Connectivity in a wireless network of mobile robots doing a searching and collecting task

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I. INTRODUCTION

Due to the considerable development in the field of swarm intelligence and multi-robot cooperation there are a wide variety of problems that can be solved efficiently by a group of autonomous robot workers. The most investigated tasks are, for example, the exploration of an unknown area [1, 2, 3] and the realization of some collective movement patterns such as gathering or chain formation [4]. The task of finding and collecting randomly distributed items into a base station is somewhat less studied problem, although it can be also of high importance [5, 6]. A general collecting task is closely related to the problem of area exploration, since the objects to be collected (let us call them food items) have to be found first, however in this case after finding a food item the robot cannot go on with searching but carries the food to the base station.

If wireless communication is possible between the individual robots or between the robots and the base station, the robot group can satisfy much higher demands, since any information got by a specific robot can be shared with a part of the group or with the whole group. Moreover, the contact with the base station can be also important in many cases. That makes it possible to control and coordinate the work of the group by a higher computing intelligence. This includes the possibility of sending alarm messages from the base station if the group must return immediately in case of some danger (storm, military attack, etc.).

Recently Rooker and Birk [3] tested a new area discovery algorithm by simulation with and without ensuring the wireless contact to the base station. They noted that maintaining such a contact implies a constraint for the area can be explored by the robot group of \( N \) robots: this area is limited to a disk of radius \( N \cdot R \), where \( R \) is the radius of the wireless coverage circle of a robot. When the group reaches the furthest point from the base station it forms a linear multi-hop chain from the base station to the point. In these simulations, however, there was not item collecting task to solve, the robots just had to visit any reachable spot in an imaginary map.

A few years ago Kieger and Billeter [5] carried out a food item collecting experiment by 12 Khepera robots built of turret modules. Here the experimental area was relatively small (~10 m²) so all of the robots could be reached at the same time by a control station broadcasting from outside the area. The robots followed a random search algorithm, and the basic idea was to maintain the energy level of their nest, therefore not all but only a few robots were searching at the same time.

If we have a number of robots for searching a much bigger area, probably the best strategy is to divide the area into regular zones [7, 8], let us call them working cells, and direct each robot into a working cell, where it carries out a search process until its cell is covered entirely. This strategy was applied in a map covering algorithm by Rekleitis et al. [8].

In the present work our purpose is to find an optimal strategy for a task of food collecting from a big area by a number of robots under the constraint of maintaining the communication with the base station by a multi-hop ad hoc network. Besides, we try to describe the quality of the network communication at the various measures of the searched area. Here we employ the idea of dividing the area into working cells and keep working all of the robots simultaneously in their cell. At the present phase of our research the proposed scenario is tested by computer simulation and real implementation is left to future work. In the next section the food collecting method is described in details together with the parameters of the computer simulation. In Section 3 the results are discussed and in the final section conclusions are drawn.

II. THE COLLECTING TASK AND NETWORK CONNECTICITY

According to the area division strategy the food searching algorithm is based on the followings (for notations see Table 1):

- The area to be searched is divided into \( N \) working cells (corresponding to the number of robots), and each robot is assigned to a cell.
- The side of a cell ($C$) is chosen so that in two neighboring cells the two robots remain in wireless contact independently from their positions inside the cells. Thus the relation between $C$ and the coverage radius is $C = R / \sqrt{5}$ (see Figure 1).
- Inside a cell a robot follows an exhaustive searching path [8] as given in Figure 1.

In addition to these we will study the problem under the following assumptions:

- The food items are distributed uniformly in the area with a density $\rho$.
- The robots are equipped with a satisfactory navigation system which helps them to find their working cells and follow the regular searching path inside the cell. This assumption is realistic, because in addition to odometry there are advanced navigation methods such as the RF-ultrasound time-difference system [9].
- There is an efficient physical collision avoidance algorithm implemented on the robots.
- The coverage radius of the wireless contact is approximately $R = 100m$, which corresponds for example to the performance of the ZigBee system. Besides, the robot group uses a fast ad hoc routing algorithm. A recent scenario for that can be seen in [10] or in [11].

As it was mentioned in the introduction the biggest covered area is a disk of radius $N \cdot R$, which is achieved by forming a linear multi-hop communication chain. However, the connectivity of such a chain is very vulnerable because the robots that find an item leave their cell for a time while traveling to the base station with their load and then back to the cell. Under this period the robot is missing from the communication chain, so the group is disconnected. The time of this chain-break is proportional to the distance between the robot’s cell and the base station, that is, the further is the working cell from the base station the higher is its influence on the connectivity.

The performance of such an unreliable ad hoc network was studied by Liu and Srikant [12] in linear (one dimensional) and in two dimensional cases. There the nodes switched between active and inactive states in a random manner and the probability of a node being inactive for a long time was small. In our case, however, the chain break is guaranteed for a relatively long time which cannot be tolerable in many cases.

From a connectivity viewpoint the network is much more tolerant if a node (searching robot) has more than two neighbors i.e. we are in a lattice with dimension greater then one [12, 13]. Therefore the connectivity can be improved on the expense of the measure of the searched area, that is, by decreasing the radius of the disk to be searched the average number of the neighbors of the cells, and so the connectivity, can be increased. Considering these, in our solution the cells are situated not in a in a single row but inside a slice of the disk area as shown in Figure 2. (The figure shows only a quarter of the area disk.) This arrangement of the cells has two benefits: the one is that the further is the cell from the origin (the location of the base station), the more tolerant is the network against the case when the robot is missing from the cell. It is a consequence of that the average number of the neighbors of a cell is increasing with the distance from the origin. The other benefit is that this division of the disk area is approximately free of overlaps and it gives a full coverage of the disk. The searching of the slices can be scheduled: one slice is searched under a certain time, and when it is ready the group moves to the working cells of the next slice. To be honest, it is not exactly true if the disk slices are too narrow (i.e. the disk is divided to too many slices): it can be seen in Figure 2 that when we divide the quarter disk into five slices (or more) then there are slices that has no contact to the base station, that is, at least one cell from the neighboring slice must be added to them to ensure connectivity.

Thus the robustness of the connectivity is enhanced in the wider part of the slice (far from the base station), however, there is a the narrow part of the slice (close to the station) where the number of neighbors of a cell is two, so the case of a simple chain occurs with its weak connectivity. So this seems to act as a communication bottleneck of the network. In percolation theory such a bottleneck is called cutting edge, since by cutting it the connectivity is broken. Actually, this problem is solved by the collecting process itself, because the robots loaded by food items are traveling through the territory of this bottleneck and can contribute to the connectivity of the network. The same is true when they are going back to their cell from the base station. In other words, it is a busy

![Figure 1. Two neighboring working cells with the searching path (dashed lines). The radius of the wireless coverage is indicated by dashed dotted line.](image1)

![Figure 2. Division of the searched area into three (a) and into five (b) slices. Each slice is covered by 30 cells corresponding to the 30 robots. The cell boundaries are denoted by dashed lines and the cells of the neighboring sectors are distinguished by different colored squares. The base station is represented by filled circle and the parameter L shows the radius of the searched area in cell size units.](image2)
road, which improves connectivity. So the robustness of connectivity in the part far from the base station is ensured by the higher number of the neighbors, while in the part close to the base station by the higher average density of robots.

III. SIMULATION AND RESULTS

The main purpose of the computer simulations was to get a qualitative picture about the multi-hop connectedness of the robot group network meanwhile doing their collecting task. The simulation program was written in the MATLAB developing environment. The main parameters of the simulations are given in Table 1. The searching path and the speed ratio parameters were approximated by our earlier experiments with LEGO NXT robots. The radius \( L \) of the searched disk shaped area was set to the desired value by dividing the disk into more or less slices. Simulations were performed for the different values of \( L = 9, \ldots, 25 \) measured in \( C \) units. All of the simulations used the same slice of the disk, which was chosen to be the first i.e. the vertical one by the means of Figure 2 and Figure 3, because this case is free of the mentioned geometric anomalies. One simulation experiment started with the situation that each robots is in its working cell and at the starting point of its searching path, and it is ended when all of the robots reached the end of their searching path. While a robot was searching the event of finding a food item occurred with the probability \( p \). It is easy to calculate that \( p \) is related to \( \rho \) (the density of food items) by

\[
p = \frac{1}{\lambda} \cdot d \cdot \delta \cdot \rho, \tag{1}
\]

(see Table 1). Four different values of \( \rho \) were used in the interval given in the table.

Not all robots finish with the searching and collecting task at the same time, since the ones closer to the base station spend less time with traveling than the further ones. If a robot has finished with searching then just waits idle in the center of its cell until the end of the experiment but still serves as a member in the communication network.

Figure 3 shows an illustration of the simulation. Ten experiments were carried out for each pair of values of \( \rho \) and \( L \). The connectivity of the total network was checked in every time-step. The network was considered to be disconnected if a robot could not be reached from the base station by a multi-hop way. At the end of each experiment the longest time period while the network was disconnected continuously (\( t_{d}^{\text{max}} \)) was recorded. The value of \( t_{d}^{\text{max}} \) was averaged from the ten experiments for each pair of \( \rho \) and \( L \), so we got a picture about the expected value of the length of the longest time period while some of the robots are unreachable. Figure 4 and Figure 5 show the dependence of \( t_{d}^{\text{max}} \) on \( L \) and \( \rho \), respectively (the \( \{ \} \) sign is stands for the expected value). The radius \( L \) is given in \( C \) and the time value is given in \( C / v_{f} \) units (this is the time interval needed for a robot to travel across a cell parallel to the side). It can be seen that the logarithm of \( t_{d}^{\text{max}} \) is approximately a linear function of the radius \( L \) (Figure 4), that is, \( t_{d}^{\text{max}} \sim \exp(k \cdot L) \), (2)

where \( k = 0.19 \pm 0.02 \), which is the average slope of the approximated lines. This means that the expected value of the continuous disconnected time increases very fast by raising the searching radius. The situation is completely different in the case of the dependence on the food density (Figure 5): after an increasing part in the low density region the value of \( t_{d}^{\text{max}} \) reaches a saturation plateau, that is, does not increases considerably with the increasing value of \( \rho \). For the first sight this seems to be a contradiction, because for higher values of \( \rho \) the events when a robot finds a food item and leaves its cell occur more frequently, so the total time of its being absent increases. In the other hand, if the food finding events are
more frequent when the traffic in the narrower (bottleneck) part of the disk slice is higher. Therefore the communication through this region is more stable, so eventually the two effects compensate each other. This can explain the approximately constant region of the $t_{\text{max}}$ versus $\rho$ function.

IV. CONCLUSIONS AND FUTURE WORK

From the results above the following conclusions can be drawn:

- The multi-hop wireless connectedness of the collecting robot group can be maintained effectively by arranging the robots’ working cells into disk slice geometry.
- The robots on the way to the base station and then back to their working cells contribute considerably to the performance of the communication network in the bottleneck region of the disk slice.
- The expected value of the time while the communication network is disconnected increases exponentially with the radius of the searched area i.e. the radius of the disk.
- This value is much less sensitive to the spatial density of the food items distributed in the area. Above a certain value of the food density it does not increases considerably.

The present scheme is used for a disk area, because it was implied by symmetry of the problem, however, in many cases the area to be cleared is not a disk. An interesting possible improvement of the presented collecting strategy is to apply it to an area of arbitrary shape (rectangle or arbitrary polygon). The other problem worth for further investigation is the optimal geometry and size distribution of the working cells. The robots closer to the base station finish with their work sooner, therefore the size of their cells should be bigger than that of the further ones. Taking into consideration this effect leads to a nontrivial irregular lattice of the working cells.

REFERENCES


