Self-Optimizing Algorithms for Mobile Ad Hoc Networks based on Multiple Mobile Agents

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Abstract: This paper presents algorithms that form optimal connecting configurations for Mobile Ad Hoc Networks (MANETs). MANET is a computer network that is dynamically formed by autonomous mobile nodes. Today, the communication network is one of the most important infrastructures. When it is lost by either natural or accidental disaster, the recovery of the communication network should be one of the first priorities. We are proposing a way of constructing an extemporized communication network on the spot by a herd of mobile robots that communicate by wireless link. The networks we are considering are formed by multiple relay robots; therefore the algorithms are naturally distributed ones and executed by the herd of relay robots. The relay robots move cooperatively but without any central control. In order to collect and to distribute enough information to coordinate the behaviours of participating relay robots, we employ mobile software agents that we have developed and succeeded in using many applications. There are a number of multi-robot systems that take advantage of MANET, and look for efficient use of relay robot while maintaining connectivity. Our study contributes this line of investigation. The numerical experiments show that our algorithms provide optimal configurations in certain cases.

1 INTRODUCTION

In the modern society, the communication network is one of the most important infrastructures. When it is lost by either natural or accidental disaster, the recovery of the communication network should be one of the first priorities. Under such an assumption we have conducted a project that constructs an extemporized communication network on the spot by a herd of mobile robots that communicate by wireless link. They are expected to form a Mobile Ad Hoc Network.

Mobile Ad Hoc Network (MANET) is a computer network that is dynamically formed by autonomous mobile nodes. Such mobile nodes are connected through wireless links without relying on any central controller or established infrastructure. The participating mobile nodes can freely and dynamically self-organize into arbitrary and temporary network topologies.

The application we have in our mind is constructing a temporary communication network in a contaminated area polluted by radioactive substances or dangerous gas because of natural or accidental disaster that prevent human activities. Under such conditions, constructing MANET by using a multi-robot system should be a natural choice. It may be desirable for us to connect arbitrary two points. For example, we may want to connect the control centre of a nuclear power station and a reactor with problems by using scattered mobile robots with minimum costs so that robots can work as long as possible without human intervention.

A multi-robot system consists of a large number of homogeneous robots that have limited capacity, but when combined into a group, they can generate more complex behaviours (Parker, 2008). In multi-robot systems, robots communicate with each other to achieve cooperative behaviours. There are three major advantages of multi-robot systems over single robot systems (Stone and Veloso, 2000) (Yasuda and Ohkura, 2005). The first is parallelism; a task can be achieved by autonomous and asynchronous robots in a system. The second is robustness; this is

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realized through redundancy. The system can have more robots than required for a certain task. The third is scalability; a robot can be added to or removed from the system easily. We have taken advantage of these properties.

We have implemented several multi-robot systems such as cooperatively assemble themselves at energy-wise optimal locations (Kambayashi et al., 2012), and serialize themselves (Shintani et al., 2011). For all the multi-robot systems, we have designed and implemented multi-agent systems that control the robot systems. A control system based on multiple software agents can control robots efficiently. Multi-agent systems introduced modularity, reconfigurability and extensibility to control systems which had been traditionally monolithic. It has made easier the development of control systems on distributed environments such as multi-robot systems.

On the other hand, excessive interactions among agents in the multi-agent system may cause problems in multi-robot environments. In order to mitigate the problems of excessive communication, we have developed mobile agent methodologies for distributed environments (Kambayashi and Takimoto, 2005). In a mobile agent system, each agent can actively migrate from one site to another site. Since a mobile agent can bring the necessary functionalities with it and perform its tasks autonomously, it can reduce the necessity for interaction with other sites. In the minimal case, a mobile agent requires that the connection is established only when it performs migration (Binder et al., 2001).

We have achieved energy saving multi-robot systems through multiple mobile software agents that migrate in a herd of mobile robots to collect information about them, as well as drive the minimum number of them based on the collected information. Moving software agents instead of physical robots greatly save energy consumption.

In this paper, we propose a multi-robot system that employs MANET through which software agents migrate. By using the software agents, the relay robots in MANET can cooperatively coordinate themselves into optimal locations to make the shortest communication route with a minimum number of relay robots. We propose two algorithms to form a optimal route via relay robots, and discuss the pros and cons of the two.

The structure of the balance of this paper is as follows. In the second section, we describe the background of our research. In the third section, we present the two algorithms to form optimal configurations. In the fourth section, we present the numerical experiments through simulations to demonstrate the effectiveness of our algorithms and discuss our observations. In the fifth section, we conclude our discussions and suggest future work.

2 BACKGROUNDS

There are a number of multi-robot systems that take advantage of MANET. Heo and Varshney considered the sensor coverage problem for the deployment of wireless sensor networks (Heo and Varshney, 2003). They have proposed a distributed algorithm for the deployment of mobile nodes, not necessary autonomous robots, to cover a certain region by limited number of nodes and limited communication range. They focus on the sensor coverage problem and did not discuss the multi-hop relay problem of ours.

Voyles et al. introduced a new multi-hop protocol (Voyles et al., 2009). As we have done, they used Bluetooth ad hoc wireless communication for use in sparse, highly volatile networks by multi-robot system. They developed a hybrid routing protocol, i.e. proactive and reactive routing protocol, demonstrated a high data transfer rate and showed low recovery time in various cases. Their protocol could cope with frequent network failures in not-so-good network topologies. The authors claimed that their protocol provided the best compromise between latency and throughput for sparse highly volatile networks. They, however, acknowledged that routing protocols solve only part of problems in multi-robot systems. They were aware of the need for methodologies for maintaining efficient connectivity of nodes while simultaneously achieving task goals. We believe our humble study can contribute this line of investigation. We are not aware of any study of creating optimal route with minimum number of relay robots.

As Voyles et al. have done, we have employed Bluetooth ad hoc wireless communication called scatternet (Cuomo et al., 2004). A scatternet is a number of interconnected piconets that supports communication between Bluetooth-equipped devices. Figure 1 shows a scatternet that consists of three piconets. A piconet is the type of connection that is formed between two or more Bluetooth-equipped devices. Since a piconet consists of one master node and at most seven slave nodes, it can only handle at most eight devices. Therefore a considerably large scale ad hoc net must be formed by using scatternet. Scatternets can be formed when a member of one piconet (either the master or one of the slaves) elects to participate as a slave in a second, separate piconet. The device participating in both piconets can relay data between members of both ad hoc networks.

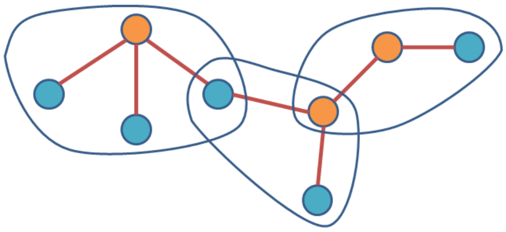


Figure 1: Three piconets construct a scatternet.

One of the most closely related previous researches is the "chain based path formation" of swarms of robots conducted by Nouyan and Dorigo (Nouyan and Dorigo, 2006). The concept of robot chains stems from Goss and Deneubourg (Goss and Deneubourg, 1992). A similar system was implemented by Drogoul and Ferber (Drogoul and Ferber, 1992). As these previous approaches, in the system of Nouyan and Dorigo, every robot in a chain emitted a signal indicating its position in the chain, and they utilized the "cyclic directional patterns" in order to give the chains directionality.

Unlike our proposing system, their purpose of the research was investigating the capabilities of the swarm robots that were self-organizing into chains from random positions. They have found the impact of the two parameters which determine the rate at which a robot aggregates into, and disaggregates from, a chain. They have also shown that their system scales quite well with respect to the number of robots. They, however, did not claim any particular application for that chain forming, and they stated that they were interested in studying control algorithms that allow swarm of robots to form arbitrary shapes instead of serializing.

Our purpose, on the other hand, is improving an already established MANET connection with arbitrary two points with scattered mobile robots with minimum costs.

3 ALGORITHMS

The basic concept of optimizing the arrangement of mobile robots that relay ad hoc communication is to serialize the relay robots, and then to make redundant robots leave from the relay line as shown in Figure 2.

In order to make the relay robots move to form a line, it is necessary to obtain the vector value of each pair of adjacent robots. In order to accomplish this we employ a mobile software agent to travel from the source robot (robot A) to the destination robot (robot E) as shown in Figure 3.

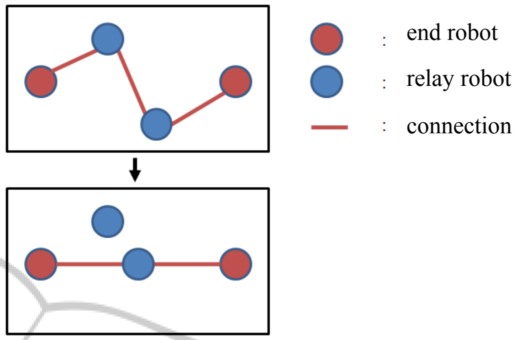


Figure 2: Optimal configuration.

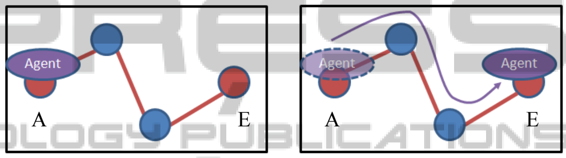


Figure 3: The mobile agent is created at the source robot and travels toward the destination while obtaining the vector values.

Assume robot A is communicating with robot E by using ad hoc wireless communication with several relay robots. We also assume that both of them are engaging some tasks at their current locations and cannot move. Each time the mobile software agent migrates one robot to another robot (one hop); it checks the source robot through the camera on the destination robot and obtains the vector value from the destination to the source robot. Therefore, when the mobile agent arrives at the final destination robot (robot E), it has a sequence of vector values of all the pairs of adjacent relay robots.

Upon arriving at the destination robot, the software agent goes back the same route from the destination robot to the source robot, and gives the corresponding vector values to all the relay robots as shown in Figure 4. When the mobile agent distributes the vector value to each corresponding relay robot, it adjusts the vector value so that it points to the destination node robot. When the mobile agent arrives at the source robot where that agent was created, and the agent completes distributing all the vector values it has collected during the forward travel, its task is over and vanishes.

Figure 5 shows the vector values given by the mobile agent. Each letter represents the end robots and relay robots. Robot A is the source robot where the mobile agent was created and E is the destination robot. Since robot A and E cannot move, we want to make other robots B, C, and D move to form a straight line (optimal formation) to relay the ad hoc connection.

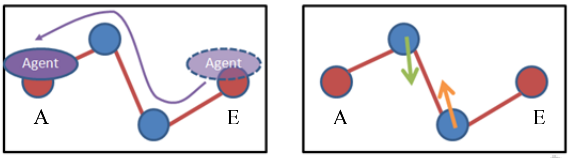


Figure 4: The mobile agent distributes the vector values to all the relay robots.

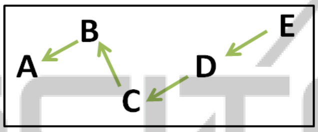


Figure 5: Each robot has its vector value.

3.1 Algorithm 1: Move All the Participants

The moving algorithm makes all the participating robot that are relaying the communication from the source robot, i.e. robot A, to the destination, robot E, move to form a straight line from A to E. The algorithm consists of two phases. The first one is to form a straight line, and then the second phase finds redundant relay robots.

The idea is as follows. As shown in Figure 6, the desired straight line is AE; therefore we want to move the relay robot at point B to point B'. In order to achieve this requirement, we need to obtain the vector value $\overrightarrow{BB'}$ as follows:

$$\overrightarrow{BB'} = \frac{n\overrightarrow{BA} + m\overrightarrow{BE}}{m+n} \tag{1}$$

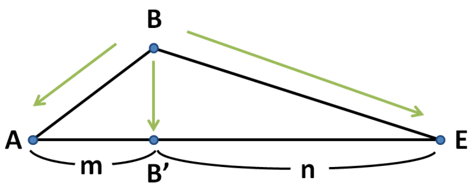


Figure 6: The first phase; a relay robot moves to an internal dividing point.

Since $\overrightarrow{BA}$ and $\overrightarrow{BE}$ are known values, and m is the number of hops from the source point of robot A and n is the number of hops from the destination point of robot E, it is straightforward to calculate the vector value $\overrightarrow{BB'}$.

When applying this algorithm to the relay robots, all the relay robots move to the internal dividing points on the line AE, and distances between adjacent robots are shorten. Then some redundant robot must be produced. Redundant robots means two or more relay robots exist in a range of ad hoc connection. When a relay robot recognizes it is redundant itself, it tries to leave from the connection. We describe the leaving algorithm in Section 3.3 in detail. After successfully forming a straight line in the first phase, the robots on the connection sequence start to eliminate further redundancy in the second phase as follows.

The second phase begins by dividing the relay robots into roughly two groups, the left half and the right half as shown in Figure 7.

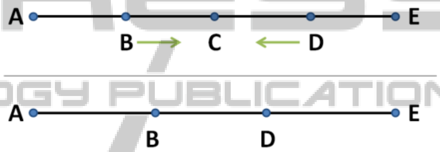


Figure 7: The second phase; a robot in the left group moves toward right-hand side and a robot in the right half group moves toward left-hand side to find a redundant robots.

The relay robots in the left half group move toward the right hand side as far as they can maintain their connection to the adjacent relay robots, and the relay robots in the right half group move toward the left hand side also as far as they can maintain their connection, so that some relay robots can have new and redundant connection.

When new connection is produced and a relay robot becomes redundant, it tries to leaves from the connection. We describe how a redundant relay robot departs from the connection in section 3.3.

3.2 Algorithm 2: Move Minimum Number of the Participants

Since moving all the participating relay robots are rather inefficient, it is desirable if we can move minimum number of robots to form the same straight line. For this purpose, we extend the algorithm 1 as follows. First, we number all the relaying robots and if we have more than twice as many robots as we need to construct a straight line connection, we only move the even numbered robots. If we do not have such enough robots, we choose the least necessary number of robots from the source robot side, and move them.

Since we know the straight line distance from the source robot to the destination robot, it is straightforward to calculate the least number of robots to maintain the connection.

3.3 Relay Robot's Leaving from the Connection

As described in the previous sections, when we have succeeded in forming a straight line connection of the relaying robot, we have some redundant robots. In this section we describe how to find the redundant relay robots, and how to make them leave from the connection.

When the relay robots move based on the syntheses of vector values described in the previous section, some of them find new connections. Figure 8 shows the situation that moving relay robots (blue ones) find a new connection, and one of them becomes redundant.

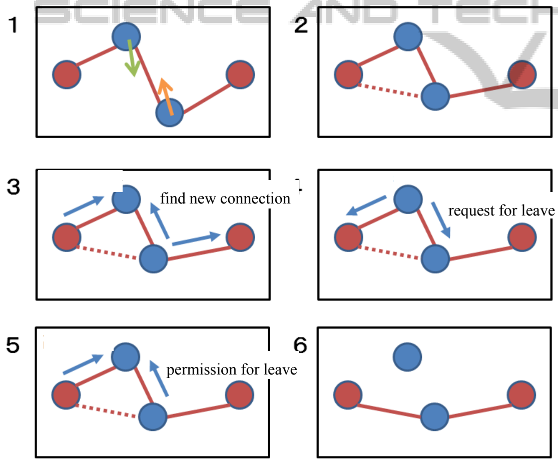


Figure 8: A redundant robot leaves from the connection.

When a relay robot finds a new connection, it notifies its finding to the neighbouring robots. If a relay robot receives such notifications from both of the adjacent robots, it recognizes it is the redundant node of the connection (Figure 8-3). Then that relay robot requests both of the adjacent robots the permissions of leave (Figure 8-4), and if it receives the acknowledgements from both of them (Figure 8-5), it disconnects and leaves from the connection (Figure 8-6).

When two adjacent relay robots find them redundant and request for leave simultaneously, the request-for-leave messages make collision each other as shown in Figure 9. In such situation, the two relay robots cancel their request for leave and try again after randomly selected waiting time.

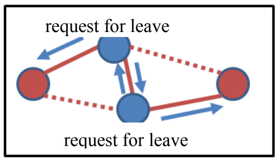


Figure 9: The collision of the request-for-leave.

Figure 10 shows another case of disconnection of relay. In this case, the relay robot C wants to move upward to straighten the connection A to D. But to do so, it must leave the connection range with robot E. If it finds connection to robot E is not active at that time, it cuts the connection to E and moves outside of the connection range of E, and otherwise it stays in the connection range of E. In that case, it cannot move and stay at the current position.

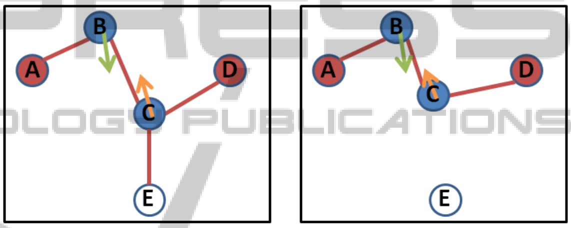


Figure 10: A relay robot disconnects to move to the optimal location.

4 NUMERICAL EXPERIMENTS

In order to demonstrate the effectiveness of our algorithms in a realistic environment, we have implemented a simulator for ad hoc networks based on multiple mobile robots, and conducted numerical experiments. On the simulator, communication scope, moving and rotating speed of robots, and time lags required in agent migration and object recognition are based on the data obtained from the preliminary study using a herd of i-Robots Create and Bluetooth scatternet. In the experiments, we set the following conditions:

1. Robots are scattered in a 440×380 rectangular field in the simulator.
2. The number of the robots is one hundred.
3. Each robot is represented as a circle that radius is five.
4. The communication range of each robot is seventy-five.
5. The distance that each robot can move in one step is two.
6. The coordinates of the source and destination robots are (10, 10) and (430, 370), respectively.

7. *Their initial locations of other ninety-eight robots are randomly decided without overlapping.*

The Figure 11 shows the initial configuration. The green lines indicate the established links of robots via wireless ad hoc network. The red nodes indicate the robots that are contributing to the communication from the source node robot at the upper left corner to the destination node robot at the bottom right corner. Eleven robots are participating in forming a connection from the source robot to the destination robot. The blue nodes indicate robots that are not participating in that particular communication.

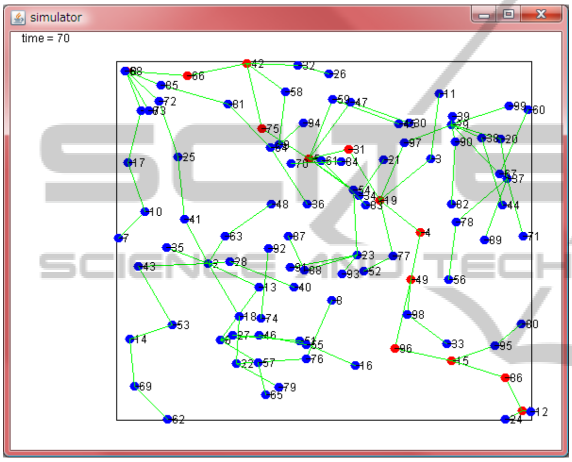


Figure 11: The initial configuration.

The Figure 12 shows the stable configuration after 216 steps in the simulation that employs the first algorithm that moves all the participating robots. We have observed that four robots out of eleven left the connection. The report says the total distance and total angles all the participating robot move and rotate are 814 and 3990, respectively.

The Figure 13 shows the stable configuration after 150 steps in the simulation that employs the second algorithm that moves minimum number of robots. The algorithm also produces connection with seven robots, that is the optimal configuration from the source robot to the destination robot, but it moves only seven robots out of eleven. The total distance and total angles that seven robots move and rotate are 452 and 580, respectively.

From the observation above, it may appear that the algorithm that moves minimum number of robots is superior to the algorithm that moves all the participating robots. But we have found that the algorithm that moves minimum number of robots has not always succeeded in reducing the number of the relay robots minimal. The above example is the ideal case. The Figure 14 shows the success rates of the two algorithms. The two graphs show how much percent could actually depart from the connection successfully. The Figure 14a shows the case of moving all the participating robots and Figure 14b shows the case of moving the minimum number of robots. The algorithm that moves all the participants successfully remove all the redundant robots (100%) sixty-three out of hundred patterns. On the other hand, Figure 14b shows that the algorithm that moves minimum number of robots cannot achieve such successes. The algorithm failed to remove entire redundant robots in most cases.

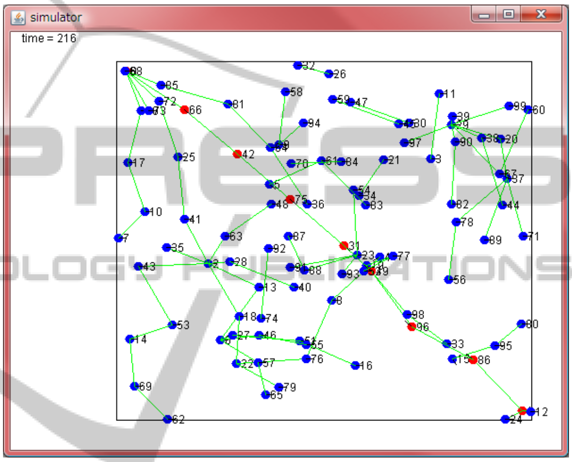


Figure 12: The stable configuration after moving all the participating relay robots.

The reason why the second algorithm that moves the minimum number of relay robots shows such low success rate is frequent occurrences of deadlocks. As we mentioned in the previous section, a relay robot that have plural active connection often cannot move. Even in one sequence of connections, we have found frequent deadlocks. In contrast, the first algorithm makes all the participating robots move toward the same straight line, the robot rarely stack in deadlocks.

The Figure 15 and 16 show the moving distances and rotation degrees, respectively. The algorithm that moves all the participants takes twice as long as the algorithm that moves only minimal participants. Also the former algorithm takes three times as much degree as the latter algorithm. This phenomenon can be easily understood, because the algorithm that moves all the participants consists of two phases as well as moves more number of robots.

In addition to the inefficiency, the algorithm that moves all the participants has one big disadvantage. That is the number of disconnections of network links. We have found the algorithm that moves all

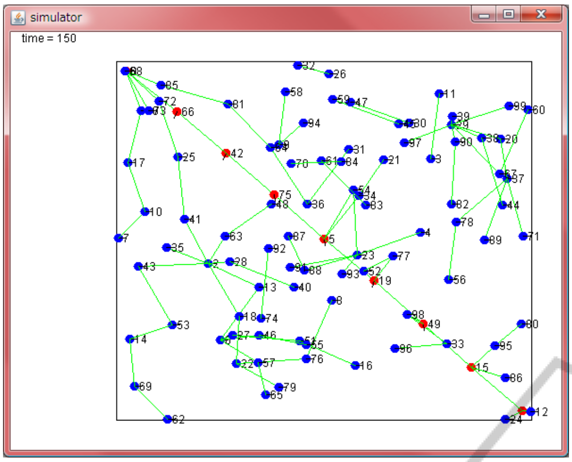
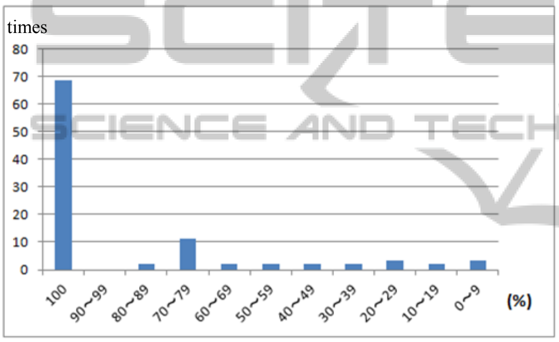
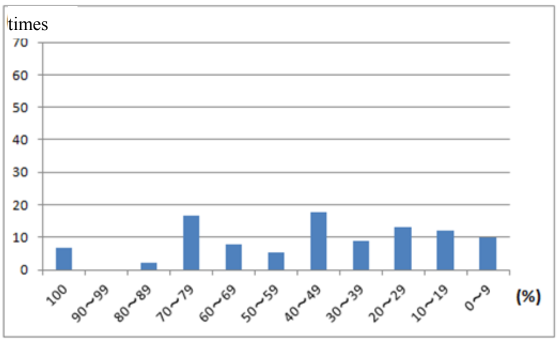


Figure 13: The stable configuration after moving the minimum numbers of participating relay robots.



(a): The success rate of moving all the participants.



(b): The success rate of moving the minimum participants.

Figure 14: The success rates of the two algorithms.

the participants disconnect links about three times as many as the algorithm that moves minimal participants. Moreover, the algorithm that moves all the participants tends to change the network topologies and thus produces many disconnected robots.

Therefore if we focus to provide optimal connection only between certain two nodes, the first algorithm that moves all the participants excels at

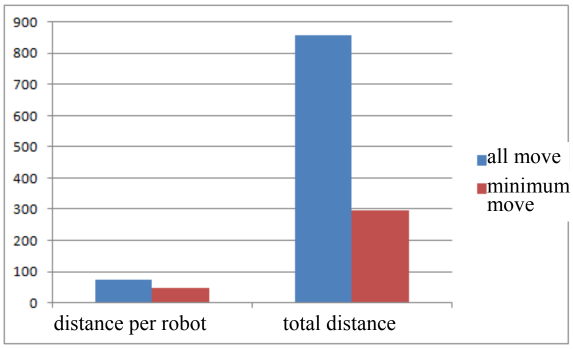


Figure 15: The moving distances.

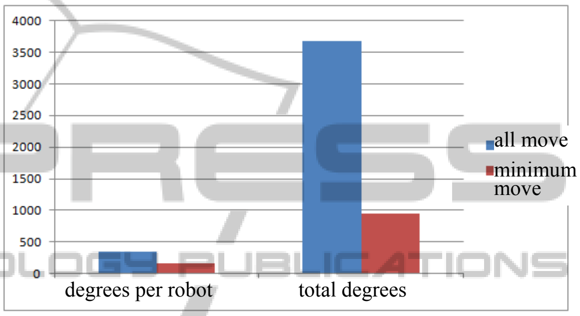


Figure 16: The rotating degrees.

forming the optimal configuration. If we observe wider scope, however, and find several ad hoc connections request their own optimal formations simultaneously, we may have another story. In such cases, the side effects produced by moving relay robots for one sequence of connections affect other sequences of connections. The situation where multiple ad hoc connections are active in parallel is so complex that measuring the side effects are hard to accomplish.

In our present study, we consider only one sequence of connections, and have to conclude that moving all the relay robots almost always provides the optimal configuration, but that algorithm may produces side effects that we yet to know how harmful they are. We only know that the fewer the moved relay robots, the less side effects occur.

As the future work we need to investigate the situation where multiple connections of ad hoc wireless network exist simultaneously. The situation should not be difficult to handle; simply we need to add one mobile agent for each connection. Then the autonomous mobile software agent should all the jobs. We believe our model is quite scalable. We only need to polish the first algorithm so that the entire moving cost is minimal, or to polish the second algorithm so that the success rate is high.

5 CONCLUSIONS AND FUTURE WORK

We have presented two algorithms that form optimal configuration of ad hoc networks with multiple mobile robots. One algorithm moves all the participants and succeeds in configuring the optimal connection (minimal number of relay robots) more than sixty percent. But this algorithm naturally takes more time to reach stable configuration and moves more robots, and thus consumes more energy. The other algorithm moves only minimum participants and often fails to produce optimal connection. It often fails to eliminate redundant robots too. But this algorithm is naturally more efficient. For connecting certain two nodes, the algorithm that moves all the participants provides better result. However, this algorithm changes the network topologies and thus produces more disconnected robots. When we consider the network topologies changes a lot in multiple robot environments, and such environments need to connect arbitrary pairs of nodes, this side effect may cause serious problem. Therefore we need to investigate the algorithm that moves minimum participants and improve the success rate of that algorithm.

An additional problem may occur in the cases of applications of both algorithms, due to the constraint of piconet. Since Bluetooth allows a master can have only seven slaves, if a master already has the maximum number of slaves, it cannot connect to a new node even though it finds a new node as shown in Figure 17. In order to establish a new connection, it must cut one of the existing connections. Selecting the most promising relay robots is a big problem worth to investigate. We plan to pursue this direction too.

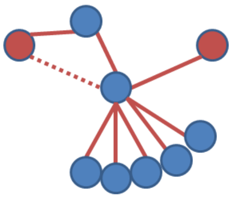


Figure 17: Too many slaves.

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