# Coordination Strategies Between UAV and AUVs for Ocean Exploration

P.B. Sujit, João Sousa, F. L. Pereira

***Abstract*— Autonomous underwater vehicles (AUVs) have limited and low bandwidth communication capabilities. In order to communicate a host, they need to surface. To increase the operational period of the AUVs and decrease the surfacing time, we deploy a single Unmanned aerial vehicle (UAV) that cooperates with AUVs in performing an ocean exploration mission efficiently. A team of AUVs are deployed in the ocean and surface when their mission leg is completed. The UAV flies over the AUVs, acquires the information, and provides a new mission plan to the AUVs. 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 mission plan. Hence, the UAV has to take the uncertainty of AUV surfacing into account while generating the next mission plan to the AUV. We develop a robust route planning algorithm for the UAV and path generation algorithm 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

Recently, AUVs have been used for various ocean missions like, bathymetry, plume tracking, etc. Usually, the AUVs have low communication range and cannot communicate with the host frequently. In most of the mission, the mission control may want to interact with the AUVs periodically for situational awareness. When the base station is stationary, the AUVs have to visit the base station vicinity often, thus reducing total mission effectiveness.

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 flying 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 sprit, 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.

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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 hence they cannot communicate with the command and control center (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 with an initial path and surface time. Based on this information, the UAV will schedule a route to visit the AUVs. The UAV will collect the information from the AUVs and provides a new path with the associated surface time 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 satisfies the sortie time constraint. Additionally, during the exploration, the AUVs can meet other AUVs and change their goals. Since, the AUVs are below surface, 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, its subsequent path.

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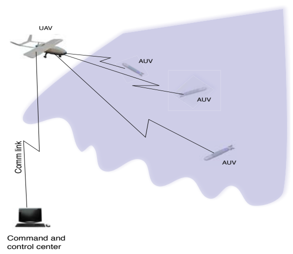
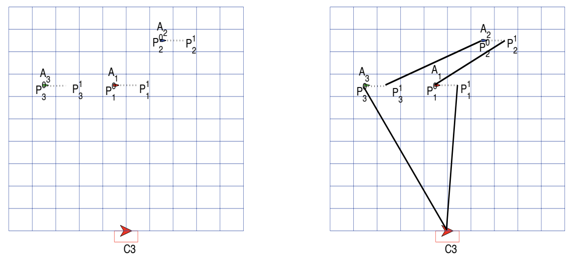



Fig. 1. Scenario of a mission where the command and control center communicates to the AUVs through UAV.




(a) (b)

Fig. 2. (a) A mission with three AUVs with their assigned paths and the C3 (b) The route of the UAV meeting the three AUVs and the C3

Sometimes the AUVs may not be able to complete the assigned task, in which case, they will surface. Hence, the UAV has to take this uncertainty into account during route planning stage otherwise, the UAV may not be able to generate a route satisfying the sortie time constraint. Assume, that 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:

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

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

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

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

where $\gamma_i$ represents the search effectiveness of choosing a path $P_i$, $T_j$ is the time taken to perform the $j^{\text{th}}$ 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 $\Delta$ units, where $\Delta \geq 1$.

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 than on explored regions. These two objectives aim at achieving the mission quickly and efficiently. The constraint given in Eq (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 given Eq. (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. To achieve the objective of minimizing the surface time, we need to 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 that the AUVs 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. While the UAV also has limited sensor and communication ranges and travels at constant velocity. Both the 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. We assume that the order in which the AUVs need to be visited are pre-assigned. Let UAV meets $A_i$ at time $t$, then it predicts the worst possible position of the other AUVs taking their paths into account 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 long. 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.

### A. Generating the route

Consider a situation as shown in Figure (2(a)), 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, UAV visits 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 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 less.

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 2(b). 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 2(b)) 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 $\tau_i^a$ time units to reach the agent $A_i$ at $P_i^q$. If $i = 1$, then $\tau_i$ 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 $\tau_i^p$. 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 $\tau_i$ into account rather than $\tau_i^a$. 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 $j^{\text{th}}$ sortie as shown in the Figure 2(b) is given as: $T_j = \tau_1 + \tau_2 + \tau_3 + \tau_b$, where $\tau_i = \tau_i^a + \tau_i^p$ and $\tau_b$ 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 route time for the $j^{\text{th}}$ sortie. If an agent $A_i$ surfaces at location $P_i^z$ instead of $P_i^0$ as predicted, then the 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 $j^{\text{th}}$ 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 $j^{\text{th}}$ 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 $j^{\text{th}}$ 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 determine a path to $A_i$. To generate a path, the UAV requires the knowledge of the other AUV locations. Due to surfacing uncertainty the UAV may not have the accurate address. We develop a path planning algorithm for the UAV that utilizes the worst case scenario of the other AUVs and generates a conservative path satisfying the sortie time constraint.

### B. Path planning algorithm

The AUVs survey the region and we discretize the region into cells. When 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

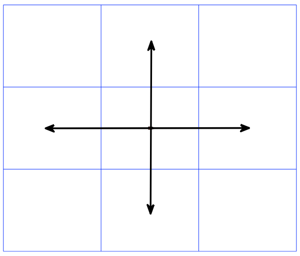


Fig. 3. The directions in which the AUV can move.

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 $M$. We assume that the underwater vehicles can move is four directions as shown in Figure 3. 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 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 $\lambda$) that the UAV can use to select a path for the AUV such that $\tau_i + \tau^a_{i+1} \leq \lambda$. If $\lambda$ 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 2(a), 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 that 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 it 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 $\tau_3$ 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 $\tau_2$ 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 $\tau^a_1, \tau^p_1$, and $\tau_b$. 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.

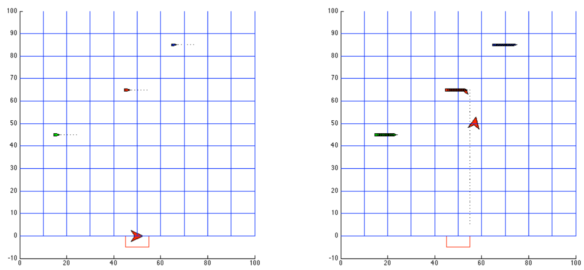
After broadcasting the path to $A_1$, the air vehicle travel towards $A_2$. Assume that it meets $A_2$ at $P^1_2$. Since, UAV has met $A_1$, it knows the $\tau_1$ precisely and does not predict where $A_1$ will traverse; as the UAV did for $A_2$ and $A_3$ when it met $A_1$. But, the air vehicles has 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 accurately. 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 1.

The Algorithm 1 determines the path that the UAV provides to agent $A_i$. The UAV determines $\tau_k$ 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 *determine*$\tau$ function. Then $\lambda$ is evaluated, using which the UAV decides a path for the agent $A_i$.

**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)
        k++
    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)
```



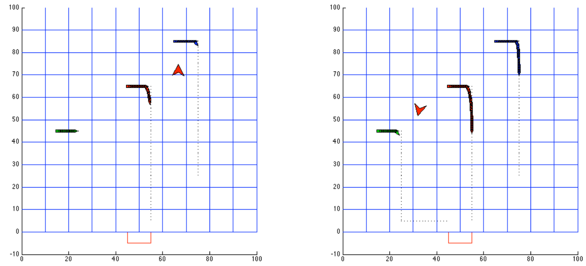
(a) (b)

Fig. 4. The AUV initial positions and when the UAV meets the AUV at $t = 14$ sec.

## IV. Simulation Results

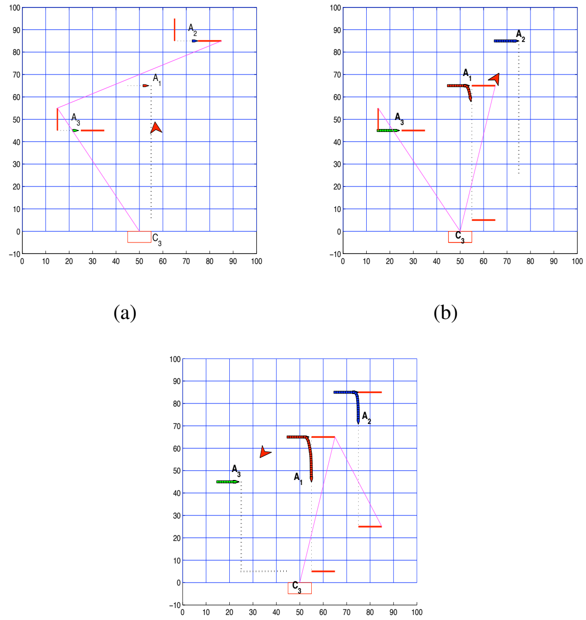
The path planning algorithm for the AUVs along with the route generation for the UAV is validated using simulations. We consider a region of 100m×100m. The velocity of the AUV is 1m/s, while that of UAV is 4m/s. We consider the width of each cell to be 10m and the communication range of the UAV is 20m. 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 4(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 $\Delta_p$ path lengths for the agents $A_2$



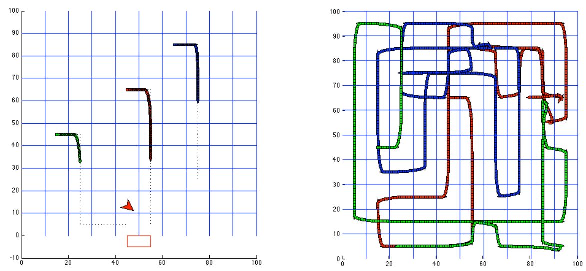
(a) (b)

Fig. 5. (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.



(c)

Fig. 6. (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) (b)

Fig. 7. (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.

and $A_3$ as shown in the thick red lines in Figure 6(a)). The UAV determines the longest route using the projected possible paths and evaluates $\lambda$. The $\lambda$ was 24.2 and Using Algorithm 1, the UAV determines a route as shown in Figure 4(b). The same path is also shown Figure 6(a) with a thick dotted black line, taking $\lambda$ 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 6(b). The $\lambda$ was found to be 27.4. Using this information, the UAV generates a path to $A_2$ as shown in Figures 5(a) and 6(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 6(c) in magenta color. The $\lambda$ was found to be 32.14 and uses this information to generate a path as shown in Figure 5(b) and the same path is shown in Figure 6(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 7(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 7(b). During the simulation, the sortie time constraint was not violated. However, the neglect time associated with the idle surfacing of the AUVs is about $20\%$ of the mission. The first AUV contributing to $4.35\%$, the second AUV contributing to $8.48\%$ and the last AUV to $7.17\%$. From these results we can see that with a fixed path length for the AUVs, the neglect time is high.

The neglect time is due to late arrival of the UAV to the AUVs. Therefore, if we develop techniques such that depending on the available time, if the UAV can generate a path length that can be varied, then the neglect time can be further decreased. In future, we will report these finding.

## V. CONCLUSION

In this paper, we proposed a path planning algorithm for multiple AUVs that is generated by a UAV flying 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. The neglect time for the AUVs is found to be $20\%$ of the mission which is high and to reduce the neglect time we need to develop new techniques for changing the path length generated for the AUVs.

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