An Algorithm for Collaborative Surveillance Systems with Unmanned Aerial and Ground Vehicles

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Abstract—*In the past decade Unmanned Vehicles have become a topic of interest in many research organizations. Unmanned vehicles based systems are integrated to many applications in various areas ranging from military missions to wildfire detection. Recently, there has been a great interest to design collaborative systems of unmanned aerial vehicles and unmanned ground vehicles. This paper proposes a new algorithm that can be used to calculate optimal paths of unmanned air vehicles and quantities of unmanned ground and air vehicles to cover a target area. This algorithm is useful for patrolling systems based on the collaboration of unmanned air vehicles and unmanned ground vehicles.*

Keywords — *Path planning, Robot collaboration, Unmanned systems*

I. INTRODUCTION

An unmanned system is a kind of device that includes data processing equipment, sensors, automatic control, and communications systems and is can perform missions autonomously without human intervention. Unmanned systems can include unmanned aircrafts, ground rovers, underwater or surface explorers. An unmanned aerial vehicle (UAV) is an aircraft that can move without a human pilot. An UAV can be controlled autonomously or the remotely by commands of an operator. An unmanned ground vehicle(UGV) is a vehicle that moves without a human operator onboard. UGVs can be used in dangerous applications for human operators.

In recent years, unmanned robots have been taken their places in robotic applications gradually. In addition, there is a high demand for using unmanned robots together in a collaborative manner. As a result of this, UAV-UGV collaboration based missions have been getting an interest for both researchers and engineering institutions and industry.

In literature, the studies including UAV-UGV collaboration are generally performed under the topics: intelligence surveillance and reconnaissance (ISR), object tracking, path planning, localization and formation control of multi-robot teams. ISR is providing accurate information and intelligence to human operators. Significant researches on ISR type missions including UAVs and UGVs are given in [1], [2], [3], [4], [5], [6], and [7]. The object tracking is defined as the estimating the movement of an object in the image plane during its motion. Path-planning is a significant subject for autonomous robots that lets them to find the optimal paths between pre-defined waypoints. Localization of a robot includes answer of the question: where is the robot? In order to find location of a robot position sensors and specific computing approaches that will process the sensor data should be used. There are noteworthy studies related with object tracking, path planning and localization. The significant examples of these studies including UAVs and UGVs can be found in [8], [9] and [10]. Formation control of a group of autonomous vehicles/robots includes one of the important applications of collaborative control. Research on formation control also focused on better swarming of autonomous robot groups. References [11], [12], [13] and [14] includes notable studies based on formation control of unmanned vehicle groups.

In this paper, an algorithm for collaborative patrolling systems is proposed for ISR type missions. In contrast to the most of the studies in literature, our proposed algorithm considers UAV energy capacities which UAVs need to follow the UAV trajectories. In addition to this, our algorithm can calculate the number of required UAVs and UGVs to cover entire area where the patrolling task will be carried out. Beside this, the proposed algorithm can calculate optimal UAV paths.

II. THE PROPOSED ALGORITHM

The purpose of this study is to calculate the required number of UAVs and UGVs to cover all the waypoints in a target area for a surveillance mission and also to calculate optimal UAV paths for UAVs.

In order to achieve this, an algorithm has been developed. Firstly, we define "apu" that is an available assignment point for the UGV that is used to carry UAVs to target area. Then the algorithm finds the farthest waypoint to apu and calculates the direct distance between these two points, we call this distance as dfw2c(distance from the farthest waypoint to carrier UGV). Then the algorithm calculates mrbl(minimum required battery level) of UAVs by considering the energy consumption of an UAV while cruising the total distance that is the summation of the distance from apu to farthest waypoint and the distance from the farthest waypoint to apu, and also by considering the energy consumption of UAV during its take-off, climbing to cruise altitude, descent from cruise altitude and landing. If the specified energy capacity of an UAV is enough to cover the mrbl of UAV, our proposed algorithm decides that one UAV is enough to complete the patrolling of this area. Otherwise, the algorithm decides to increase number of UAVs and divide the area according to the new number of UAVs. The algorithm checks the same conditions for all UAV waypoint clusters. When the UAV energy capacity becomes higher than the mrbl of each cluster, algorithm stops the increasing number of UAVs and decides that the last calculated number of UAVs is enough to cover all the waypoints of specified area. Figure 1 shows the frame of the proposed algorithm.

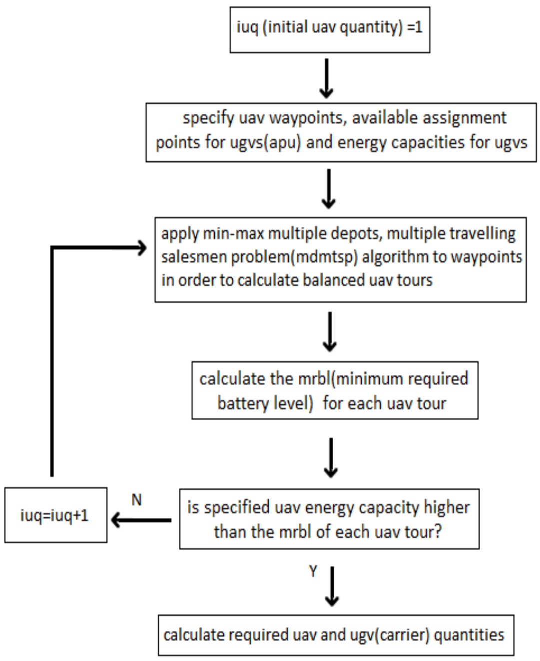

Fig.1. The frame of the proposed algorithm

Figure 2 shows, under the mark a) all the waypoints in a target area, under the mark b) optimal path(starts and ends on apu) that is calculated for one UAV and under the mark c) the farthest waypoint to apu for one UAV.

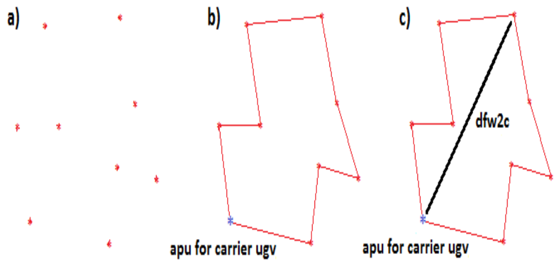

Fig.2. a) all the waypoints in a target area, b) optimal path(starts and ends on apu) that is calculated for one UAV by using tsp formulation and c) the farthest waypoint to apu for one UAV

Figure 3 shows, under the mark a) the unbalanced UAV tours that are not appropriate to decide the minimum UAV quantity and under the mark b) balanced UAV tours that are calculated by mdmtsp formulation. These balanced UAV tours are appropriate to decide the minimum number of UAVs enough to cover target area.

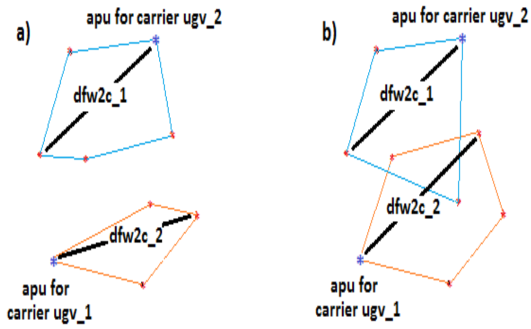

Fig.3. a) the unbalanced UAV tours that are not appropriate to decide the minimum number of UAVs and b) balanced UAV tours that are appropriate to decide the minimum number of UAVs that is enough to cover target area

The formulation of mdmtsp (multi depot multiple travelling salesmen problem) with minmax objectives were used in our proposed algorithm. The formulation and detailed information of mdmtspwere taken in [15] and [16]. Genetic algorithm is implemented to this formulation to search the optimal solution [17]. This formulation considers two objectives: the first objective is called as MinSum and aims to minimize the sum of traveling distances of the entire group, which is the classic MTSP (multiple travelling salesmen problem) goal. The second objective is called as MinMax and aims to minimize the longest traveling distance of any agent in the group. Since the second objective provides balanced routes for each UAV, it is possible to calculate optimum number of UAVs and carrier UGVs.

Since there is not a standard power consumption model for UAVs in literature, power consumption model of UAVs must be composed experimentally by testing them(quad-copters for this study) in windy air conditions. In this study, we used a very simple power consumption model for the UAVs used for the proposed algorithm. However, more detailed consumption models can be developed by considering all air conditions and UAV speeds. Our proposed algorithm can be modified and used successfully with such models including various parameters. We assumed that the UAVs consume 0.033% of their battery charge for each meter that they pass while cruising, climbing and descending. It means that an UAV used in the proposed algorithm can travel approximately 3000 meters with its fully charged batteries.

In order to test our algorithm, we simply used a set of 3 dimensional waypoints. In our sample scenario, we assume that we send carrier UGVs with 2 UAVs on them for a continuous patrolling of a target area. When carrier UGV reaches to a target area, one of the UAVs starts to follow the path suggested by our proposed algorithm. It is inevitable that the battery level of mid-air UAV will decrease during its motion on its defined path. In this situation, continuous patrolling is provided by directing the mid-air UAV onto carrier UGV with an UAV battery replacement platform when battery charge level of mid-air UAV falls under a specified cel(critical energy level). At the same time, the UAV waiting on a carrier UGV with its already fully charged battery is directed in place of the mid-air UAV that was directed onto the carrier UGV. According to this scenario, UAVs climb a specified altitude from a carrier UGV in order to reach the first waypoint above the carrier UGV and cruise the waypoints and turn back to the first waypoint. UAVs continue its cruise until it remains “cel” in their battery and then send a signal that means a mission exchange demand to waiting UAV. This critical energy level is considered as the energy that each UAV needs to reach the farthest waypoint to carrier UGV and also to turn back to first waypoint and then land on its carrier UGV. Mid-air UAV must continue its cruise until the other UAV comes to take over the mission from it. The worst case for the battery charge level of mid-air UAV is to fall under specified “cel” to turn back to its carrier UGV when it is on the farthest waypoint. Thus, by considering this possibility for any current position of mid-air UAV, in order to provide a safe turn back, we considered the distance from carrier UGV to farthest point of each UAV tour in calculation of “cel” of UAV batteries. Since the longest distance from the carrier UGV to the farthest point of any tour is dfw2c, “cel” value to turn back to the carrier UGV can be calculated as the expression given in (1) for each tour.

$$cel=2*(dfw2c+first\ waypoint\ altitude)*0.033 \quad (1)$$

According to our proposed algorithm, mrbl of each tour is composed with the summation of three times of the energy consumed while passing its dfw2c distance and also three times of UAVs climbing-descending distance for its first waypoint above the carrier UGV. UAV must pass dfw2c distance firstly to reach farthest waypoint, and this move makes its battery energy level equal to “cel”. Then mid-air UAV sends its mission exchange message to UAV waiting on carrier UGV. Helper UAV can reach the current location of mid-air UAV, by passing the total distances of dfw2c and the distance from carrier UGV to the first waypoint. It means that mid-air UAV also needs to an energy level while it is waiting the other UAV. After the mission exchange between mid-air and helper UAVs accomplishes, UAV that needs recharging must pass the total distances of dfw2c and the distance from carrier UGV to the first waypoint in order to reach to carrier UGV. If we sum all of the distances that UAV needs to turn back to carrier UGV, we can get mrbl of each UAV tour. Mrbl of each tour can be formulated as given in (2). In this situation, it is obvious that an UAV battery level must be higher than the calculated mrbl of each tour in order to make a safe turn back to its carrier UGV.

$$mrbl= 3*(dfw2c+first\ waypoint\ altitude)*0.033 \quad (2)$$

We tested our proposed algorithm on a target area includes 20 waypoints, by using Matlab program as computation environment. We firstly applied our algorithm to this target area for only one UAV. After 2217 iterations, proposed algorithm calculated the UAV path shown in Figure 4. Dfw2c and total length of the trajectory for one UAV was calculated respectively as 1250 meters and 3774 meters.

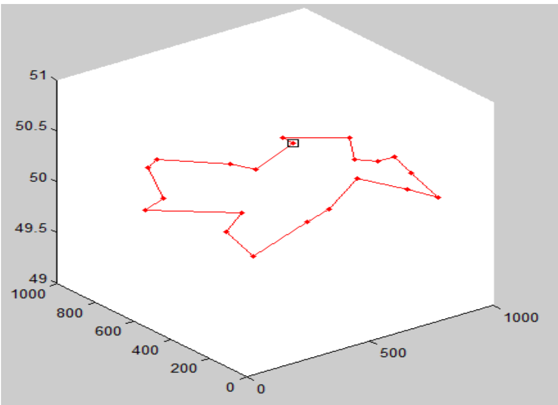

Fig.4. 3D positions of waypoints in target area

2D projection of waypoints of one UAV tour with dfw2c distance and the best solution history for one UAV path are given in Figure 5a and Figure 5b respectively.

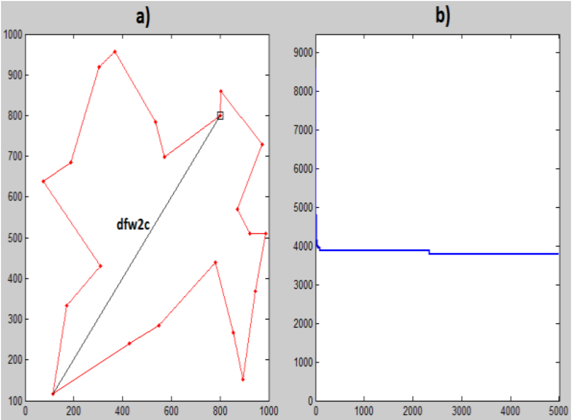

Fig.5. a) 2D projection of waypoints of one UAV tour, b) best solution history for one UAV path

According to Eq.2, mrbl for one UAV was calculated as 133. Since calculated mrbl value higher than maximum battery capacity of UAVs considered for this study, our proposed algorithm informed us that one UAV can not cover the target area. Proposed algorithm demanded from us to define a new apu for a new carrier UGV.

As we mentioned before, when multi apu were defined, mdmtsp part of our proposed algorithm tries to make the longest tour minimum while also trying to minimize the total lengths of all tours. We added a new apu to target area, then we run the proposed algorithm for two UAV paths. After 284 iterations, calculation of the longest tour was ended. When 1000 iterations passed, since there is not a change in the length of the longest UAV path, proposed algorithm stops the calculation of the total length of all UAV tours by finding it as 4312 meters. Best solution history for the longest UAV path and best solution history for the total of all paths in target area were given in Figure 6a and Figure 6b, respectively.

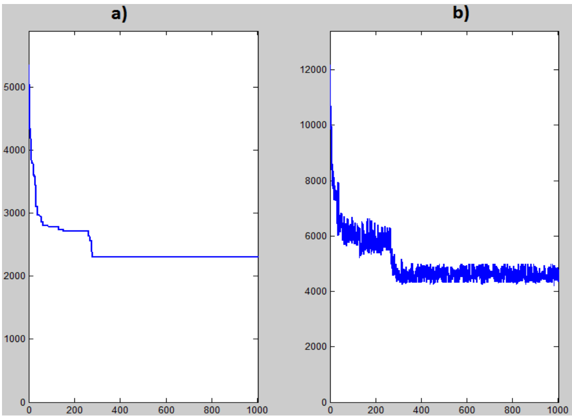

Fig.6. a) Best solution history for the longest UAV path, b) Best solution history for the total of all paths in target area

Dfw2c values and tour lengths of two UAV paths are calculated as respectively dfw2c_1=653 meters, dfw2c_2=557 meters, length of the first UAV path= 2013 meters, length of the second UAV path= 2299 meters. 2D projection of waypoints of two balanced UAV tours with dfw2c distances was given in Figure 7.

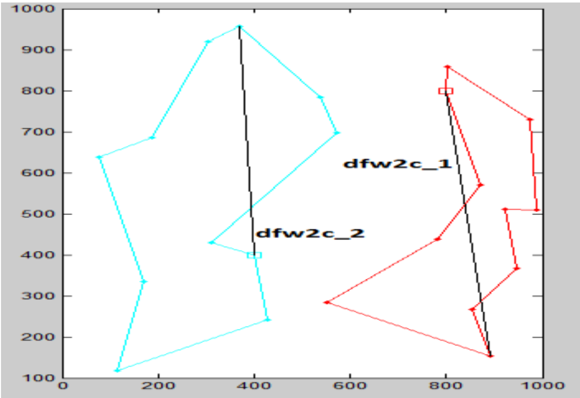

Fig.7. 2D projection of waypoints in target area for two balanced tours

In this situation, our algorithm considered higher dfw2c value which is 653 meters. According to (2), proposed algorithm calculated maximum mrbl value for this area as 74.5. Since maximum mrbl value is lower than battery capacity of UAVs considered for this study, our algorithm decides that two UAVs are enough to carry out a safe patrolling mission in considered target area.

III. CONCLUSION AND FUTURE WORK

In this paper, an algorithm for patrolling systems based on the collaboration of unmanned air and ground vehicles was proposed. In contrast to the most of the studies related with ISR type missions in literature, the proposed algorithm considers the UAV energy capacities which the UAVs need to follow the UAV trajectories. Our proposed algorithm can calculates the optimum number of the UAVs and UGVs to cover entire area where the patrolling task will be carried out. By using the proposed algorithm, any area considered as dangerous for the tasks that requires human operators can be observed continuously with optimum number of UAVs and UGVs. This provides the patrolling system designers to decide more efficient systems.

In this study, in order to get UAV paths, we used Genetic algorithm that is a heuristic method provides us a near optimal solution. However, the other methods that can give exact solutions should be investigated to get more precise results for UAV paths.

As a future work, our proposed algorithm will be implemented for a patrolling system created in Matlab 3d animation environment. The mathematical models of quad-copters and unmanned ground robots will be developed in Simulink environment and then they will be connected to 3d models in virtual environment created in VRML editor, and finally, it will be tested in a real life environment. Our future work will aim to provide a continuous patrolling for each UAV paths. This will be provided by directing the mid-air UAV onto an UGV with UAV battery replacement platform. At the same time, the UAV waiting on a carrier UGV with its already fully charged battery will be directed in place of the mid-air UAV that was directed onto the carrier UGV. This planned application is important to show the feasibility of the proposed algorithm.

Since design and implementation of an automatic battery replacement system is a completely different research area, it was assumed that that these battery replacement systems will be used on the carrier UGVs. These UAV battery replacement systems were studied and tested successfully in real conditions. The real environment tests showed that UAV battery replacement systems can automatically replace UAV batteries within seconds. Detailed information about these systems can be found in [18] and [19].

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