UAV and AUVs Coordination for Ocean Exploration

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Abstract— **In this paper, we develop a coordination mechanism for multiple Autonomous underwater vehicles (AUVs) and a single Unmanned aerial vehicle (UAV) cooperatively performing a ocean exploration mission. The UAV and the AUVs have limited sensor and communication constraints. The AUVs are deployed in the ocean and surface when their mission leg is completed. The UAV flies over the AUV, acquires the information procured by the AUV and generates a new mission plan to the AUV. The UAV has to meet all the AUVs and reach the base station within a prescribed sortie time. However, the AUVs may not complete the assigned task and may surface anywhere along the current mission leg. Hence, the UAV has to take the uncertainty of AUV surfacing into account while it generates the next mission plan to the AUV otherwise it may not satisfy the sortie time constraint. We develop a robust mechanism of determining the route for the UAV and path generation for the AUV such that the UAV always reaches the base station within the sortie time limit. Theoretical results are presented to show the robustness of the algorithms. Simulations are carried out to show how the mission is accomplished.**

I. Introduction

The toll on the fragile marine life has peaked with an increase in the naval operations over the years. For situational awareness, usually the underwater exploration missions are conducted manually. These mission require significant amount of time spanning several weeks to survey a large region. However, the environmental conditions change quickly due to high pollution levels, hence we need new methodologies to acquire the information quickly. Unmanned aerial vehicles (UAVs) with their ability to travel at greater speeds can be used to cover a large region, but they can only skim through the surface and cannot provide insight into the marine life. Thus we need to deploy Autonomous Underwater Vehicles (AUVs) for ocean exploration. These AUVs have limited sensor and communication ranges and can autonomously navigate to acquire the required data. Due to limitations with sensor and communication ranges it is desirable to deploy a team to AUVs that can perform the task quickly. Although deploying multiple agents can significantly enhance the mission performance, it also introduces new challenges in designing coordination mechanisms.

For situational awareness, the base station also called as the command and control center (C3) requires the gathered information from the UAV periodically and also to command the AUVs to survey some particular regions of interest. The AUVs are exploring and may be distant from the base station to receive instructions and send the acquired information. Hence, they may need to travel towards the base station (that could be at a large distance) to provide the data. As the objective is to explore the region quickly, the AUVs are spending significant amount of time in traveling towards the base station, thus decreasing the mission effectiveness and and, thus, the need to develop new mechanisms for improving the mission performance arises.

To achieve such a mission in an effective way, we deploy a team of AUVs and a UAV. The AUVs carry out the exploration mission and periodically surface to provide the information to a UAV which will be ying over the AUV. Once the information is transferred from AUV to UAV, the UAV may provide a new path to the AUV or the AUV may broadcast its next leg or the human operator may send a path through AUV for exploration. The UAV will meet all the AUVs, collect the information, and returns to the base station periodically to provide the acquired information.

Achieving coordination between agents that could be AUVs, UAVs and robots have been addressed previously by many authors [1]- [13]. However, most of the research is focussed on developing theoretical and experimental frameworks for a single class of vehicles for instance coordination between various multiple robots [1]- [4], between multiple UAVs [5]- [7] and between AUVs [8]- [10]. There has been limited research on using multiple UAVs and robots [11]- [13]. Throughout the years researchers have seldomly concentrated on using UAVs and AUVs for cooperative missions. Healey et al. [14] develop an algorithm for a stealth mission using a single UAV and AUV. This paper highlights the fact that the UAVs and AUVs can be used for cooperative missions. In the same spirit, we develop a coordination algorithm for multiple AUVs performing an exploration mission and a single UAV that visits these AUVs for transfer of knowledge acquired by the AUV sensors.

The rest of the paper is organized as follows: Section II describes the objectives of the mission and the proposed approach to achieve the mission. In Section III we describe the methodology involved in route planning for the UAV and determining the path for the UAV. Simulation results are presented in Section IV and we conclude in Section V

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II. Problem Formulation

A. Scenario

Consider the scenario as shown in Figure 1 where three AUVs are deployed to carry out an ocean exploration mission. The AUVs have limited sensor and communication ranges, and, hence, they cannot communicate with the C3 directly. In order to carry out the mission efficiently a UAV is deployed that acts like a relaying agent between AUVs and the C3. The mission is carried out in the following way: The AUVs are deployed and an initial path is provided to them where they need to visit and also the time when the AUVs will surface to provide the acquired information to the UAV. Based on the AUV path and surface time, the UAV will schedule a route to visit the AUVs at the specified time of surfacing. The UAV will collect the information from the AUVs and a new path with the surface time is given by the UAV to the AUV. The AUV will use the new path to explore. The UAV performs this sequence of actions to all the AUVs and then visit the base station to deliver the information within a prescribed time limit called as *Sortie time* (L).

The AUVs are searching the region and have better environmental perception, therefore the AUVs can command the UAV their next leg of operation. Also to improve the search performance the AUVs can coordinate with each other and determine their paths. In either of these cases, the AUV commands the UAV its way-point. When AUVs command their intentions, then there may be a possibility where the UAV is unable to determine a route to satisfy the sortie time constraint. Additionally, during the exploration, the AUVs can meet other AUVs and change their goals. Since, the AUVs are underwater they cannot communicate this information to the UAV. This modus operandi creates a chaos in the coordination of the AUVs and UAV. Therefore, to have a command over the operation we assume the UAV will command the AUV subsequent path.

Sometimes the AUVs may not be able to complete the assigned task, in which case the UAV has to search for the AUV. Since, the AUV is traveling from its previous location to the new location and also has the surface time when it should surface, the UAV can travel from its desired point of meeting towards the old position. Since, the surface time has elapsed, the AUV will surface along the assigned path. When the UAV meets the AUV, based on the current location of the AUV, the UAV has to generate the new path. Due to the uncertainty of the location where the AUV can surface, the UAV has to take this aspect into account while generating the new path to the AUV otherwise, the UAV may not be able to generate a route satisfying the sortie time constraint.

Assume the surface time of the AUV A_i is represented as S_i, then the objectives and the constraints for the UAV is given as:

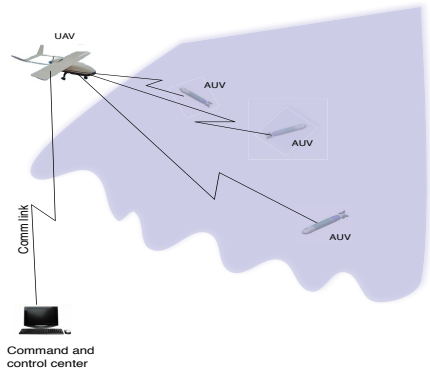

Fig. 1. Scenario of a mission where the command and control center communicates to the AUVs through UAV.

$$\text{Objective}: \quad \min \textstyle\sum_{i=1}^{N} S_i \tag{1}$$

$$\max \textstyle\sum_{i=1}^{N} \gamma_i \tag{2}$$

$$\text{Constraints}: \quad T_j \leq L, \ \forall j \tag{3}$$

$$|P_i| \geq \Delta_p \tag{4}$$

where γ_i represents the search effectiveness of choosing a path P_i, T_j is the time taken to perform the jth sortie visiting all the AUVs, L represents the time to complete a sortie and $|P_i|$ represents the magnitude of the path length that has to be of at least Δ_p units, where $\Delta_p > 1$.

The exploration time can be minimized through two quantities given by the objectives (1) and (2). The objective (1) emphasizes the fact that minimizing the surface time of the AUVs will allow the AUVs to explore for longer periods, thus enhancing the search performance. While objective (2) ensures that the paths generated by the UAV are such that the AUVs spend their search effort on exploring the unknown regions. These two objectives aim at achieving the mission quickly and efficiently.

The constraint 3 forces the UAV to meet all the AUVs and visit the base station within the Sortie time, thus enabling the personnel at the C3 have up-to-date information on the mission. The constraint 4 ensures that all the AUVs perform the exploration for a minimal path and are not idle thus aiding the objective 2. In this paper, we design mechanisms to achieve the desired objectives.

B. Approach

In order to efficiently carry out a mission it is necessary to build an architecture by which the operations at different levels take place. We use a top-down architecture where the base station is at the top level and the AUVs at the bottom level. In this architecture a chain of command exists as shown

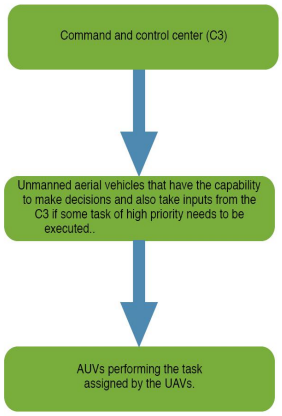

Fig. 2. Top-down architecture of the mission

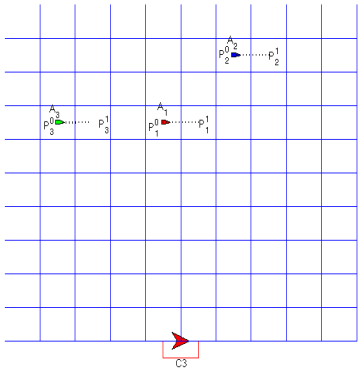

Fig. 3. A mission with three AUVs with their assigned paths and the C3

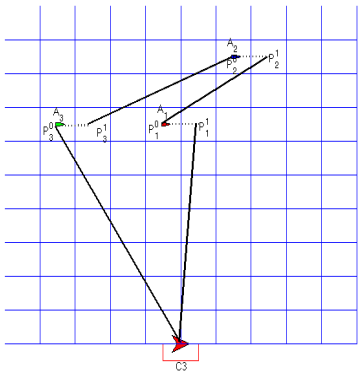

Fig. 4. The route of the UAV meeting the three AUVs and the C3

in Figure 2. To achieve the objective of minimizing the surface time, we need go determine a solution to the route planning problem for the UAV meeting the constraints 3 and 4. To realize the second objective we need to design strategies for the AUVs that maximizes the search effectiveness.

In order to carry out the mission successfully, we assume the following for the vehicles:
AUVs: These class of vehicles have limited communication and sensor ranges and can autonomously navigate towards a desired way-point. They have constant velocity and will surface when they reach their final way-point of the path or when the surface time is reached.

UAVs: UAV also has limited sensor and communication ranges and travels at constant velocity. Both classes of vehicles have kinematic constraints.

During the path generation, the UAV has to take the loiter time constraint and the surface time uncertainty of the AUVs into account. Assume the UAV meets underwater vehicle A_i at time t, then it predicts the worst possible position of the other AUVs taking their paths and designs a longest route from the C3 covering all the vehicles except A_i. The longest predicted path will determine the unused travel time, that can be used in determining the region around which the UAV can generate a path to A_i satisfying the loiter time constraint. The process of determining the path is described in the next section.

When the UAV meets the AUV, the UAV has to generate a new path for the AUV. If we assume the AUVs to operate on a continuous space then we need to take the area previously covered by the AUVs into account. This task is difficult in continuous space hence we partition the exploration space for the AUVs into a set of square cells and the UAV generates a path P_i that is a sequence of cells. The AUVs use the path and travel from the center of one cell to another.

III. Route planning

At the beginning of the mission, each agent is given a path and then deployed. Assume the path of agent A_i is denoted as P_i and P_i is a sequence of cells $P_i = \{C_i^0, C_i^1, \ldots, C_i^q\}$, where C_i^0 is the current cell of the path while C_i^q is the last cell of the path and the path is q cells length. Any cell in the path is represented as P_i^z, where $z = \{0, 1, \ldots, q\}$. Later, in this section we will describe how the paths are generated and selected. The UAV has to determine the sequence on which it has to meet the underwater agents. During this process it has to take the uncertainty of the surface location of the AUVs. For this purpose it is necessary to generate a route connecting the vehicles such that the agent meets the loiter time constraint.

A. Generating the route

Consider a situation as shown in Figure3, where the three AUVs A_1, A_2 and A_3 are initially given some paths that are shown in dotted lines with surface times S_1, S_2, and S_3 respectively. Assume that the sequence of visiting the AUVs

be A_1, A_2, and A_3. In order to determine a route, we first visit the agent A_1 at time S_1. If the agent do not surfaces at position P_i^1, then the UAV travels towards P_1^0. This method of traveling is more logical than waiting at P_1^0 till S_1 and then travel towards the P_1^1 since, the UAVs are traveling towards their assigned route and the probability of failure in completing the mission is lower than otherwise.

Assume that the UAV meets A_1 at P_1^0, then it travels to P_2^1. If we also assume that A_2 is stationed at P_2^0 as the worst case scenario, then UAV will travel to P_2^0 and from there to P_3^1. We will again assume the worst case scenario for A_3, hence UAV will travel from P_3^1 to P_3^0 and then to C3. The route traveled by the UAV is shown in Figure 4. The route generated using this mechanism of visiting the last cell of the assigned path and if the AUV does not surface by its assigned surface then move towards the agent last known location (as shown in Figure 4) enables the UAV to meet the AUV without failure.

Theorem 1: If UAV travels from P_i^q to P_i^0, then the UAV is guaranteed to meet the AUV A_i.

Proof: Let the surface time of A_i be S_i. When current time $t > S_i$, then AUV has to surface. The UAV will arrive at P_i^q at time t. Therefore, if A_i is located at P_i^q then UAV will meet A_i, otherwise A_i has surfaced at some other location $P_i^z, z < q$. Since, UAV did not meet A_i at t and $t > S_i$, it will move towards cells $P_i^{q-1}, P_i^{q-2}, \ldots, P_i^{q-q}$ in P_i. Since $P_i^z \in P_i$, the UAV will meet A_i at cell P_i^z. □

Assume that the UAV takes τ_i^a time units to reach the agent A_i at P_i^q. If $i = 1$, then τ_i represents the time taken by the UAV to reach A_1 from C3, otherwise it is the time the UAV from its previous agent in the visiting sequence to A_i. In the worst case situation, when A_i is located at P_i^0, then the additional time taken by the UAV to meet A_i along the path is τ_i^p. Therefore, the total time taken by the UAV to meet A_i is $\tau_i = \tau_i^a + \tau_i^p$. When the UAV generated the route to meet all the AUVs, it takes τ_i into account rather than τ_i^a. This process of designing the route taking the worst case scenario into account will ensure that the route always satisfies the loiter time constraint and can handle the uncertainty where the AUV may surface at P_i^z.

The predicted time taken by the UAV to visit all underwater agents at the jth sortie as shown in the Figure 4 is given as: $T_j = \tau_1 + \tau_2 + \tau_3 + \tau_b$, where $\tau_i = \tau_i^a + \tau_i^p$ and τ_b represents the time taken by the AUV to visit the base station from the last agent. If any of the agents or all of the agents surface at P_i^z instead of P_i^0 or P_i^q, then the new sortie time $T_j' \leq T_j$. Thus the process of visiting the AUVs by traveling from P_i^q to P_i^0 guarantees to that $T_j' \leq T_j$ due to uncertain surface location of A_i.

Theorem 2: Let T_j be the predicted worst case route time for the jth sortie. If an agent A_i surfaces at location P_i^z instead of P_i^0 as predicted, then the new route time is $T_j' \leq T_j$.

Proof: We will consider three positions in the visiting sequence where the change in surface location may effect. There locations are A_1, A_k, and A_N.

Assume that $A_i = A_1$ and let $T_j^- = T_j - \tau_1 - \tau_2^a$. The time taken by the air vehicle to visit A_i is $\tau_i' = \tau_i^a + \tau_i^{p'}$ and $\tau_i' \leq \tau_i$. If $\tau_i = \tau_i'$, then $\tau_2^a = \tau_2^{a'}$, therefore $T_j' = T_j$. If $\tau_i' < \tau_i$, then $\tau_2^{a'} < \tau_2^a$, therefore $T_j' = T_j^- + \tau_{1'} + \tau_2^{a'}$ and $T_j' < T_j$. Therefore, when $A_i = A_1$, $T_j' \leq T_j$.

Assume that $A_i = A_k, 1 < k < N$ and let $T_j^- = T_j - \tau_k - \tau_{k+1}^a$. If UAV meets A_k at P_k^z then the new predicted time of the jth sortie is $T_j' = T_j^- + \tau_k^a + \tau_k^{p'} + \tau_{k+1}^{a'}$. Since $z > 0$, $\tau_k^{p'} \leq \tau_k^p$ and $\tau_{k+1}^{a'} \leq \tau_{k+1}^a$, therefore $T_j' \leq T_j$.

Now considering the final case where $A_i = A_N$ and let $T_j^- = T_j - \tau_N - \tau_b$. Assume that UAV meets A_i at P_i^z, then the new predicted time of the jth sortie is $T_j' = T_j^- + \tau_N^a + \tau_N^{p'} + \tau_b'$. If, $\tau_N^{p'} < \tau_N^p$, then $\tau_b' < \tau_b$. Therefore $T_j' < T_j$, otherwise $T_j' = T_j$. Hence, the new sortie time of the jth sortie $T_j' \leq T_j$. □

Through Theorems 1 and 2 we have showed that the process of allowing the UAV to travel from P_i^q to P_i^0 ensures the UAV will meet A_i and takes the uncertainty of the AUV surfacing into account. When, UAV meets A_i, the air vehicle has to generate a path to A_i. To generate the path, the UAV has to know other AUVs location, but there is an uncertainty in the location of the other UAVs hence it is difficult to produce paths for the AUVs. We develop a path planning algorithm for the UAV that considers the worst case scenario of the AUVs and uses that information to generate a conservative path that meets the sortie time constraint.

B. Path planning algorithm

The AUVs survey the region and we discretize the region into cells. When the UAV meets A_i at time t, then the UAV has to generate a path for A_i and will take at least $t + L$ time units to visit again. So, the UAV will generate a path that takes L units of time and consists of q number of cells.

Assume that each cell is of width w and the grid consists of $N_x \times N_y$ number of cells, where N_x represents the number of cells along the horizontal axis and N_y represents the number of cells along the vertical axis. Initially, each cell $C_k, k \in \{1, \ldots, N_x \times N_y\}$ has a value $V_i(C_j) = 1$ and when A_i visits C_j, the value of the cell is updated as $V_i(C_j) \leftarrow \frac{V_i(C_j)}{2}$. The cells and their values constitutes the map of the UAV that is denoted as M. the We assume that the underwater vehicles can move is four directions as shown in Figure 5. We use these four directions because for survey purposes horizontal and vertical scanning is preferred. Therefore, the UAV can generate 4^q number of paths from the current location of the AUV. Let

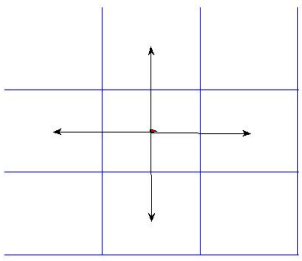

Fig. 5. The directions in which the AUV can move.

these set of paths be represented as $\mathcal{P}_i$ of agent A_i, and let each path in $\mathcal{P}_i$ is represented as P_{im}, where $m = 1, \ldots, |\mathcal{P}_i|$. Although, UAV has $|\mathcal{P}_i|$ number of paths, choosing some of these paths may not satisfy the sortie time constraints. Hence, we need to segregate those paths that satisfy Equation (3).

C. Generating feasible set of paths

In order to generate a feasible set of paths we need to predict the longest route that the UAV may take meeting all the agents except A_i. The time consumed (represented as L^-) in traveling the longest route will determine the unused time (represented as λ) that the UAV can use to select a path for the AUV such that $\tau_i + \tau^a_{i+1} \leq \lambda$. If λ is large then the UAV can generate a deep path into the unknown region otherwise the path may explore regions closer to the current location of the AUV.

Consider the example as shown in Figure 3, where three AUV are deployed with initial paths. These paths are of length $q = 1$ and $\Delta_p = 1$, that is, when air vehicle meets A_i it has to generate a path whose length is of at least one cell. Let the sortie be of L time units and the sequence in which the UAV meets the underwater vehicles be A_1, A_2, and A_3. Assume, the UAV meets A_1 at time t at P^1_1, then it has to generate the path for A_1. Let $\mathcal{P}_1$ be the set of paths generated (since $q = 1$, $|\mathcal{P}_1| = 4$) and to select a path from $\mathcal{P}_1$, it has to predict the possible location at which the agents A_3 and A_2 can be present and the longest route that the UAV may take from the base station to meet these two agents.

Since, A_1 is the first agent, the UAV determines a path from the C3 to A_3, and $A_3 - A_2$. If A_3 is located at P^0_3 then it has four paths to choose, for the next sortie. The UAV uses the map and determines the path that has the maximum value, assume path $P^{0'}_3$ be maximum value path. Similarly, if A_3 is located at P^1_3, the UAV also has four paths to choose from, and assume that it chooses $P^{1'}_3$ to be the path. Now, the UAV determines the path from the $C3 - P^{0'}_3 - P^0_3$ is the longest or the path $C3 - P^{1'}_3 - P^1_3$. Assume that $C3 - P^{1'}_3 - P^1_3$ is the longest path and it takes τ_3 time units.

Next, the UAV chooses the agent A_2, similar to A_3 assume that the UAV has to choose a path from $P^1_3 - P^{0'}_2 - P^0_2$ or $P^1_3 - P^{1'}_2 - P^1_2$ and the UAV chooses $P^1_3 - P^{0'}_2 - P^0_2$ with τ_2 time units. The total time consumed is $L^- = \tau_3 + \tau_2$ and $\lambda = L - L^-$. Now the UAV verifies if $P_{1m} \in \mathcal{P}_1$, $\forall m$, satisfies the sortie time constraint or not. If we consider path P_{11}, then the UAV determines τ^a_1, τ^p_1, and τ_b. If $\tau^a_1 + \tau^p_1 + \tau_b < \lambda$ then P_{11} is considered to be a potential path that can be selected. Let the set of paths that satisfy the sortie time constraint be $\mathcal{P}^s_1$. After verifying all the paths, the UAV determine the path $P_{1m} \in \mathcal{P}^s_1$ that has the maximum value and provides this information to the AUV. In this way, the UAV determines a path to the AUV.

After broadcasting the path to A_1, the air vehicle travel towards A_2. Assume that it meets A_2 at P^1_2. Since, UAV has met A_1, it knows the τ_1 precisely and does not predict where A_1 will traverse; as the UAV did for A_2 and A_3 when it met A_1. But, the air vehicle has not yet met A_3, hence it predicts its location as described above. Let $L^- = \tau_1 + \tau_3$ and $\lambda = L - L^-$ and the UAV determines if $\tau^a_2 + \tau^p_2 + \tau^a_1 \leq \lambda$ for each of the paths $P_{2m} \in \mathcal{P}_2$ and creates a feasible set of paths $\mathcal{P}^s_2$. The UAV determines a path that has the maximum search value and provides that path as the next path for the AUV.

Then the UAV visits A_3 and assume that A_3 is located at P^0_3. The UAV carries out the similar process and determines a path for A_3. However, as the UAV meets the agents in the sequence, the UAV is able to get better accuracy about the position of the AUVs. Hence, it can estimate the paths that satisfy sortie time constraint better. Initially, the UAV does not know about any of the other AUVs location and it has to predict all the AUV locations. When the UAV is at A_2, it knows for certain where A_1 is and uses that information. So this process is more conservative at the beginning of the sortie and liberal as the UAV meets the agents. The process of determining the paths for the agents taking the sortie time constraint is described using Algorithm III-C

The Algorithm 1 determines the path that the UAV provides to agent A_i. The UAV determines τ_k for agents which it has already met while it predicts τ_k using *wcell* and *bcell* in lines 4 and 5 in Algorithm 1. The *wcell* and *bcell* determine the path that the agent A_k may choose if located at cells P^1_k or P^0_k using getGreedyCell function. Lines 10 to 20 determine how L^- is evaluated using determineτ function. Then λ is evaluated, using which the UAV decides a path for the agent A_i.

Note that in this section, we assumed that the sequence of the agents is fixed. But, as the agents conduct the survey, it may be effective to change the order in which the UAV has to visit the agents. Since, the UAV predicts the position of the AUVs for generating the path, if it also considers the sequence into account which also has uncertainty, then the problems becomes complicated. Hence, we assumed in this paper that the sequence in which the UAV meets the agents is fixed. In future we would like to take the sequence also into account.

Algorithm 1 Algorithm to determine the paths for AUV A_k

```
k=1;
for i=1:N do
    if i > A_k then
        wcell(k)=getGreedyCell(M, P_i^q)
        bcell(k)=getGreedyCell(M, P_i^0)
    end if
end for
k= k-1;
L^- = 0; seqFlaq = 0; b = 0;
for i=1:N do
    if i ≠ A_i and seqFlag == 0 then
        L^- = L^- + τ_i
    else if i == 1 then
        seqFlag = 1;
    else
        τ = determineτ(wcell(k − b), bcell(k − b));
        b = b + 1
    end if
end for
λ = L − L^-
path = getPath(q, P_k^0, M, λ)
Return(path)
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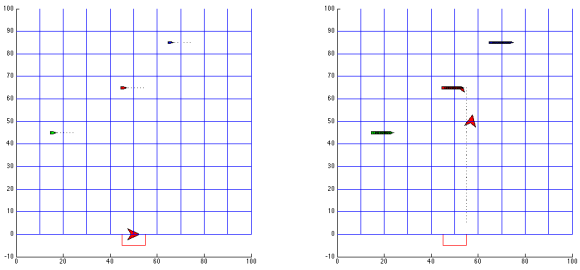


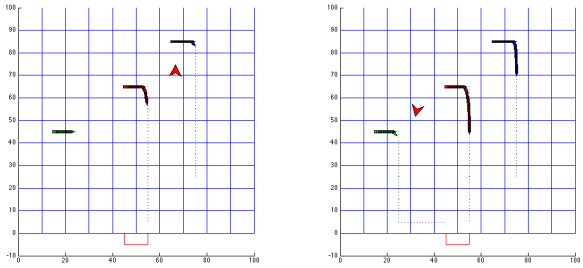
(a) (b)

Fig. 6. The AUV initial positions and when the UAV meets the AUV at $t = 14$ sec.

IV. Simulation Results

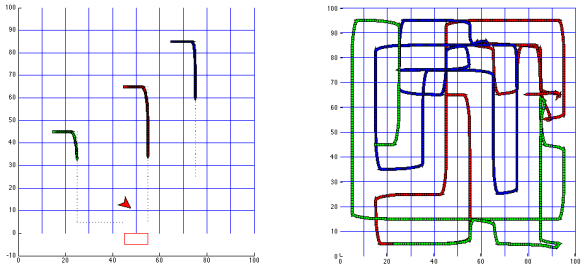
The path planning algorithm for the AUVs along with the route generation for the UAV is validated using simulations. We consider a region of 100m×100m. The velocity of the AUV is 1m/s, while that of UAV is 4m/s. We consider the width of each cell to be 10m and the communication range of the UAV is 20m. The visiting sequence of the UAV is A_1, A_2 and A_3 with sortie time constraint of 60 seconds and $\Delta_p = 1$. Since $L = 60$ and the width of the cell is 10m, we consider $q = 6$. The mission time is for 500 seconds.

The initial locations of the AUVs with initial paths is shown in Figure 6(a). The UAV is at the base station as shown by a rectangle. The UAV starts its mission to first visit A_1 and communicates with A_1 at time $t = 14$ seconds. The UAV evaluates the Δ_p path lengths for the agents A_2 and



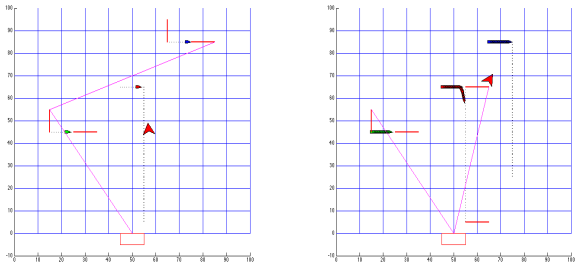
(a) (b)

Fig. 7. (a) The new path generated for A_2 at $t = 20$ sec. (b) After meeting A_2, the UAV meets A_3 at $t = 33$ sec and generates a path.

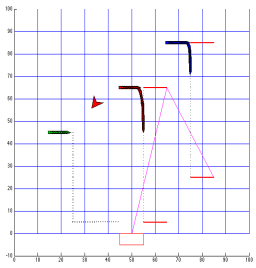


(a) (b)

Fig. 8. (a) After meeting A_3 the UAV return to the base station to provide the procured information at $t = 44$ sec. (b) The paths of the AUVs at the end of the mission.



(a) (b)



(c)

Fig. 9. (a) The predicted route for A_2 and A_3 and the path for A_1 (b) The predicted routes for A_1 and A_3 with the generated new path for A_2. (3) The predicted route for A_1 and A_2 and the generated path for A_3.

A_3 as shown in the thick red lines in Figure 9(a)). The UAV determines the longest route using the projected possible paths and evaluates λ. The λ was 24.2 and Using Algorithm 1, the UAV determines a route as shown in Figure 6(b). The same path is also shown Figure 9(a) with a thick dotted black line, taking λ into account. In the figure we can see that the AUV has received a path that is straight line. During the selection mechanism, we give higher weight to agents that have straight paths than to those paths that have turns.

After providing the path to A_1, the UAV visits the next agent in the sequence - A_2. The projected paths and the route is determined as shown in Figure 9(b). The λ was found to be 27.4. Using this information, the UAV generates a path to A_2 as shown in Figures 7(a) and 9(b). Even for agent A_2, the UAV was able to generate straight line path. After visiting A_2, the UAV continues it journey towards A_3. The air vehicle meets A_3 at time $t = 33$ seconds and determines a worst case route as shown in Figure 9(c) in magenta color. The λ was found to be 32.14 and uses this information to generate a path as shown in Figure 7(b) and the same path is shown in Figure 9(c) in a think dotted black line. The path of A_3 has has one turn. The agent A_3 cannot have straight path because the other agents A_2 and A_1 survey the cells that intersect with the straight line cells of A_3, hence those paths yield lower cost and are not selected.

After visiting all the agents, the UAV returns to the base station to provide the acquired information at time $t = 44$ seconds, as shown in Figure 8(a). The mission was to explore the entire region and the agents achieve this task in 456 seconds. The routes traversed by the AUVs is shown in Figure 8(b). During the simulation, the sortie time constraint was not violated.

V. Conclusion

In this paper, we proposed a path planning algorithm for multiple AUVs that is generated by a UAV ying over them. The AUVs have uncertain surface times and to take this uncertainty into account, we also developed a robust mechanism. The route generation mechanism for the AUV takes the sortie time constraint into account. Through simulations we have shown how the system carries out its operation.

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