Reconnaissance into Distant Spaces by Multi-Robot Rescue System with Ad Hoc Networking

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Abstract—The system procedure of a victim detection system (VDS) is investigated to reconnoiter distance spaces. VDS is a previously proposed multi-robot rescue system, which searches for victims in urban disaster areas, that consists of mobile robots and one monitor station with operators. An ad hoc wireless network, which connects all of them, is continuously maintained by autonomous path recovery (APR) executed by each robot. The proposed VDS procedure adopts autonomous classification of robots into search and relay robots that act based on the behavior algorithms of each class of robot to configure chain networks threading a path to the spaces. The rules of classification and the behavior algorithm refer to the forwarding tables of each robot constructed for ad hoc networking. Simulation results show that VDS can reconnoiter distant spaces autonomously even though two or three spaces exist beyond different corridors stemming from the safety zone where the monitor station is established.

Index Terms—multi-robot, USAR, adhoc network, rescue system.

I. INTRODUCTION

Urban search and rescue (USAR) is becoming one of most urgent investigation subjects due to such disasters as earthquakes, hurricanes, or terrorism against manmade constructions in urban areas [1]. We previously proposed a USAR multi-robot scheme called the victim detection system (VDS) [2] that consists of mobile robots and one monitor station (MS) with human operators. An ad hoc mobile network based on DSDV [3], which connects all of them, is continuously maintained by autonomous path recovery (APR) executed by each robot. Robots are instructed to search for victims in disaster areas autonomously, while operators at stationary MS monitor information sent from each robot.

In this paper, we investigate a VDS procedure to reconnoiter distance spaces, which are assumed to exist within unknown regions of buildings and that might be distant from the safety zone where the MS is established. The procedure consists of the autonomous classification of robots into search robots (SR) and relay robots (RR) and behavior algorithms of each class of robot (this method is referred to as search and relay robot classification or SRRC). SRs reconnoiter the distant spaces, and RRs act as relay terminals between SRs and the MS. They autonomously configure a chain network threading paths to distant spaces even within unknown regions.

II. SEARCH AND RELAY ROBOT CLASSIFICATION

Robots must configure a chain network to reconnoiter one of the spaces, and then the chain is transformed to reconnoiter another one. These processes must be repeat until all spaces have been searched.

To allow VDSs to execute these processes, we propose search and relay robot classification (SRRC) in combination with a decision-theoretic approach [4]. In SRRC, robots classify themselves autonomously into SRs and RRs. SR is one whose position is the endpoint of the network. It recognizes its position based on a predetermined rule called the rule of SR/RR classification.

RR recognizes itself as not being an SR. Each RR selects its master search robot (MSR) among the SRs in the network based on a predetermined rule called the rule of MSR selection. RR acts as a relay terminal within the path from its MSR to MS and moves appropriately to maintain the path based on a behavior algorithm.

As mentioned above, there are two rules in SRRC processing: SR/RR classification and MSR selection. In addition, a behavior algorithm is specified that each robot follows depending on its class.

A. SRRC processing rules

The rules for SRRC refer to the forwarding table that each robot stores for the routing process of a DSDV ad hoc network.

1) Forwarding table: Figure 1 shows a VDS with nine robots A~I and an MS. Among these, robot C is selected to show an example of a forwarding table in Fig. 2. The table consists of entries for each destination (denoted by dst). As shown here, elements are classified into transmitted ones and a derived one. The former denotes directly updated elements by update packets, and the latter denotes the element derived from the former ones. In addition, the former is subclassified into inherent elements in DSDV and the introduced ones for SRRC processing (from now called DSDV elements and SRRC elements, respectively).

DSDV elements consist of dst, nxt, and hop. nxt and hop indicate the next hop to dst and the hop count to there, respectively. In particular, the next hop recorded in the entry for the MS is called NMS. The NMS of robot C is robot B, as shown in the first row.
SRRC elements consist of location, inv, and cls. location indicates where the destination is located in the global coordinate system [5]. inv indicates an inverted NMS that indicates which robot recognizes robot C as its NMS. cls shows the classification results of each robot destination.

Each robot transmits its own location and cls to all other robots by attaching them to update packets, but it only transmits its NMS to neighboring robots. This information makes inv of the neighboring robots.

Derived element msr indicates the MSR of robot C if C is classified as an RR. msr is selected among SRs listed in the cls column.

2) SR/RR classification rule: Classification depends on column inv in its forwarding table. If nothing is listed in the column, then the robot recognizes its position as an endpoint and classifies itself as an SR. On the other hand, if one or more indexes are listed in inv, then the robot recognizes that its position is not an endpoint and classifies itself as an RR.

In Fig. 1, because robots E, F, and I find no indexes in their invs, they classify themselves as SRs. However, since other robots have one or more indexes such as robot C shown in Fig. 2, they classify themselves as RRs.

3) MSR selection rule: Each RR selects its own MSR among the SRs in the network and moves appropriately to maintain the path between the MSR and MS. These robots must configure a chain network where MSR and MS terminate at both endpoints and RR is at some intermediate.

Satisfying this requirement, the MSR of each RR must be the furthest robot from MS because the furthest one might be the front of the chain network and RRs must support this SR to extend the chain as long as possible.

Fig. 1. Example of VDS

<table>
<thead>
<tr>
<th>MS</th>
<th>B</th>
<th>(d_{\text{in}})</th>
<th>location</th>
<th>cls</th>
<th>msr</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>2</td>
<td>(210.9, 502.1)</td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>2</td>
<td>(222.4, 533.6)</td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>D</td>
<td>1</td>
<td>(293.6, 574.4)</td>
<td>* RR</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>D</td>
<td>2</td>
<td>(114.5, 364.8)</td>
<td>* SR</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>B</td>
<td>1</td>
<td>(189.6, 553.4)</td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>1</td>
<td>(271.6, 519.6)</td>
<td>* RR</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>H</td>
<td>2</td>
<td>(288.4, 485.6)</td>
<td>SR</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Forwarding table of robot C

The behavior algorithm that each robot follows is shown in Fig. 3 as a flowchart. In this flowchart, the potential NMS means the neighboring robots that have paths to MS and are not the NMS yet.
C. System operation of VDS

At the beginning of system operation, robots are set close around the MS and autonomously perform ad hoc networking. When the network is completed, each SR determines its next target and moves to there. Because the farthest SR from the MS possibly be selected as the MSR of many RRs, this SR and RRs gradually configure a chain network threading a corridor to a distant space.

When the space is searched, the SR updates the next target and the chain network transforms itself to reconnoiter another space beyond the new target. This process of the chain network transformation is explained with Fig. 4 where two blind corridors only exist for the simplicity.

The part (1) of this figure shows when the SR (robot A) reaches the end of a corridor and its next target is updated to one of frontier cells. This target locates in front of unknown region of another corridor indicated by current target. At this moment, RRs (B and C) also update their target to the same point as their MSR (A). In the part (2), robot B becomes SR after some movement of A and, because B memorizes the same target as A, both robots moves to the same next target. In the final part (3), as the SR (robot A) approaches the current target within frontier cells, the frontier advances along with the corridor and other robots follow A to maintain the chain network.

III. COMPUTER SIMULATION

Reconnaissance into distant spaces by VDS with the proposed SRRC system procedure was confirmed by computer simulation1. The simulation model is shown in Fig. 5. The three spaces indicated by cells 1∼3 exist beyond corridors stemming from a safety zone where an MS is established. A barrier indicated by dashed lines is set when a case with two spaces (cells 1 and 2) is simulated.

Reconnaissance into these cells is estimated by search rate and search time for each cell. Search rate denotes the percentage of the scanned area to the whole area of each cell, and search time denotes the elapsed time of system operation when the search rate achieves 100%. Here, a point in the cell is assumed to be scanned when the sensor range of a robot includes the point and simultaneously the robot has a path to the MS.

Figure 6 shows the simulation results when the barrier is set in Fig. 5 and the chain transformation from targeting cells 1 to 2 is estimated. The horizontal axis represents the elapsed time of the system operation, and the vertical axis represents the search rate for each cell. Because the chain transformation of one direction is concerned, simulation results indicating the other case (cells 2 to 1) are discarded, and the remaining results are averaged over many simulations.

The normal moving speed of a robot and its accelerated speed when it traces another are set to 1 and 2 [km/h], respectively. The transmission rate of the network is assumed to be high enough that packet collisions do not occur. The

1 The simulator is constructed based on the modules of an autonomous multi-robot simulator [6] and a DSDV ad hoc network simulator [7].
frequency of forwarding table updates is set to ten times per second.

If the number $N$ of robot is enough to reconnoiter either of the cells, first, the chain network accomplishes reconnaissance into cell 1, and second, it transforms to reconnoiter cell 2. The graphs at $N$ equals 12 almost correspond with this case. On the other hand, when $N$ equals 6, because the number may not be sufficient, reconnaissance into a cell is not accomplished in one time. In this case, the transformation is repeated many times and the search rate for either cell hardly increases. The graphs at $N$ equals 9 show the intermediate case.

Figure 7 shows search time $T$ for all cells 1~3 versus transmission radius $r_t$. The barrier is eliminated from the simulation model. The lower bounds $T_{low}$ of $r_t$ and $T_{low}$ of $T$ are indicated. This figure shows that transmission radius $r_t$ possibly compensates for the lack of robots. In the previous Figure 6, $N$ must be large enough to reconnoiter distant spaces. However, when $r_t$ exceeds about 30 [m] in Fig. 7, search time $T$ approaches lower bound $T_{low}$ regardless of $N$ because fewer RRs are necessary to reconnoiter all cells if $r_t$ is set large enough.

On the other hand, as $r_t$ falls below 30 [m], $T$ gradually increases and a difference between $N$ appears. However, until $r_t$ approaches lower bound $T_{low}$ of each $N$, it is confirmed that reconnaissance into all cells is possible within a reasonable time.

IV. CONCLUSION

An SRRC system procedure of VDS was investigated to reconnoiter distant spaces within unknown regions. The performance of the procedure was confirmed by computer simulations.

REFERENCES