amongst the UAVs such that all the waypoints are visited in minimum time. In the current formulation, the cost function assigns each UAV a set of waypoints that are closest to it. Each UAV then computes the order to visit the waypoints that results in the the shortest path. As described in section 2, this approach uses a centralized task generation and allocation scheme, performed by the top-level mission controller, which has full knowledge of the waypoint locations and vehicle current states. On the other hand, the detailed trajectory design and navigation is distributed to the UAVs/UGVs.

In general, there are 3 cases to consider:

1) $m = n$
2) $m < n$
3) $m > n$

Case 1 is trivial, since there is an equal number of agents and tasks, an obvious solution would be to assign each agent the task closest to it. Case 2 is a simple extension of case 1, where dummy tasks of cost 0 can be imposed to make m = n, where the dummy task corresponds to the task of doing nothing.

The following constraints are imposed:

1) Each task can only be assigned to exactly one agent, i.e. each waypoint is visited only once.
2) For the case $n < m$, each agent must be assigned at least 1 task.
3) Each agent can only be assigned at most n_{max} tasks, where $n_{max} < m$, due to watertank capacity.

Optimization problem

Case $n < m$:

$$\min z = \sum_{j=1}^{n} \sum_{i=1}^{m} p_{ij} x_{ij}, \qquad x_{ij} \in 0, 1 \tag{1}$$

subject to:

$$\sum_{j=1}^{n} x_{ij} = 1, \; i = 1, ..., m \tag{2}$$

$$\sum_{i=1}^{m} x_{ij} \geq 1, \; j = 1, ..., n \tag{3}$$

$$\sum_{i=1}^{m} x_{ij} \leq n_{max}, \; j = 1, ..., n \tag{4}$$

Case $n = m$:

$$min \; z = \sum_{j=1}^{n} \sum_{i=1}^{n} p_{ij} x_{ij}, \qquad x_{ij} \in 0, 1 \tag{5}$$

subject to:

$$\sum_{j=1}^{n} x_{ij} = 1, \; i = 1, ..., n \tag{6}$$

$$\sum_{i=1}^{n} x_{ij} = 1, \; j = 1, ..., n \tag{7}$$

The formulated integer linear program can be easily solved using MATLAB's optimization routine which implements the Branch and Bound algorithm [11]. The current task allocation formulation only consider static waypoints and vehicle positions. Current work aims at formulating the task allocation problem for a highly dynamic environment, where the dynamic behaviour of waypoints and UAVs are known. The cost function and constraints should take advantage of expected changes in the environment due to the actions of the vehicles. In the context of wildfire fighting, this knowledge can be obtained from wildfire growth models. The main objective is to assign waypoints to UAVs such that the shortest route for each UAV results in a local and global sense. This requirement is necessary for fuel efficiency from UAV point of view and for slowing down the fire propagation from the application point of view.

V. Simulation platform

To demonstrate and validate the developed co-ordination algorithms, a simulation platform involving a blimp, 2 quadrotors and 2 rovers is currently being developed at UTIAS. Figure 2 illustrates the simulation setup. The simulation platform consists of a main PC, and 4 Gumstik devices, one for each quadrotor/ground vehicle. All real-time computation and data processing performed by the mission controller is implemented on the main PC. The simulation platform operates in a Linux-based environment. All high-level code is written in C or Matlab and Simulink. To simulate the hierarchical control framework, the code is generated on the main PC, uploaded to each Gumstik for compilation and execution, then data and status are sent back to the main PC via wireless networks. For the wildfire fighting scenario, wildfire simulation, task generation and task allocation routines are implemented on the main PC. The tasks are then distributed to the appropriate Gumstik device. The high-level controller on the Gumstik device autonomously computes detailed trajectories subject to dynamic and kinematic constraints, while the low-level controller generates physical control inputs to the vehicle model/platform for stabilisation and tracking.

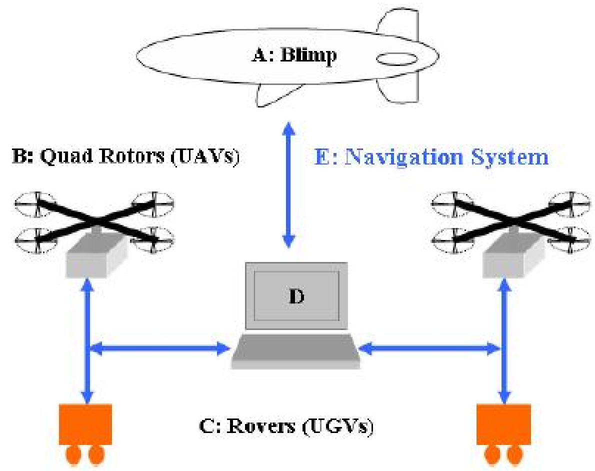

Fig. 2. Simulation platform

VI. Conclusions

Each vehicle platform and its applications pose different challenges that motivate the development of specialized control architecture and algorithms. This paper presents a 3-layered UAV/UGV vehicle platform and the corresponding hierarchical co-operative control framework. Its potential application to wildfire fighting is proposed, along with the co-ordination problems being investigated and proposed approaches. A brief introduction to the simulation platform is given, which will be used to demonstrate and validate the proposed co-operative control framework. The objective of current ongoing research is to develop algorithms for the task generation and task allocation problems for the proposed vehicle platform in the context of wildfire fighting application.

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