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Efficient Communication and Allocation of Mobile Robots in Rescue Systems

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Abstract— Several real life scenarios, such as fire fighting, search and rescue, surveillance, etc., need multiple mobile robot coordination and task allocation. Such scenarios generally include distinct regions of interest that require the attention of some robots. Multi-robot systems require efficient and accurate planning in order to perform mission-critical tasks. However, algorithms that find the optimal solution are usually computationally expensive and may require a large number of messages between the robots as the robots need to be aware of the global spatiotemporal information. In this paper, we introduce an efficient task allocation and communication approach for mobile robots. The objective function contains four basic requirements of a multi-robot system serving this purpose: control regions of interest, provide communication between robots, control maximum area and detect regions of interest. Our solution determines optimal locations of the robots to maximize the objective function for small problem instances while efficiently satisfying some constraints such as avoiding obstacles and staying within the speed capabilities of the robots, and finds an approximation to global optimal solution by correlating solutions of small problems.

Keywords— Mobile robots, Rescue systems, Emergency surveillance, Robot allocation, Distributed heuristics

I. INTRODUCTION

Emergency response scenarios involving large-scale casualties, release of hazardous substances, or the need to augment human responders will require inexpensive robots that can be deployed rapidly and whose positions can be reconfigured rapidly, with minimal human intervention. For example, sensing of concentration gradients of a substance over a region, triage support, and general situational awareness can benefit from teams of high-speed robots that are readily controlled by one operator. Commercial robots for keeping humans out of harm's way have proven to be an indispensable component of military campaigns [1,2]. However, the affordability of even one such robot is limited for local first responders, and maintenance/upkeep can be beyond the budgets of many emergency response organizations. The need for inexpensive high-speed robots, as well as for techniques to control large numbers of them in large-scale emergency response scenarios, is well-recognized.

Multi-robot systems require efficient and accurate planning in order to perform mission-critical tasks. Traditionally, during a disaster, civilians may use whistles or some form of radio-transmitting personal emergency device 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 optimize different key objectives, such as time or energy. In [3] we have introduced the novel optimization problem of maximizing 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 centralized 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.

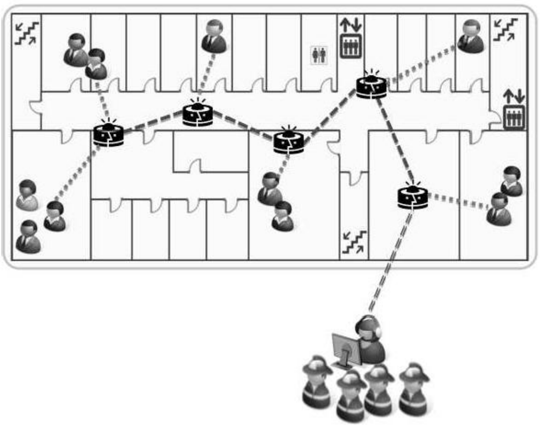

Fig. 1 Example scenario: A group of robots establish communication with trapped civilians

Ad hoc networking for the collaboration of search and rescue robotic operations was first suggested in [4] and further investigated in [5, 6], 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 optimize network criteria, such as fault tolerance via bi-connectivity [7], area coverage [8] and power-efficiency [9]. Nevertheless, they do not attempt to directly maximize 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 [10], but do not have to satisfy any connectivity constraint. Robotic networks for disaster management purposes have also been proposed in [11, 12], 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.

II. NETWORKED MOBILE ROBOT DESIGN ISSUES

There are some desired characteristics of networked robot systems such as fault tolerance, scalability, adaptively controlled coordination, reconfigurability and communication. These issues are gaining importance in parallel with the increase of complexity of high level robotic tasks. Primary design factors particular to decentralized mobile robot systems are surveyed in this section.

A. Coordination Control

Coordination between robots means that they cooperate to achieve a given common goal. The usage of multiple robots has several advantages over single robot systems: cooperating robots have the potential to achieve a given task faster than a single robot by working in parallel [13]. Complex and high level tasks cannot be accomplished by a single robot even if they have high sensing and actuation capabilities. Moreover, the overall performance of the solution for a single robot system cannot be improved, while for a network of robot unit’s coordination and cooperation enhance the efficiency of the system performance in terms of time, energy and data fusion [14,15].

B. Fault Tolerance

Any system that is not affected by a single point of failure (either in communication or in robot coordination by failure of some units) is called a fault tolerant system, which is a crucial property especially for decentralized systems such as networked mobile robots undertaking strategic and complicated tasks. Homogenous centralized systems composed of robots with the same capabilities, both hardware- and software-wise, are more fault tolerant then heterogeneous ones since the failure of a robot member can be easily compensated by other network members that are identical to the failed one. However, homogenous systems cannot adapt themselves easily to complex and high level tasks where cooperation of different skills is required. This is the primary need for the emergence of heterogeneous robot networks.

C. Scalability

Scalability is one of the desired characteristics of robot networks. A robot network control strategy can be called scalable if the performance of the system does not decay by increasing the number of robots in the network. Existing networked robot research has only focused on small teams comprised of 5–10 robots. These networks have to be extended into large multi-robot teams in order to increase the system performance and generate more robust solutions.

Although simulation studies have been considered as a valid methodology, constructing reliable scalable mobile robots for developing simple, robust, efficient and low–cost robot platforms is crucial for accomplishing scalable real world robotic research [16–19].

D. Holonic Reconfigurability

Robotic researchers have always shown interest towards reconfigurable and scalable distributed robotic structures. Holonic reconfiguration was the early attempt in reconfigurable and scalable networks. Holons, introduced by Hirose, usually work in cooperation with other holons of a group, forming a modular flexible system [20]. The basic property of a system having a holonic architecture is that it is built from simpler components working in a colony so as to achieve a global behavior of a higher order [20,21].

E. Communication

Communication between robot units in the network is essential for real world applications because of situational awareness. In particular, cooperation and coordination in networked systems requires a robust communication ability to accomplish a given mission accurately. Communication methods in networked robot systems are classified as implicit communication, also called stigmergy, and explicit communication. The effect of communication on the system performance is shown in a variety of works; non-verbal communication efficiency in human–robot teamwork [22], target search task performance evaluation with no communication, reflexive and deliberative communication [23], communication range effects on robot search task on two distinct search algorithms which are spiral search and informed random search [24]. Çayırpunar *et al.* [24] developed a cooperative search method in complex environments and shows the effect of communication in the target search mission on real experimental setups. In these experiments, e-puck robots try to find a hidden object via explicitly communicating with their local neighbors. They concluded that the system performance improves with increasing communication range, in terms of the task accomplishment time. Robots can exchange information about the other robots' internal states and environmental conditions via explicit communication protocols, which also improves the system performance. Meanwhile, this yields a considerable computational burden to the robot team and these systems may not be robust to single point failures.

III. 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 Rciv with which they can connect to the robotic network. Also, the wireless equipment of each robot has range Rrob. 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 if their euclidian distance is smaller than the minimum of their respective ranges, $d(c, r) < \min\{Rrob, Rciv\}$. 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 represented with the graph G, is known to the robots. Examples of robot allocations are shown in Fig. 2.

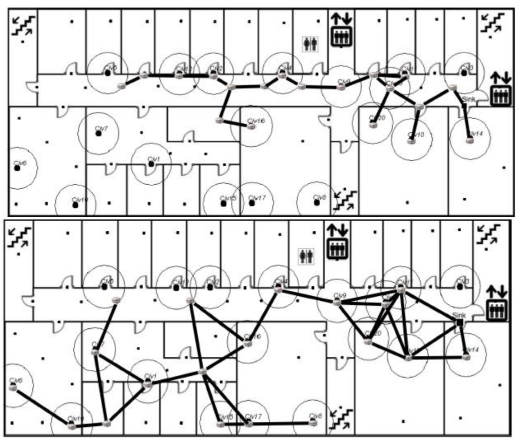

Fig. 2 Robot allocations for (i) Rrob=8m and Rciv=4m
(ii) Rrob=14m and Rciv=4m

IV. 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 Rrob+Rciv. 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 robots 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

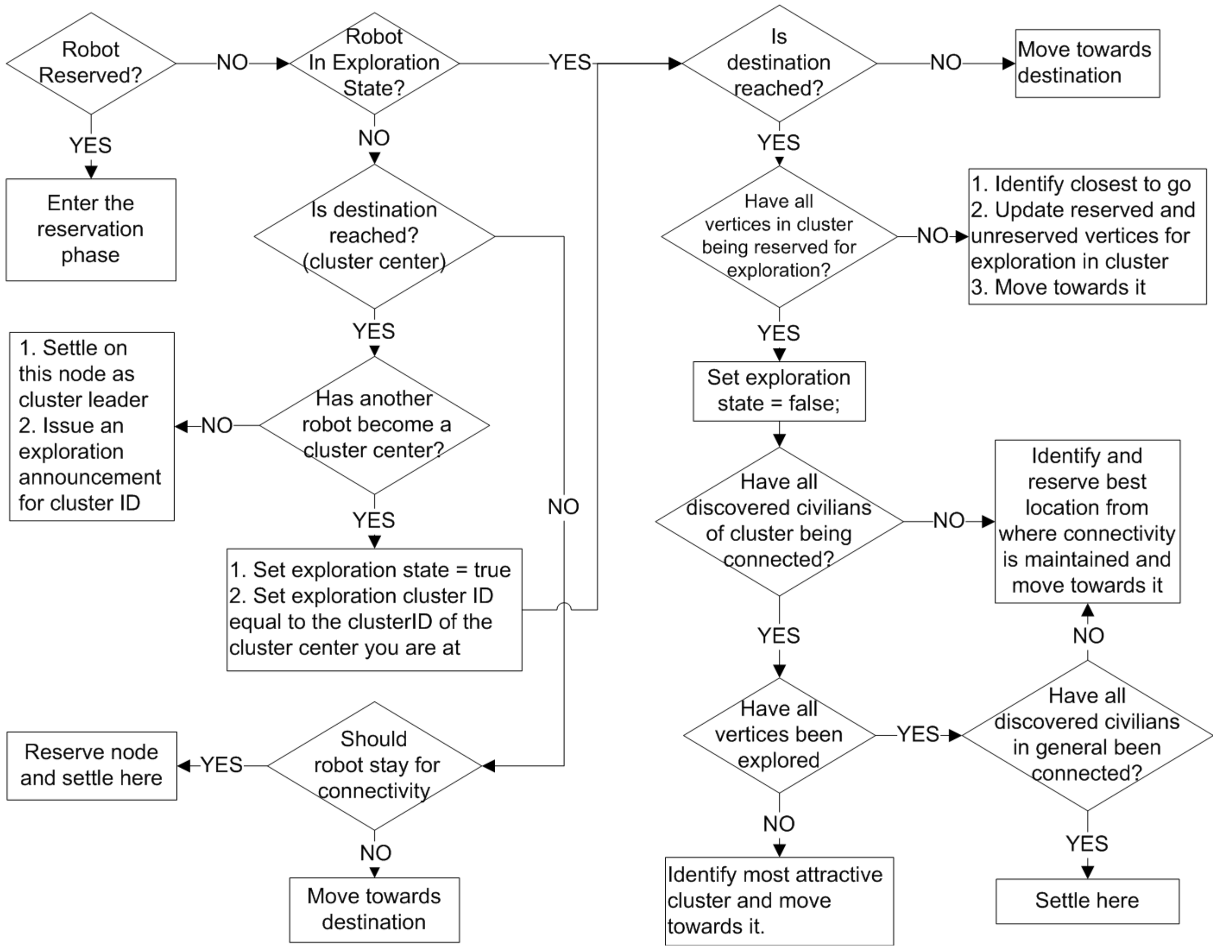

Fig. 3 General flow diagram of the distributed heuristic algorithm

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 of the two. A good trade-off is to use the ratio of these two metrics so as to maximize the number of connected civilians and minimize 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 ESq(u), borrowed from the field of financial risk management. ESq(u) shows the expected number of civilians on location u in the worst q% cases [25]: ESq = E(Xu|Xu < m) where m is determined by Prob(Xu < 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 ESq 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 ESq > l. They cluster these locations according to the k-means clustering algorithm, where the value of k is the smallest feasible value for which all clusters have radius smaller than Rrob + Rciv. When the cluster leader issues the exploration announcement, the available 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.

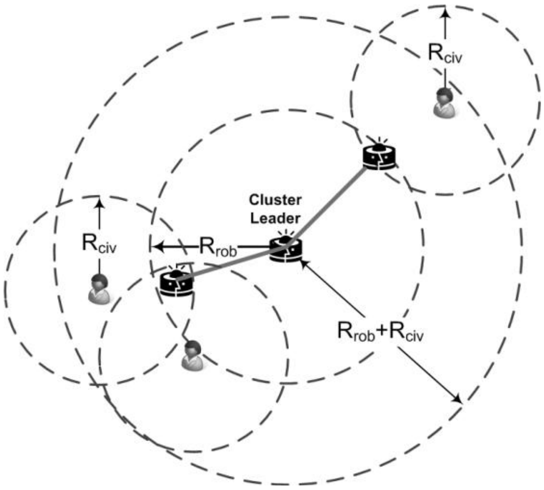

Fig. 4 Connectivity is guaranteed within a cluster if its radius is smaller than Rrob+Rciv

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 ESq limit. It then informs the other robots so that they choose a new one. Thus, as soon as high-ESq 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.

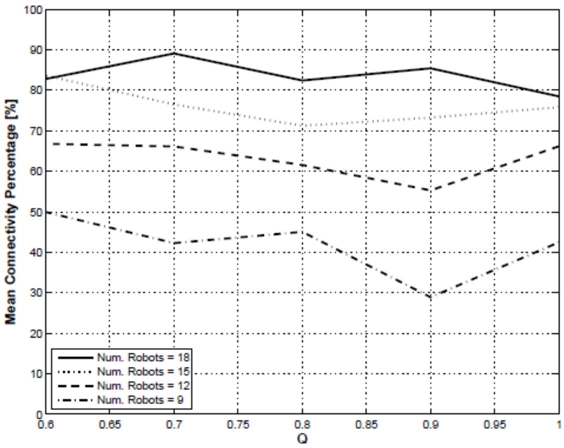

Fig. 5 Percentage of connected civilians for 9, 12, 15, and 18 robots for varying *q*

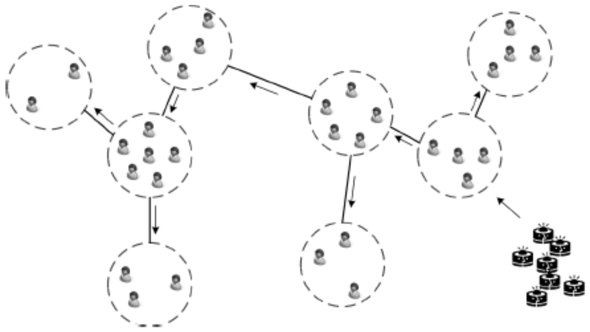

Fig. 6 Illustration of the minimum spanning tree formed by the clusters and the movement options of the robots

We evaluated this algorithm as the movement decision model of robot agents in the Building Evacuation Simulator, for Rrob = 16m and Rciv = 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.

V. 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 maximize 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 optimization problems, such as the optimal exploration choices within a cluster to minimize 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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