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Finding the optimal location and allocation of relay robots for building a rapid end-to-end wireless communication

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ABSTRACT

This paper addresses the fundamental problem of finding an optimal location and allocation of relay robots to establish an immediate end-to-end wireless communication in an inaccessible or dangerous area. We first formulate an end-to-end communication problem in a general optimization form with constraints for the operation of robots and antenna performance. Specifically, the constraints on the propagation of radio signals and infeasible locations of robots within physical obstacles are considered in case of a dense space. In order to solve the formulated problem, we present two optimization techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Finally, the feasibility and effectiveness of the proposed methods are demonstrated by conducting several simulations, proof-of-concept study, and field experiments. We expect that our novel approach can be applied in a variety of rescue, disaster, and emergency scenarios where quick and long-distance communications are needed.

1. Introduction

In a disaster area, where previously established networks are destroyed, one of the top priorities of search-and-rescue missions is regaining or rebuilding a communication link between the base and rescuers as quick as possible in order to secure the safety of both rescuers and survivors [1]. A group of autonomous relay robots carrying wireless communication devices can be deployed to rapidly build the wireless connection between two end nodes, and thus enabling end-to-end communication[1] [2]. This would effectively give firefighters, rescuers, and first responders the ability to communicate with command center and search the best evacuation route as shown in Fig. 1 [3]. Since an immediate and optimal deployment of relay robots plays a pivotal role in such an event, we tackle these deployment problems in this paper.

Given two endpoints and basic map information such as the physical location of buildings on a plane, multi robots carrying wireless devices can be deployed to relay a communication signal between two points in a cascaded communication chain. We assume that robots are initially located around one of the points, e.g., a command center, and an initial communication between the end points does not exist. With a rapid establishment of a wireless backbone is our primary goal as a robot deployment planner, the research aim is: *How do we find optimal locations and allocations of the robots to construct the end-to-end communication promptly and efficiently?*

For effective deployment of relay robots, we divide the deployment problem into two fundamental sub problems - *Location* and *Allocation*, which needs to be solved simultaneously. The *Location* problem consists of finding optimal

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[1] Throughout this paper, the term “end-to-end network” or “end-to-end communication” refers to the communications link between two end nodes, e.g., a command center and an end (lead or exploring) node.

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Fig. 1. A firefighter linked to command center through a set of relay robots.

locations, where networked robots need to be located to relay radio signal between two end nodes in the quickest time. The *Allocation* problem consists of finding which robots need to be assigned to each location.

The problem of building communication bridge on a plane is classified as NP-hard problem [4]. The *Location* problem is approachable with continuous variables and the *Allocation* problem is approachable with discrete variables. Thus, an optimization problem can be formulated as a combinatorial problem. In this research, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are employed to solve the optimization problem with evolutionary heuristic methods.

The primary contribution of this study is introducing a simple and effective way of applying evolutionary algorithms to robotic sensor deployment problems. Since we consider most constraints of end-to-end communication problem that can be observed in the real world, solutions found by the proposed algorithms are highly feasible and robust. In addition, as the proposed algorithms are evolution based, they are easy to add or remove robots (i.e., it is scalable), which is very important in that they can be applied to a wide range of environments. We expect that this research will play a significant role in creating a rapid and advantageous communication bridge for complex environments and will stimulate an active and vibrant research field where robotic sensor network related problems could be approached with or solved by evolutionary algorithms.

The remainder of this paper is organized as follows. First, in Section 2, we describe related works; the end-to-end communication, *Location* and *Allocation* problems, and our previous research. In Section 3, we address the basic concept of an end-to-end wireless network and formulate the fundamental problem to be solved. Also, we present additional constraints to deal with the establishment of the network in more complex environments. Then, we present two applied optimization algorithms in Section 4. Simulation results and proof-of-concept study in Section 5, and field experiments in Section 6 are shown to verify the performance of the proposed algorithm. Lastly, conclusions and future works will be summarized in Section 7.

2. Related works

2.1. End-to-end communication

Due to the high mobility and flexibility of operating mobile robots, those such as aerial vehicles and mobile robots have been widely used to establish or maintain ad hoc networks in field of robotics [5]. For example, a mobile unit can be used to form a desired shape of network if a wireless device is mounted on the mobile unit. Then, the mobile unit turns out to be a relay or router. Task of building end-to-end communication can be divided into two categories depend on types of node; dynamic end node and static end node.

First, building end-to-end communication for dynamic end nodes can be achieved by deploying a team of leader-follower robots in a convoying arrangement [6–10]. In this way, multiple robots can be used, and only the leader requires navigation capabilities to create the network while followers do not require any planning. Alternatively, they need to follow the leader or the precedent robot. Therefore, this approach is more suitable for dynamic environments where situation can be frequently changed because it is performed based on reactive approaches rather than pre-planning.

Second, building an end-to-end communication for static end nodes can be realized by planning final robot positions prior to deployment [11–15]. This planning should be designed to optimize the communication link, and thus this approach is suitable for a static environment rather than dynamic environments. This is also useful for cases where a rapid establishment of the network is required, because this approach does not require a search task.

Besides, as the extension to an end-to-end communication study, maximizing coverage area of mobile robot network [16], a distributed algorithm for improving coverage [17] and an algorithm for coverage [18,19] have been studied. While these studies focus on an establishment of the optimal network, we mainly focus on building an end-to-end communication as quick as possible because this research considers that sending a group of robots out an emergency situation where recovering or rebuilding network connection has to be a top priority.

2.2. Location and Allocation problems

In this paper, we define a problem of finding optimal positions of robots as a series of *Location* and *Allocation* problems. In order to solve *Location* and *Allocation* problems, many of researches in various areas such as industrial engineering for operation research [20–24] have been done. However, our approach can be novel because we consider this problems as a combination of the robot and sensor network deployment.

The problem of *Location* and *Allocation* is also known as the *multi-weber* problem or the *p-median* problem. For example, [21] tackles finding optimal locations of facilities and allocation of customers to the facilities so that the total distance customers moved and the operating expense is minimized. With consideration of obstacles and some