

Autonomous Networked Robots for the Establishment of Wireless Communication in Uncertain Emergency Response Scenarios

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ABSTRACT

During a disaster, emergency response operations can benefit from the establishment of a wireless ad hoc network. We propose the use of autonomous robots that move inside a disaster area and establish a network for two-way communication between trapped civilians with uncertain locations and an operation centre. Our aim is to maximise the number of civilians connected to the network. We present a distributed algorithm which involves clustering possible locations of civilians according to their expected shortfall; clustering facilitates both connectivity within groups of civilians and exploration that is based on the uncertainty of these locations. To achieve efficient allocation in terms of time and energy, we also develop a modified algorithm according to which the robots consider the graph that the cluster centres form and follow its minimum spanning tree. We conduct simulations and discuss the efficiency and appropriateness of the two algorithms in different situations.

Categories and Subject Descriptors

I.2.8 [Artificial Intelligence]: Problem Solving, Control Methods, and Search; C.2.4 [Computer-Communication Networks]: Distributed Systems

General Terms

Algorithms

Keywords

Autonomous Robots, Emergency Response, Minimum Spanning Tree, Uncertainty, Disaster Management

1. INTRODUCTION

Traditionally, during a disaster, civilians may use whistles or some form of radio-transmitting personal emergency de-

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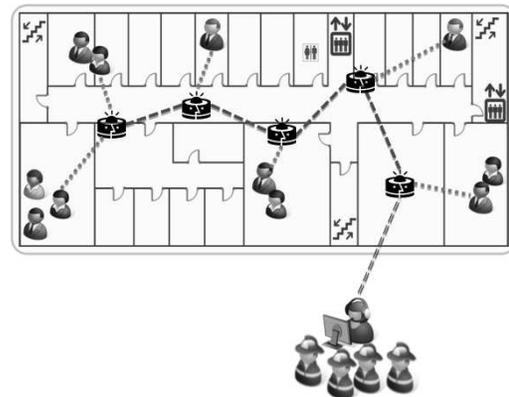


Figure 1: Example scenario: A group of robots establish communication with trapped civilians

vice to facilitate their detection. From detection to rescue, however, a long period may pass during which communication between civilians and rescuers is vital. Let us assume that the civilians carry a device with low-range wireless capabilities. A group of robots can act as wireless routers and establish a wireless network between civilians and an operation centre or a group of rescuers (Fig. 1).

Mobile robots are routinely used in disaster management operations to reach areas that are inaccessible to humans. Usually, they are designed to search for victims, inspect the structural integrity of buildings, or detect hazardous materials, but with recent advances in small-size robotics and wireless communications, emergency response robots can also be used to form ad hoc networks. The network could be used to accommodate real-time VoIP or live video-streaming connection, and environmental or biomedical sensor data, so that the rescuers can better assess the condition of the civilians and plan their own actions accordingly. These capabilities cannot be provided with the traditional whistle or personal emergency devices, but an actual network is needed.

For this emergency communication paradigm, the fact that we have a limited amount of robots means that they need to be deployed efficiently to optimise different key objectives, such as time or energy. In [7] we have introduced the novel optimisation problem of maximising the number of civilians connected to the network while maintaining connectivity between the robots and a wireless sink. We assumed a

priori known locations of civilians and we presented a centralised formulation that provides an exact solution to this problem. Here, we extend this work with a distributed algorithm that each robot runs individually and we consider uncertainty for the locations of the civilians.

Ad hoc networking for the collaboration of search and rescue robotic operations was first suggested in [12] and further investigated in [3, 9], but their authors assumed star topology with a control station in the centre of the search area, which is usually impractical during a disaster. Commonly, robotic networks are formed so that they optimise network criteria, such as fault tolerance via bi-connectivity [2], area coverage [14] and power-efficiency [6]. Nevertheless, they do not attempt to directly maximise the number of civilians that are connected to the network, which should be of central concern in an emergency. In that respect, a related problem is the autonomous search for mines according to which the robots explore an area by moving within detection range of as many mines as possible [4], but do not have to satisfy any connectivity constraint. Robotic networks for disaster management purposes have also been proposed in [10, 11], although they are used for the collaboration of a group of robots to detect a single victim and not for communication with civilians.

The rest of this paper is structured as follows: In Section 2, we start with the description of the problem at hand and our technical assumptions. In Section 3 we continue with a first distributed heuristic algorithm that can run autonomously on each robot. We evaluate it with an emergency response simulator and we identify its main weaknesses. In Section 4, we suggest a modification of the basic algorithm that addresses these weaknesses, whilst in Section 5 we conclude with our final remarks and suggested directions for future work.

2. PROBLEM STATEMENT

In this work, we address the problem of forming a wireless network of mobile robots that are deployed in a disaster area to establish communication between rescuers and trapped civilians. Our focus is on the constrained environments typically encountered in emergency response operations. Thus, instead of a continuous or grid representation of the area, we choose a graph $G = (V, E)$ representation, which is preferable for environments where the number of locations of interest to the robots is limited. A similar approach is taken in [8] where the search environment for surveillance robots is decomposed into a graph.

We assume that the civilians carry a wireless device of range R_{civ} with which they can connect to the robotic network. Also, the wireless equipment of each robot has range R_{rob} . For the sake of simplicity we use the ideal case of the euclidian distance as the connectivity criterion: a civilian c is considered to be in two-way wireless connection with a robot r if their euclidian distance is smaller than the minimum of their respective ranges, $d(c, r) < \min\{R_{rob}, R_{civ}\}$. The goal of the robots is to provide multi-hop wireless connectivity between the civilians and a wireless sink. The locations of the civilians are considered to be uncertain in the sense that only the probability distribution of the number of civilians at a particular location is known. A civilian is successfully connected to the network if it is in range with a robot that in turn maintains single-hop or multi-hop connectivity to the sink. Furthermore, we presume that the area, as repre-

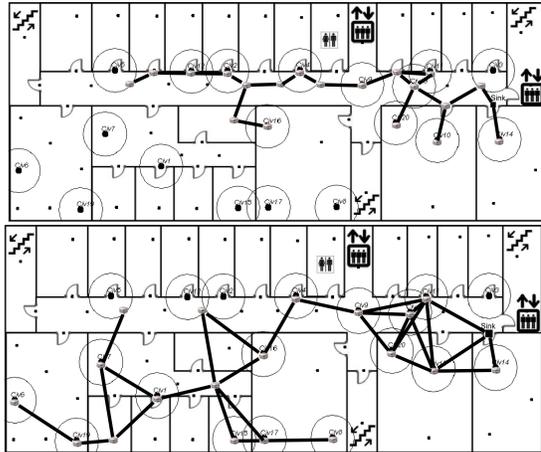


Figure 2: Robot allocations for (i) $R_{rob} = 8m$ and $R_{civ} = 4m$, (ii) $R_{rob} = 14m$ and $R_{civ} = 4m$

sented with the graph G , is known to the robots. Examples of robot allocations are shown in Fig. 2.

3. A DISTRIBUTED HEURISTIC

The above problem is particularly challenging because connectivity between the robots must be maintained, which constraints their movements and requires their efficient cooperation to achieve their common goal. We have developed a distributed heuristic algorithm with which the robots can autonomously relocate in the disaster area and take appropriate actions independently and in a timely fashion. A general flow diagram of the algorithm is shown on Fig. 3.

The problem can be significantly simplified if the locations of the civilians are clustered so that their maximum radius is smaller than $R_{rob} + R_{civ}$. In that case, by locating a robot at the centre of this cluster, the connectivity constraint is always satisfied within the cluster (Fig. 4). Clustering the locations of the civilians in a disaster scenario is not unrealistic, because the civilians are naturally clustered in groups, either because they were together when the disaster occurred or grouped with others in their effort to survive. The robot that settles on the cluster centre acts as a cluster leader and is responsible to issue an exploration announcement to all available robots in the network, which in turn explore the cluster for civilians and connect the ones that they find. Between clusters, chains of robots are formed to ensure connectivity. Within a cluster, a robot chooses to move to the location from which a maximum number of discovered and unconnected civilians will become connected.

Essentially, our heuristic approach is composed of two stages:

- Move to most attractive cluster of civilians forming a chain of robots to maintain connectivity between clusters
- Discover and connect the civilians of this cluster and move to the next one

Each of the robots greedily selects the cluster to which it is attracted the most. Several attractiveness metrics can be used such as the number of civilians in each cluster, the distance between the robot and each cluster, or a combination

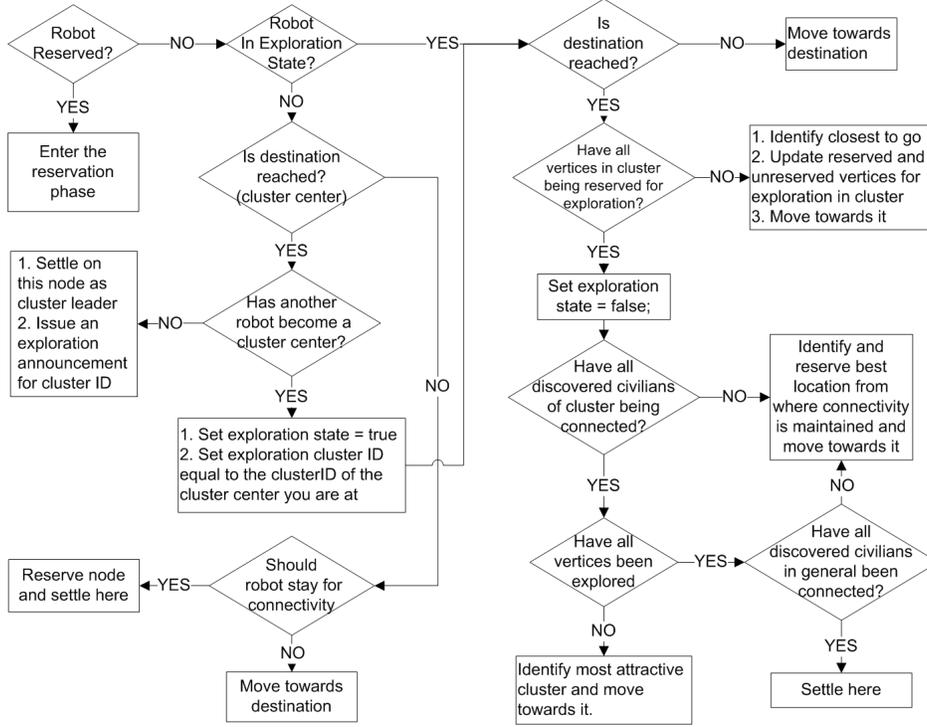


Figure 3: General flow diagram of the distributed heuristic algorithm

of the two. A good trade-off is to use the ratio of these two metrics so as to maximise the number of connected civilians and minimise the number of robots that settle to maintain connectivity between clusters.

In order to avoid having multiple robots at the same location, each one reserves the location where it intends to settle to act as a cluster leader, to connect civilians, or to maintain multi-hop connectivity between cluster leaders. A robot does not reserve a location from where it would lose connectivity, and this ensures that the final robotic network will be connected.

Since the robots do not have complete knowledge of the locations of the civilians they must move so that they first cover areas of high probability of existence of civilians with low risk. For this reason, we employ a risk measure for the number of civilians on each location, the Expected Shortfall $ES_q(u)$, borrowed from the field of financial risk management. $ES_q(u)$ shows the expected number of civilians on location u in the worst $q\%$ cases [1]: $ES_q = \mathbf{E}(X_u | X_u < m)$ where m is determined by $Prob(X_u < m) = q$ and q is the given threshold. Note that for $q = 100\%$, the expected shortfall is equal to the expected number of civilians. In practice, by using the ES_q measure, the operation centre determines the risk with which the autonomous robots will perform their exploration and connection tasks.

The introduction of uncertainty naturally leads to the need for dynamic exploration. At the beginning, the robots set a predetermined threshold l and take into account only the locations where $ES_q > l$. They cluster these locations according to the k -means clustering algorithm [13], where the value of k is the smallest feasible value for which all clusters have radius smaller than $R_{rob} + R_{civ}$. When the cluster leader issues the exploration announcement, the avail-

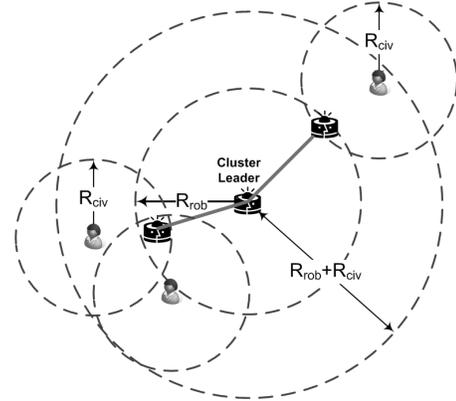


Figure 4: Connectivity is guaranteed within a cluster if its radius is smaller than $R_{rob} + R_{civ}$

able robots move to unexplored areas within the range of the cluster leader and identify locations of civilians until all have been explored. Each time a robot moves to the nearest candidate location for exploration. A necessary number of robots stay to connect these civilians and the rest continue to the next cluster centre. When both the exploration of the cluster and the connection of its civilians are completed, the cluster leader dynamically computes a new set of clusters by reducing the ES_q limit. It then informs the other robots so that they choose a new one. Thus, as soon as high- ES_q locations are completed, less probable locations start to be considered by the robots. In other words, the robots tend to move from locations of high probability of finding civilians towards less probable ones, until they connect them all.

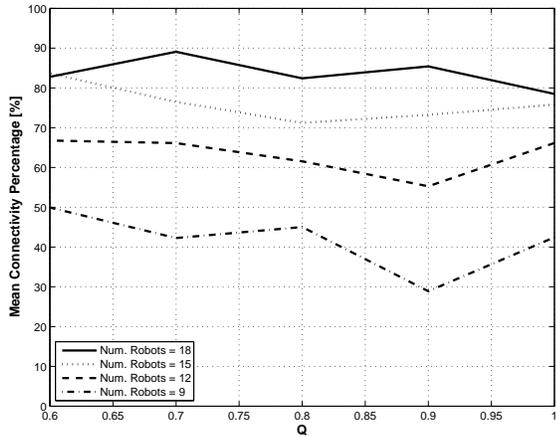


Figure 5: Percentage of connected civilians for 9, 12, 15 and 18 robots for varying q

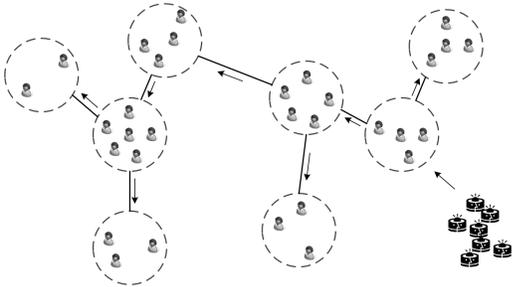


Figure 6: Illustration of the Minimum Spanning Tree formed by the clusters and the movement options of the robots

We evaluated this algorithm as the movement decision model of robot agents in the Building Evacuation Simulator [5], for $R_{rob} = 16m$ and $R_{civ} = 10m$, and varying number of robots and risk parameter q as demonstrated on Fig. 5. Apart from the trivial observation that the more the robots the more the connected civilians, it is also worth noting that generally, choosing a low risk parameter ($q=0.6$) yields better results than higher risk ones. That is because a high-risk strategy ($q = 100\%$) often leads the robots to distant locations where their expectations may not be met.

4. MST-BASED MODIFICATION

The above algorithm has two significant weaknesses. It does not allow the robots to move towards different clusters at the same time and it selects the next best cluster without planning its next steps. To address these issues we look at the clusters of the civilian locations as the vertices of an overlay graph. The robots again need to move from cluster to cluster to connect the civilians, but this time they do so probabilistically. Whenever they are to choose a new cluster, they consult the minimum spanning tree (MST) of the overlay cluster graph as seen in Fig. 6. The MST is computed by one of the robots at the beginning and is communicated to the rest of the robots. Whenever a cluster is completely explored and all its civilians connected to the network, the remaining robots need to move to a new cluster. If more than one options exist, the probability of choosing

each new direction is proportional to the estimated ratio of robots needed at the specific direction. The estimation is based simply on the expected number of civilians and the distances between clusters. By choosing probabilistically, the robots do not have to negotiate with each other, they spread more quickly in the area and essentially they decide by taking into account their future options. This is a significant improvement over the algorithm shown in Section 3, where the robots were looking for the most attractive cluster ignoring their future options. However, unlike the previous algorithm, the MST-based approach dictates the use of static clustering, since the MST will not provide dependable paths if the overlay cluster graph keeps changing.

We investigate this tradeoff with experiments for 10, 15 and 20 robots, the results of which are shown in Fig. 7. For 10 robots, the first approach presented in section 3 performs better than the MST-based one. The reason is that the number of robots is not sufficient to connect many civilians and the planning of the MST-based algorithm does not bring the desired outcome. On the contrary, for 15 and 20 robots the MST-based approach outperforms the first one since there is sufficient number of robots that can deploy effectively using the MST. We can argue that the first approach is more efficient when the number of robots is small, while the MST-based modification is better when the robots suffice to achieve high connectivity.

5. CONCLUSIONS

We have proposed the use of autonomous robots that move inside a disaster area and establish a wireless network for two-way communication between trapped civilians and an operation centre. We presented a distributed algorithm that is run on each robot so that they collectively maximise the number of civilians connected to the network by clustering possible locations of civilians. To deal with the uncertainty of the civilian locations the Expected Shortfall risk measure was employed. To achieve efficient allocation in terms of time and energy, we have also developed a modified algorithm according to which the robots consider the overlay graph of the clusters and follow its minimum spanning tree. Simulation results showed that the first algorithm is better when the number of robots is small, while the modified algorithm is more appropriate when the number of robots is sufficient to achieve high connectivity.

This work opens the way for a number of new research challenges. For example, the employment of clusters for civilian exploration and connectivity leads to interesting optimisation problems, such as the optimal exploration choices within a cluster to minimise the exploration time or the energy expenditure. Finally, robust approaches that take into account any robot or communication failures should be developed to ensure the uninterrupted connectivity of the robotic network.

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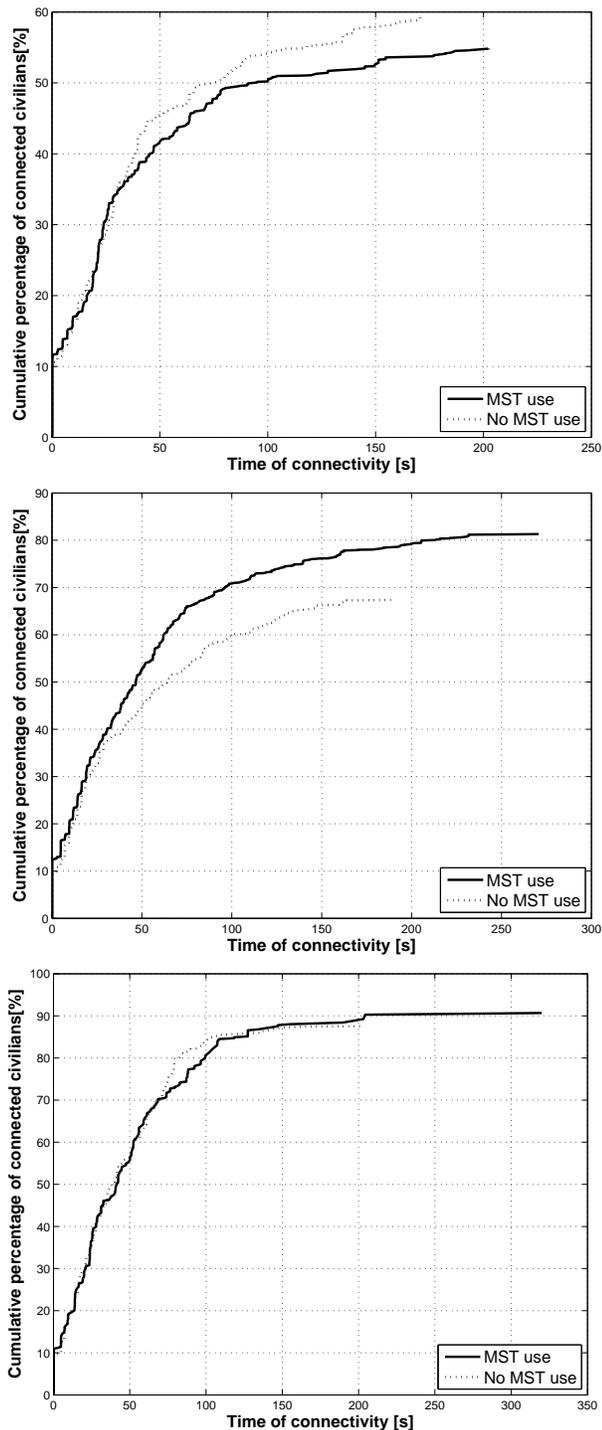


Figure 7: Percentage of trapped civilians connected against time for 10, 15 and 20 robots.

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