On Reduced Time Fault Tolerant Paths for Multiple UAVs Covering a Hostile Terrain
(Short Paper)

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ABSTRACT

We present a method for finding reduced time coverage paths of multiple UAVs (Unmanned Air Vehicles) monitoring a 3D terrain represented as height fields. A novel metric based on per time visibility is used that couples visibility gained at a terrain point with the time spent to reach the point. This coupled metric is utilized to form reduced time paths by maximizing the visibility gained per unit time at every step. We compare the results of this approach with an approach that covers the terrain based on a per distance visibility metric, which reduces the sum, over distances covered by each UAV path. The comparisons show that the current method gives substantially time reduced paths albeit with an expected increase in sum over distances of UAV paths. We also show that time taken to cover the terrain based on the current metric is far less than prevalent methods that try to decompose the terrain based on visibility followed by time or time followed by visibility in a decoupled fashion. The method is further extended to provide for fault tolerance on a hostile terrain. Each terrain point is guaranteed to be seen by at-least one UAV that has not been damaged due to any calamity, shot or otherwise.

Categories and Subject Descriptors
I.2.9 Robotics : Multi-Robotics

General Terms
Algorithms

Keywords
Surveillance, Coverage, Formal models of multi-robot plans

1. INTRODUCTION

The essential motivation of this effort has been to find paths for multiple UAV such that they cover the terrain in as less a time as possible. The 3D terrain is represented as a height field over a set of points. Coverage is in the sense that each point in the terrain has been seen by one or more UAVs. The UAVs are assumed to possess discrete visibility capabilities in that they take snapshots at discrete intervals of time to cover the terrain.

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In hostile environments, more the time an UAV spends in surveillance, the more likely of it being shot or disabled. Hence, we present a method that reduces the time to cover a terrain. This effort vividly discerns reduced time coverage from reduced path coverage and further extends the comparisons to the fault tolerant scenario. Importantly, Firstly, it shows that the time taken to cover the terrain by the current approach using a coupled metric is better than existing prevalent approaches that first decompose the terrain based on visibility followed by time or time followed by distance. Secondly, it is shown that for the same number of UAVs and same starting locations, the current approach covers the terrain in much lesser time than a method that reduces the sum over path lengths. The method is then extended to provide for fault tolerance. The motivation for fault tolerance is entailed by the scenario in which some of the UAVs get disabled and all their data is lost. In such a scenario, it becomes inevitable that a terrain point is seen by multiple UAVs. We extend our method such that each terrain point is seen by at least '*k+1*' UAVs, $k < n$ (where 'n' is the total UAVs and 'k' is the fault tolerance requirement).

The problem addressed here has not been approached elsewhere in the literature we have surveyed. It is relevant to several coverage, surveillance, stealth and reconnaissance applications. In [6] a method for finding the minimum number of guards based on finding the dominating set was reported with the best approximation bound known so far. A straightforward extension of [6] to the problem attacked here would be to use the output of [6] as the initial decomposition of the terrain based on visibility (dominating set). Then further decompose the set by allotting points to clusters such that the points in each cluster are time nearest to robot path belonging to that cluster. Another extension would be to initially decompose the terrain based on time and then find the dominating set for each of the decomposed clusters based on [6]. However both these decoupled approaches perform inferiorly when compared with the approach mentioned in this effort. Other pertinent approaches [7,8] deal with stealthy path planning in presence of sentries albeit in a 2D terrain with a single robot. [9] presents a multi robot sequential approach to stealth navigation in 2D. [12] presents a robust(fault tolerant) method for multi-robot coverage in 2D . It however uses a decoupled metric (cellular decomposition) and pertains to exhaustive geographical search (sweeping). There have been approaches that have tackled coverage and formation under constraints for UAVs [10,11] but the visibility information has been neglected or simplified as circles beneath the UAVs. They fail to take into account the rich terrain information that comes from a height map or a terrain map.

2. PROBLEM FORMULATION

Apart from the terrain, also present are hostile outposts that can shoot down UAVs on spotting. It is expected that the UAVs do not travel at any height *h* above which they can be spotted by any of the outposts. The original problem is posed as follows : Given

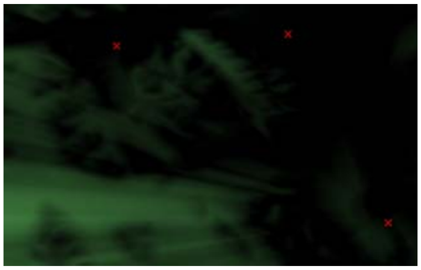


Fig. 0 : Exposure surface is in green. Greener the point the higher it is over the terrain. E need not be contiguous. Red 'X' indicate outposts. UAVs from one contiguous region cannot move into another without being spotted.

a terrain *S*, described as a set of points $S = \{p_1, p_2, \ldots, p_N\}$, where each $p_i = \{x_i, y_i, h_i\}$ with h_i denoting the terrain height at $\{x_i, y_i\}$, a set of outposts $O = \{o_1, \ldots, o_p\}$ and a set $R = \{r_1, r_2, \ldots, r_n\}$ of *n* UAVs, find *n* paths that cover *S* such that time length of each path is as reduced as possible none of the path is visible from any $o_i \in O$.

Due to presence of outposts it may not be possible to see every point of *S*. We first delineate the points that can actually be covered and then see all those with as reduced time as possible. We find the exposure surface *E* of *S* as the set of points $E = \{e_1, e_2, \ldots, e_n\}$, where each $e_i = \{x_i, y_i, z_i\}$. E characterizes the maximum height z_i above the given point p_i that an UAV can reach without being seen by any outpost . *E* at times may be composed of isolated regions $E_1, E_2, \ldots, E_q$ such that no point in E_i is connected to any point in E_j unless they pass through a point seen by at-least one outpost. For example Fig. 0 shows an exposure surface partitioned into multiple isolated regions. If the number of such partitions is more than the number of UAVs, some partitions would not be visited and points seen from them left uncovered. It needs emphasis that this inability to cover all points seen by *E* is trivial as it only arises because of the inability of UAVs to reach the isolated regions without being watched by any outposts.

3. METHODOLOGY

The algorithm operates in three phases. In the first phase, starting points for all the UAVs are determined on a contiguous exposure surface, E_c , that are sufficiently spread apart and afford high visibility. In the second phase, the UAVs build their paths through a resource allocation mechanism. A point becomes a UAV's next point of visit, when the gain in visibility for the time taken to reach that point is the best for that point-UAV pair amongst all pairings of remaining UAVs and points. The third phase contains a dynamic threshold adaptation mechanism that makes sure that a single UAV does not gobble up all the competing points. This phase ensures that the flying times for UAVs are not largely different. Essentially the second and third phase act in tandem till the terrain is covered. It is to be noted that the UAVs move on E_c to cover S_c , the set of terrain points visible from E_c .

(i) Spread Out [First Phase] : Let at some instant in this phase, the points of the set $EA = \{e_1, e_2, \ldots, e_p\}$, $EA \subseteq E_c$ be assigned to one of the UAVs in the set, $R_s = \{r_1, r_2, \ldots, r_s\}$, $R_s \subseteq R$, *p*=*s*. In other words every UAV in R_s has exactly one point from *EA* allotted to it. A point $e_e \in E_c - EA$ then becomes the staring point for any $r_r \in R - R_s$ provided that the factor $So = \Delta d V^{\beta}$ evaluates to a maximum for e_e. The factor, *So,* is called the spread out factor, *V* is the amount of terrain visibility at e_e and Δd is the change in length of the path by adding e_e to *EA*. Let the original length of the path due to points in *EA* be d_p , then the path due to addition of e_e evaluates to d_e through the edge breaking rule. This rule adds e_e to *EA* by connecting at one of the endpoints of the path or by breaking one of the *p*-1 edges, whichever of these possibilities gives the least path length increment. Then, $\Delta d = d_e - d_p$. Distance between any two points on E_c is computed by moving along E_c or under it or both, whichever is shortest.

(ii) Resource Allocation [Second Phase] : In order to decide where each UAV moves next, we define a metric 'M' to quantitatively describe the feasibility of a point $e_q \in E - EA$ as the next point from which a terrain snapshot is taken. The metric M_{PTV} , (PTV signifying per time visibility) for any such point, e_q , is defined as:

$$M_{PTV} = \frac{V(e_q)^{\alpha}}{(t_r + \Delta t_r(e_q))^{1-\alpha}} \quad (1)$$

where $V(e_q)$ is the visibility of point e_q, t_r is the total time for which UAV, *r*, has flown so far and $\Delta t_r(e_q)$ is the difference in time due to incorporation of e_q in the path of *r*. That is, $\Delta t_r(e_q)$ computes the difference in path times after and before insertion of e_q in the path of *r*. The insertion itself takes place through the edge breaking rule mentioned in section 3.1. $V(e_q)$, the visibility of point e_q, is the total number of points in S_c seen by e_q. We allocate the next point to that UAV for which (1) is the maximum among all point-UAV pairs.; This is determined as : $(e_q, r_u) = \arg\max_{i,j} M_{PTV}(e_i, r_j); \forall e_i \in E - EA, \forall r_j \in R_s$

In order to prevent any UAV from moving for an inordinately long time, we impose a threshold 'th_{ra}' , $\mathrm{th}_{ra} \geq (\Delta t_r(e_q))$, that restricts the maximum time an UAV can move in the next step.

(iii) Threshold Adaptation [Third Phase] : This happens after the resource allocation process finds a single best pairing. The UAV, r_u , to which a point was allotted in allocation phase, would have traveled for maximum time, t_{r_u} . In this phase, $\boldsymbol{r_u}$ is effectively curtailed from competing by having 't_{r_u} - t_r' as threshold for all UAVs .

$$M_{PTV2} = \frac{V(e_q)^{\alpha}}{(\Delta t_r(e_q))^{1-\alpha}} \quad (2)$$

All the future best pairings determined by (2) , are constrained such that the insertion of the allotted point to an UAV path should not increase its time length beyond t_{r_u} . This is continued till there is no such point left that can be allocated to any of the UAVs. Then resource allocation is performed again. That is , (ii) and (iii) take place in tandem till the entire terrain is covered.

3.1 The Coupling Parameters : α , β

The parameters α & β decide the amount of importance given to visibility or time. When α = 1 the terrain is decomposed purely based on visibility while α = 0 decomposes the terrain purely based on time lengths. During extensive simulations we found that any $\alpha \in (0,1)$ performs better than α = 0 or 1. Either α can be made better and better by a binary search, else if quickness is a criterion any $\alpha \in [0.5,0.6]$ is an apt choice. Since starting positions should be spread apart well, we had $\beta \in [0.25,0.35]$.

3.2 Issues with coverage in 3D

We have carried our simulations in 3D environments, although the method is equally advantageous in planar coverage too. Apart from allowing for *more realistic simulations* & *denser visibility relations* , operating in 3D had some other interesting aspects. E_c isn't planar. The surface is undulating and abrupt and does not conform to Euclidean relationships. The metric over E is non-Euclidean. Thus, adding a point to an existing path might actually decrease the path-length. More specifically, from Sec. 3, $\Delta d = d_e - d_p$ may be negative and addition of e_e will actually result in reduction of an UAV's path time length. Such points of 'negative Δt' are greedily added to the UAVs' paths first; only then metric 'M' is utilized to find the next points. Finding the shortest time distance between any two given points on E_c is not straightforward. The circumference of E_c would typically be irregular and concave. Also, E_c, although contiguous, might have several 'holes' i.e. patches over the terrain where E doesn't exist. Even if a straight line joining any two points in question lay completely below E_c , there would still be the possibility of the line running into the terrain below, if E_c is not high enough over the underlying terrain features. Thus, in order to ascertain an efficient time route between any given two points on E_c , some essential 3D path planning was also utilized.

4. FAULT TOLERANCE

The motivation for fault tolerance arises from the fact that during the course of their operation, the UAVs could get shot and their data lost. Note that by traveling below the exposure surface, we minimize the chances of an UAV getting shot. But there's still possibility of damage, shot or otherwise. It has to be noted that, within a given time, the coverage of the entire terrain is guaranteed even if k robots are shot down, if every point is viewed by least $k+1$ different UAVs by that time. So our original problem now can be stated as : Given a terrain S_c, described as a set of points $S_c = \{p_1, p_2, \ldots, p_N\}$, where each $p_i = \{x_i, y_i, h_i\}$ with h_i denoting the terrain height at $\{x_i, y_i\}$, a set of outposts $O = \{o_1, \ldots, o_p\}$ and a set $R = \{r_1, r_2, \ldots, r_n\}$ of n UAV, find n paths such that each point in S_c is visible from at least $k+1$ different paths, $k < n$; time length of each path is as reduced as possible and none of the paths is visible from any $o_i \in O$.

For achieving fault tolerance, we only needed to redefine the notion of terrain visibility. Two visibility forms were considered.

Hard Visibility : The potential visibility is defined as the number of points which have been seen less than $k+1$ times. No distinction is made between a point that has never been seen and a point that has been seen k times. This may result in pockets in terrain not seen by any UAV at all for a substantial duration of their paths, eventually leading to several UAVs inefficiently converging to those pockets. Hard visibility of a point p in S_c is :

$$V(p) = \begin{cases} 1 & ; \quad k+1-seen\_count(p) > 0 \\ 0 & ; \quad otherwise \end{cases} \tag{3}$$

seen_count(p) is the number of times p has been seen (≤ k+1). The total visibility of a point is given as : $V_T(p) = \sum_{p'} V(p')$ (4)

for all points p' that can be seen by p. Note that it is the total visibility $V_T(p)$ that appears in the numerator of (1) as $V(e_q)$.

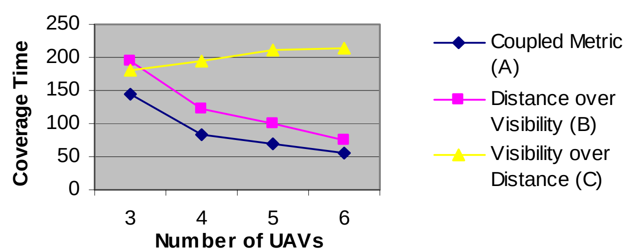
Soft Visibility : **A**lternatively , we associated a weighted metric associated with a point being seen. For a point p , it is defined as follows : $V(p) = (k+1-seen\_count(p))^{\eta k/n}$ (5)

Raising the term $k+1$ – *seen_count(p)* to k/n, weighs points with lower *seen_count* values more than those with higher values of *seen_count.* The exponential term also discerns a high value of n with lower values. When the number of robots, n, is less, the term *k+1-seen_count* is raised to a higher power than when there are larger number of robots available to cover the terrain. The factor 'η' is chosen such that it prevents an exponential increase with increase in k. The total visibility of a point is again given by (4).

5. SIMULATION RESULTS

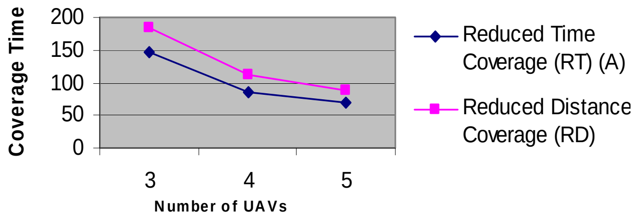
The coupled metric is empirically justified first. The coupled approach (time coupled with visibility - A) is compared with the baseline decoupled approaches (visibility followed by time - B) & time followed by visibility - C). They are extensions of [6].

Fig 1. Coupled vs Decoupled



In method B, we decompose the terrain based on visibility as given in [6]. The points output by [6] (dominating set) are then clustered such that the points in each cluster are time nearest to robot path belonging to that cluster. In 'C', we cluster the terrain based on time and find the reduced time path for the dominating set of each cluster. Results showed that method C actually gave increasing coverage times with increasing number of UAVs , indicating that 'C' may not be a suitable approach to solving this problem. The counterintuitive results are attributed to the fact that when terrain is decomposed or clustered first based on time, the visibility relations between inter terrain points are lost. When clusters are formed based on time first and visibilities considered only within the cluster, points chosen in another cluster, may see several points (sometimes all) points within the first cluster. Yet in this process one still ends up finding a tourist path for points in the first cluster by decomposing it based on visibility.

Fig 2. Reduced Time vs Reduced Distance



The coupled approach 'A' gave an average performance improvement of around 30% over 'B' and outperformed 'C'.

Fig. 2 shows the comparison between coverage times when we try to maximize the per time visibility along with adaptive threshold (RT / A) and when we try to maximize the per distance visibility (RD). UAVs have same starting positions in both methods. The difference is that 'RD' does not involve the use of dynamical threshold and it reduces the sum over path lengths using a distance measure that appears in the denominator of (1).

'RT' gave improved times of above 20% on average, over 'RD'.

Fig. 3 gives comparisons for 'Fault Tolerant' versions of 'RT' and 'RD', for 5 UAVs. The improvements were consistently around 20% with increasing fault tolerance (UAVs shot). Also, replacing the hard visibility constraint by soft visibility constraint resulted in around 7% performance improvement.

Fig 3. Fault Tolerance
Reduced Time vs Reduced Distance
Coverage for 5 UAVs

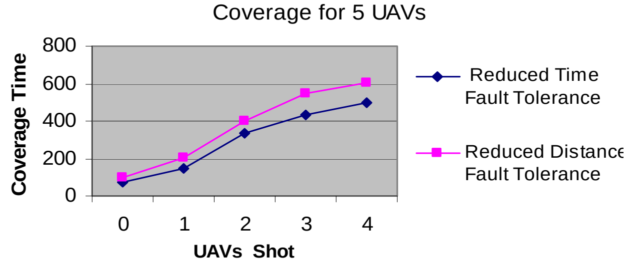


Fig. 4 shows the paths generated by the reduced time coverage method (RT / A). The simulations were carried across diverse terrains & Exposure surfaces, having various distributions of undulations, peakedness, and visibility information

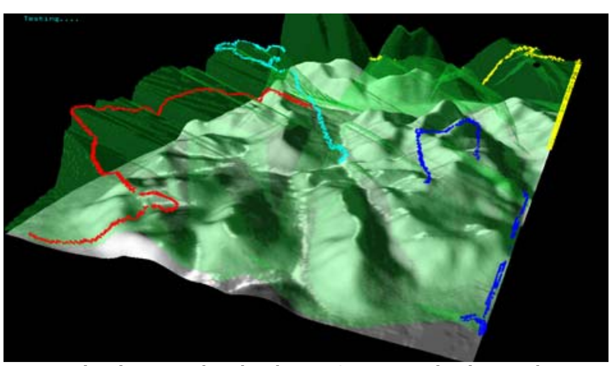


Fig. 4. Reduced Time paths taken by 4 UAVs are rendered over the Exposure Surface (Green), which itself is rendered over a typical terrain (Silver)

6. CONCLUSION

This paper has developed a framework for computing reduced time length paths for terrain coverage with multiple UAVs. It showed that the process of adaptive thresholding combined with the per time visibility coupled metric gives rise to paths with *time* lengths reduced by 20% over a method that tries to minimize the sum over path lengths of the UAVs; thereby introducing a new performance gauging comparative along the way. It is shown that the method of coupling visibility and time gives substantially improved terrain coverage times (above 25%) over prevalent methods that decompose the terrain in a decoupled fashion either based on visibility followed by time or time followed by visibility. The work extends coverage to hostile environments by introducing fault tolerance in the algorithm. Both 'Reduced Time' and 'Reduced Sum over Distances' showed similar trends, even with fault tolerance introduced. The problem addressed here has significant bearing in coverage, surveillance, stealth and reconnaissance applications, especially in 3D environments.

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