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Firemen Monitoring with Multiple UAVs for Search and Rescue Missions

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Abstract — This paper describes a multi-UAV firemen monitoring mission carried out in the framework of the AWARE Project. Several firemen were located in an area in front of a simulated building assisting injured people and moving equipment. The objective of the user was to have an estimation of the location of the firemen on the map and also images of their operations. Two autonomous helicopters were available and ready on the landing pads for this mission.

The techniques adopted to compute the required waypoints for the observation of the firemen from the UAVs are described in the paper. The detailed description of a firemen monitoring mission used to validate the approach is also provided.

Keywords: *Multi-UAV, Distributed Decision Making, Coordination, Cooperation*

I. INTRODUCTION

This paper describes a firemen monitoring mission carried out in the framework of the AWARE Project with the autonomous coordination and cooperation of multiple Unmanned Aerial Vehicles (UAVs). In this cooperation each individual executes a set of tasks (subgoals that are necessary for achieving the overall goal of the system, and that can be achieved independently of other subgoals) explicitly allocated to perform a given mission in an optimal manner according to planning strategies. Examples of cooperation among UAVs for monitoring purposes can be found in [1], [2].

Key issues in these systems include determining which robot should perform each task (task allocation) in order to maximize the efficiency of the team and ensuring the proper coordination among team members to allow them to successfully complete their mission. The multi-robot task allocation requires defining some metrics to assess the relevance of assigning given tasks to particular robots. In [3] a domain-independent taxonomy of multi-robot task allocation (MRTA) is presented. In the last years, a popular approach to solve the multi-robot task allocation problem in a distributed way has been the application of market-based negotiation rules [4], [5]. An usual implementation of those rules [6]–[8] is based on the Contract Net Protocol [9]. In those approaches, the messages

coming from the cooperating robots are those involved in the auction process: announce a task, bid for a task, allocate a task, ask for the negotiation token, etc.

Once the tasks have been allocated, it is necessary to coordinate the motions of the vehicles, which can be done by means of suitable multi-vehicle path/velocity planning strategies. Even if the vehicles are explicitly cooperating through messages, a key element in many approaches is the updated information about the configurations of the neighbors.

In [10], the AWARE Project¹ distributed architecture for the autonomous coordination and cooperation of multiple UAVs for civil applications was presented. This paper describes one of the missions performed with real UAVs in the general experiments of the AWARE Project in 2009. The paper is structured as follows: First, Section II reviews the techniques applied to compute the locations of the UAVs for the observation of the firemen. Then, Section III describes in detail the firemen monitoring multi-UAV mission carried out in 2009 to validate the approach presented in Sect. II. Finally, Section IV summarizes the conclusions.

II. OBJECT MONITORING TECHNIQUES

Different types of monitoring missions require the observation of a given object from the cameras on-board a UAV (in our case the objects of interest are firemen). Let us consider an object of interest with an associated state $\mathbf{x}(t)$. This state obviously includes the position of the object $\mathbf{p}(t)$ and, if the object is moving, it is convenient also to include the velocity $\dot{\mathbf{p}}(t)$ into the estimated state. Both are called the kinematic part of the state.

Besides, further information is usually needed. In different types of missions it is also required to confirm that an object belongs to a certain class within a set Γ (for instance, if it is a fireman). Therefore, the object state will also include information about the classification of the object. For instance, in certain applications, some appearance information could be needed to characterize an object, which also can help in the data association process among different UAVs with different camera views, i.e. the identification of each fireman. This kind

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¹<http://www.aware-project.net>

of information will be usually static and will be represented by θ .

Then, the complete estimated state is composed by the status of all the objects, where the number of objects N_o can vary with the time. The state at time t is represented by a vector $\mathbf{x}(t) = [\mathbf{x}_1^T(t), \mathbf{x}_2^T(t), \dots, \mathbf{x}_{N_o}^T(t)]^T$, where each potential object k is defined by:

$$\mathbf{x}_k(t) = \begin{bmatrix} \mathbf{p}_k(t) \\ \dot{\mathbf{p}}_k(t) \\ \theta_k \end{bmatrix}. \quad (1)$$

Apart from the UAVs, the AWARE platform is composed by a network of ground cameras and a Wireless Sensor Network (WSN). While the cameras provide bearing-only information about the firemen, the WSN provide range-only measurements. The estimation of the kinematic state of the objects is obtained by means of a decentralized Information Filter. Thus, each component endowed with perception capabilities (UAV, ground camera, WSN) runs a filter incorporating local measurements as well as fusing information received from the other filters. Details about the decentralized data fusion approach, the sensor models and the kinematic model for the firemen can be found in [11]. On the other hand, the static information to classify the objects can be obtained by processing the images accordingly.

Once the perception system has estimated the state of a particular object, a waypoint can be computed for the UAV in order to have the object in the center of the field of view of the on-board camera. The approach adopted is described in the following.

The uncertainty in the estimation of the object is used to generate a convenient waypoint for the observation in order to improve that estimation. As it has been mentioned before, a decentralized estimation of the position $\mathbf{p}_k(t)$ of each object k is available. Since these estimations are calculated with Information Filters, they are Gaussian and have an associated covariance or inertia matrix $\mathbf{C}$. This matrix can be geometrically represented as a 3σ ellipsoid as it will be shown in the following. The main axes of the ellipsoid can be computed to determine the direction with higher associated uncertainty in the estimation of the position of the object.

A quadric can be expressed in general vector/matrix form as

$$\mathbf{x}^T \mathbf{Q} \mathbf{x} + \mathbf{p} \mathbf{x} + r = 0 \quad (2)$$

where

$$\mathbf{x} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} q_{11} & q_{12} & q_{13} \\ q_{12} & q_{22} & q_{23} \\ q_{13} & q_{23} & q_{33} \end{bmatrix}, \quad \mathbf{p} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} \quad (3)$$

and r is a constant. If the quadric is an ellipsoid, $\mathbf{Q}$ is symmetric, $\det(\mathbf{Q}) > 0$ and $\mathbf{Q}$ is an invertible matrix. In order to extract useful characteristics of the ellipsoid such as the main axes directions and modules, the general form in (2) should be converted to the center-oriented form

$$(\mathbf{x} - \mathbf{k})^T \mathbf{R} \mathbf{D} \mathbf{R}^T (\mathbf{x} - \mathbf{k}) = 1, \quad (4)$$

where $\mathbf{k}$ is the center of the ellipsoid, $\mathbf{R}$ represents its rotation and $\mathbf{D}$ is a diagonal matrix. Let us include the center $\mathbf{k}$ in the first term of (2)

$$(\mathbf{x} - \mathbf{k})^T \mathbf{Q} (\mathbf{x} - \mathbf{k}) = -(2\mathbf{Q}\mathbf{k} + \mathbf{p})^T \mathbf{x} + (\mathbf{k}^T \mathbf{Q} \mathbf{k} - r). \quad (5)$$

Setting $\mathbf{k} = -\mathbf{Q}^{-1}\mathbf{p}/2$, then $\mathbf{k}^T \mathbf{Q} \mathbf{k} = \mathbf{p}^T \mathbf{Q}^{-1} \mathbf{p}/4$ and

$$(\mathbf{x} - \mathbf{k})^T \mathbf{Q} (\mathbf{x} - \mathbf{k}) = \mathbf{p}^T \mathbf{Q}^{-1} \mathbf{p}/4 - r. \quad (6)$$

Dividing by the scalar on the right-hand side of the last equation and setting $\mathbf{M} = \mathbf{Q}/(\mathbf{p}^T \mathbf{Q}^{-1} \mathbf{p}/4 - r)$

$$(\mathbf{x} - \mathbf{k})^T \mathbf{M} (\mathbf{x} - \mathbf{k}) = 1. \quad (7)$$

Since the terrain where the objects are located is known, only the uncertainty in the $x - y$ plane will be considered. Then, for two dimensions the eigendecomposition of the quadric symmetric matrix $\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{bmatrix}$ can be done symbolically and will provide the values for the eigenvectors and hence the direction of the main axis $\mathbf{v}_1$ (eigenvector associated to bigger eigenvalue λ_1) of the corresponding ellipse. In order to avoid numerical problems when m_{12} is close to zero, if $m_{11} \geq m_{22}$ then the major axis direction will be computed as

$$\mathbf{v}_1 = \frac{1}{\sqrt{(\lambda_1 - m_{22})^2 + m_{12}^2}} \begin{bmatrix} \lambda_1 - m_{22} \\ m_{12} \end{bmatrix}, \quad (8)$$

and otherwise as

$$\mathbf{v}_1 = \frac{1}{\sqrt{(\lambda_1 - m_{11})^2 + m_{12}^2}} \begin{bmatrix} m_{12} \\ \lambda_1 - m_{11} \end{bmatrix}. \quad (9)$$

Each UAV has a perception software application which is computing the covariance matrix $\mathbf{C}_k$ associated to an object k from local measurements and estimations received from other components of the platform. The matrix $\mathbf{M}$ describing the shape of an ellipse $(\mathbf{x} - \mathbf{k})^T \mathbf{M} (\mathbf{x} - \mathbf{k}) = 1$ is related to the covariance matrix of the same ellipse [12] according to

$$\mathbf{M} = \frac{1}{4} \mathbf{C}^{-1}. \quad (10)$$

From this equation, it is possible to apply the previous expressions (8) and (9) to compute the main axis direction of the ellipse, i.e. the direction with higher uncertainty in the estimation of the position of the object.

Let us consider an object with coordinates $[x_o \ y_o \ z_o]^T$ and main axis vector $\mathbf{v}_1 = [v_{1x} \ v_{1y}]^T$. The objective is to compute a location and orientation for the UAV that would allow to improve the estimation of the object of interest. Let us denote the coordinates of the observation point w by $[x_w \ y_w \ z_w]^T$ and the desired orientation for the UAV by the roll (γ_w), pitch (β_w) and yaw (α_w) angles. The initial

location of the UAV is $[x \ y \ z]^T$. First, the following constraints should be satisfied:

- 1) The altitude for the monitoring task is $z_w = z_o + z_{\Pi}$ due to safety issues. Therefore, z_{Π} is fixed beforehand with a reasonable value. Then, the UAVs are commanded to stay in hovering at different waypoints at a given altitude during the missions.
- 2) Again due to safety issues, the pitch and roll angles of the UAV are set to zero ($\beta_w = \gamma_w = 0$) in hovering. Then, the yaw angle is the only degree of freedom.
- 3) The camera of each UAV is pointing downwards with a pitch angle which is not changed during the flight.

Then, the waypoint is selected in order to obtain measurements with an optimal information gathering. Since the sensor is a camera, which provides accurate bearing information, the uncertainty in the axis perpendicular to its pointing direction is reduced. Therefore, pointing to the object perpendicularly to the main axis of the ellipse is the way in which the camera can retrieve the more information. The procedure to calculate the waypoint follows these guidelines:

- 1) The object should be in the center of the field of view. Since the height and the pointing angle of the camera are known beforehand, the required distance between the UAV and the object in order to center the field of view is calculated.
- 2) In the perpendicular line to the main axis that crosses the estimated location of the object and with the previous distance constraint, there are two possible locations $[x_{w1} \ y_{w1}]^T$ and $[x_{w2} \ y_{w2}]^T$. Then, the waypoint closer to the UAV is selected. Thus, if $\sqrt{(x_{w1} - x)^2 + (y_{w1} - y)^2} \leq \sqrt{(x_{w2} - x)^2 + (y_{w2} - y)^2}$

$$y_{w1} - y_o = -\frac{v_{1x}}{v_{1y}}(x_{w1} - x_o) \quad (11)$$

and otherwise

$$y_{w2} - y_o = -\frac{v_{1x}}{v_{1y}}(x_{w2} - x_o). \quad (12)$$

- 3) The yaw α_w of the UAV is computed to have the UAV pointing towards the object in the direction perpendicular to the main axis $\mathbf{v}_1$ of the uncertainty ellipse. Then, using the north as zero reference for the yaw angle and assuming clockwise positive, its value will be given by

$$\alpha_w = \frac{\pi}{2} - \arctan\left(\frac{y_o - y_w}{x_o - x_w}\right). \quad (13)$$

Figure 1(a) shows an example of a waypoint and UAV orientation computed following the above presented rules.

If more than one UAV is commanded to monitor the same object, the first one will follow the above mentioned rules, but the second and next UAVs will consider the places already occupied around that object. In this case, the location is alternatively chosen between the perpendicular and parallel lines to the main axis that crosses the estimated location of the

(a) Location for object monitoring with one UAV

(b) Locations for object monitoring with two UAVs

Fig. 1. Waypoint computation for object monitoring tasks. For a single UAV, its location will be in the perpendicular line to the main axis that crosses the estimated location of the object. From the two possible solutions, the waypoint closer to the initial UAV position is selected. If more than one UAV is commanded to monitor the same object, the location is alternatively chosen between the perpendicular and parallel lines to the main axis that crosses the estimated location of the object.

the object. Then, as it can be seen in Fig. 1(b), if two UAVs are commanded to monitor the same object, the first one will choose the closest location in the perpendicular line, whereas the second will be located in the closest waypoint in the parallel line.

Next section describes a people tracking mission with two UAVs that illustrates the experimental application of the techniques described above.

III. FIREMEN MONITORING MISSION

This mission was carried out on 25th May 2009 in the framework of the AWARE Project. Two firemen were located in the area in front of a simulated building assisting injured people and moving equipment. The objective of the user was to have an estimation of the location of the firemen on the map and also images of their operations. Even though both firemen were estimated by the perception system, only one of them was monitored by the UAVs in that experiment. Two UAVs (UAVs 1 and 2) were available and ready on the landing pads for this mission, both equipped with a fixed visual camera aligned with the fuselage of the helicopter and pointing downwards 45° .

On the other hand, the firemen were equipped with wireless sensor nodes that allowed to have an initial estimation of their location based on the information from the WSN deployed in front of the building [11]. Later, this information was also fused with the estimations computed from the visual images gathered by the helicopters and the ground cameras in order to decrease the uncertainty in the location of the firemen.

Two tasks of type TRACK(object_0) (τ^3 and τ^8) were sent from the platform Human Machine Interface (HMI) application to the UAVs at different times to monitor the operations of the fireman with identifier zero:

- Firstly, task τ^3 was announced and allocated to UAV 2 due to its lowest bid (lowest insertion cost) during a distributed negotiation process based on the SIT algorithm described in [13]. In order to compute the insertion cost for the tracking task, the techniques presented in Sect. II were used to find the required associated waypoint and heading. The idea is to have the camera on-board pointing perpendicular to the main axis of the uncertainty ellipse associated to the position estimation of the fireman. From the two possible solutions, the waypoint closer to the flight plan of the UAV is chosen. Once the location was reached, the UAV captured images from the fireman (labelled as object_0) and processed them in order to contribute to the estimation of his position. As it was shown in Sect. II, the UAV 2 also had to broadcast its position relative to the tracked object location; if more tracking tasks for the same object were commanded, the next UAVs would need this information to compute their positions around the object accordingly.
- Later, τ^8 was announced and allocated to UAV 1 (UAV 2 bids with infinite cost because it was already tracking the same object). A new waypoint and heading were computed to take images from a perpendicular viewpoint with respect to the current UAV allocated to the object.

Fig. 2. Messages interchanged during the distributed negotiation process in the firemen monitoring mission. The labels of the arrows representing the messages are always above them. Two tracking tasks (τ^3 and τ^8) were announced at different times, separated in the figure using two dotted horizontal lines. Each time a tracking task was allocated to a UAV, the UAV requested the token from the HMI application in order to re-announce it. In this case, there were no reallocations due to dynamic changes in the UAV's partial plans.

Again, from the two possible solutions, the waypoint closer to the flight plan was chosen.

Figure 2 illustrates the messages interchanged during the distributed negotiation process based on the SIT algorithm that follows a market-based approach. The announcement of the two tracking tasks mentioned above are separated in the figure using two dotted horizontal lines. Moreover, the labels of the arrows representing the messages are always above them.

It can be seen that each time a tracking task was allocated to a UAV, the UAV requested the token from the HMI application in order to re-announce it. In this case, there were no reallocations due to dynamic changes in the UAV's partial plans.

Table I shows the list of tasks executed during the mission (once the allocation process finished), whereas Table II shows the values computed for the parameters of the GOTO elementary tasks in the plans of both UAVs.

Figure 3 shows the trajectories followed by the UAVs during

TABLE I

TASKS EXECUTED FOR THE FIRE MONITORING MISSION AND THEIR DECOMPOSITION IN ELEMENTARY TASKS. THE VALUES OF THE PARAMETERS $\hat{\Pi}^k$ CORRESPONDING TO THE ELEMENTARY TASKS WITH TYPE $\hat{\lambda}^k = \text{GOTO}$ ARE DETAILED IN TABLE II.

τ_i^k (task id)	λ (task type)	$-\Omega$ (preconditions)	Ω^+ (postconditions)	Decomposition	$\hat{\Pi}$ (parameters)
τ_1^1	TAKE-OFF	PRE-FLIGHT_CHECK	$\emptyset$	$^1\hat{\tau}_1^1 (\hat{\lambda}^1 = \text{TAKE-OFF})$	$^1\hat{\Pi}_1^1$
τ_1^2	GOTO (wp1)	END(τ_1^1)	$\emptyset$	$^1\hat{\tau}_1^2 (\hat{\lambda}^2 = \text{GOTO})$	$^1\hat{\Pi}_1^2$
τ_1^3	TRACK (object_0)	END(τ_1^2)	$\emptyset$	$^1\hat{\tau}_1^3 (\hat{\lambda}^3 = \text{GOTO})$	$^1\hat{\Pi}_1^3$
τ_1^4	HOME	END(τ_1^3)	$\emptyset$	$^1\hat{\tau}_1^4 (\hat{\lambda}^4 = \text{GOTO})$	$^1\hat{\Pi}_1^4$
τ_1^5	LAND	END(τ_1^4)	$\emptyset$	$^1\hat{\tau}_1^5 (\hat{\lambda}^5 = \text{LAND})$	$^1\hat{\Pi}_1^5$
τ_2^6	TAKE-OFF	PRE-FLIGHT_CHECK	$\emptyset$	$^1\hat{\tau}_2^6 (\hat{\lambda}^6 = \text{TAKE-OFF})$	$^1\hat{\Pi}_2^6$
τ_2^7	GOTO (wp4)	END(τ_2^6)	$\emptyset$	$^1\hat{\tau}_2^7 (\hat{\lambda}^7 = \text{GOTO})$	$^1\hat{\Pi}_2^7$
τ_2^8	TRACK (object_0)	END(τ_2^7)	$\emptyset$	$^1\hat{\tau}_2^8 (\hat{\lambda}^8 = \text{GOTO})$	$^1\hat{\Pi}_2^8$
τ_2^9	HOME	END(τ_2^8)	$\emptyset$	$^1\hat{\tau}_2^9 (\hat{\lambda}^9 = \text{GOTO})$	$^1\hat{\Pi}_2^9$
τ_2^{10}	LAND	END(τ_2^9)	$\emptyset$	$^1\hat{\tau}_2^{10} (\hat{\lambda}^{10} = \text{LAND})$	$^1\hat{\Pi}_2^{10}$

TABLE II

VALUES OF THE PARAMETERS $\hat{\Pi}_i^k$ CORRESPONDING TO THE ELEMENTARY TASKS WITH TYPE $\hat{\lambda}_i^k = \text{GOTO}$. TABLE III DETAILS THE MEANING OF EACH PARAMETER π^j .

Parameters ($\hat{\Pi}_i^k$)	$^1\hat{\Pi}_1^2$	$^1\hat{\Pi}_1^3$	$^1\hat{\Pi}_1^4$	$^1\hat{\Pi}_2^7$	$^1\hat{\Pi}_2^8$	$^1\hat{\Pi}_2^9$
π^1	251663.94	251664.78	251674.17	251705.60	251689.77	251679.50
π^2	4121283.77	4121284.95	4121244.74	4121262.52	4121278.31	4121252.62
π^3	70.0	72.8	70.4	70.0	72.8	70.4
π^4	1.0	1.0	1.0	1.0	1.0	1.0
π^5	1	1	1	1	1	1
π^6	90.0	62.0	0.0	0.0	-28.0	0.0
π^7	0	0	0	0	0	0

TABLE III

PARAMETERS OF A TASK WITH TYPE $\hat{\lambda} = \text{GOTO}$.

Parameters (Π)	Description
$\pi^1(x)$	East UTM coordinate (m)
$\pi^2(y)$	North UTM coordinate (m)
$\pi^3(\text{Altitude})$	Altitude (m) ellipsoid-based datum WGS84
$\pi^4(\text{Speed})$	Desired speed (m/s) along the way to the waypoint
$\pi^5(\text{ForceHeading})$	1: force to the specified heading, 0: Not force
$\pi^6(\text{Heading})$	Specified heading (degree) along the way (N is 0° , E is 90° , W is -90° and S is 180°)
$\pi^7(\text{Payload})$	1: to activate the payload around the location of the waypoint, 0: not to activate

the execution of the mission. The different waypoints of the elementary GOTO tasks are represented by squares. The waypoints labelled as wp1 and wp4 are initial locations defined by the user for each UAV after taking-off. The WSN and ground cameras of the platform started to provide estimations from both firemen, labelled as object_0 and object_1. Based on these estimations, the tracking tasks were sent to the UAVs. In the case of UAV 1, the computed observation waypoint wp2 resulted very close to the first waypoint, but the heading was different as it can be seen in Table II ($^1\hat{\Pi}_1^2$ and $^1\hat{\Pi}_1^3$ parameters).

Figure 4 shows a screenshot taken from the HMI interface during the live execution of the mission.

In addition, some fragments of the live video captured from the HMI screen during the real execution of the mission are

Fig. 3. Paths followed by the two helicopters during the firemen tracking mission. The trajectories in red and blue correspond to the UAVs 1 and 2 respectively. The different waypoints of the elementary GOTO tasks are represented by squares.

available in the AWARE Project web site ².

IV. CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper presented the techniques adopted in a real firemen monitoring mission with multiple UAVs. The distributed proposed approach did not pose significant restrictions in the

²<http://www.aware-project.net/videos/firemen.avi> (this video can be played using the VLC media player - <http://www.videolan.org>)

Fig. 4. Screenshot of the platform Human Machine Interface during the execution of the mission. At the right, the view of the UAV's on-board cameras is shown.

communication layer, so it allowed to reach the coordination among the UAVs using a distributed approach at a reasonable communication cost.

Finally, future work will explore a closer feedback of the decisional architecture with the UAV perception in order to reach common perceptual objectives to all the UAVs.

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