Resource and Service Discovery for Large-Scale Robot Networks in Disaster Scenarios

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Abstract—**If robots are deployed in large numbers in disaster scenarios, the ability to discover and exchange resources and services with other robots in an open, heterogeneous, large-scale network will be essential for a successful operation. In this paper we present a discovery protocol that enables robots to efficiently locate resources and services available in large-scale networks. It is specifically designed for robot networks which are characterized by potentially highly dynamic network topologies and high service announcement-to-lookup ratios. The protocol exploits the position data of the robots to increase scalability and efficiency. A cell-based overlay structure is created, with master nodes in each cell. Through proactive intra-cell communication and reactive inter-cell communication, scalability is ensured and the effects of node movements on the overall network are minimized.**

I. Introduction

First implementations of mobile rescue robots have already been field-tested. If large numbers of rescue robots are mobilized in disaster scenarios in future, cooperation among the robots will be necessary for a successful deployment. Rescue operations in large-scale disaster scenarios require a wide range of complex capabilities which presumably cannot be all integrated into a single robot. Instead, through flexible and dynamic cooperation of heterogeneous, specialized robots, diverse tasks can be solved and at the same time reliability and robustness of the overall system can be increased. Through specialization, the single robots become more reliable and they can be more easily replaced in case of failures. Depending on the scale of the disaster scenario, large numbers of robots may be involved in the rescue operation. In the initial paper of *RoboCup Rescue* for example, the authors envision large-scale disaster scenarios with up to 10,000 heterogeneous agents [1]. Amongst others the authors identify scalability, heterogeneity, and emergent collaboration as main challenges. Service discovery can be a key component in addressing these issues. (Note: For brevity, we use the term service discovery for both resource and service discovery.)

One example is an agent requiring sensor data from a specific location. For instance a human operator who requires a photo from a disaster site to assess the situation, or a robot that requires the photo to check if the path is blocked. Using service discovery, a robot with the suitable equipment (e.g. a high resolution color camera) in that area is located and requested to take and transmit the photo. The robot performing the task is recruited from the environment. It need not be specialized in providing photos of disaster sites to other agents. Maybe it usually uses the camera for navigation or to detect victims. It was simply the most suitable robot at that time and location. On a larger scale one could imagine specialized search robots equipped with sensor systems for the detection of victims. After a successful localization of a victim, a first aid robot with suitable equipment for first aid treatments or a paramedic may be called in. Additionally, various types of auxiliary robots like debris transport robots that remove obstacles may be deployed in the area and requested by other agents.

In all these examples, heterogeneous, specialized agents (which include robots and human users with mobile computers) flexibly and dynamically exchange loosely coupled, generic services with each other. One open question is how agents can efficiently locate and request available services in the network.

The mobile agents will form so-called Mobile Ad-hoc Networks (MANET) for communication. MANETs are wireless networks of mobile nodes, and they are characterized by their decentralized organization and the potentially high dynamics of the network structure. Communication over large distances in such kind of infrastructure-less networks are achieved by multi-hop

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connections where nodes on the path between source and destination act as routers and forward received messages towards the destination. The problem of efficient service discovery in large-scale mobile ad-hoc networks is still open. Present service discovery protocols (like in Jini, UPnP, SLP, or Bluetooth [2]) are either not scalable or not designed with such kind of highly dynamic and resource-constrained networks in mind. These protocols rely on simple broadcast or use static unicast addresses to locate services and service directories.

The objective of this project is to develop a solution for service discovery in large-scale networks of mobile robot systems. In this paper we present a discovery protocol specifically designed for this purpose. In section II we give a short introduction to position-based routing algorithms for mobile ad-hoc networks and an overview of existing position-based service discovery protocols. The assumptions of and the requirements to our solution are stated in section III. In section IV we present and analyze the protocol. Finally, we conclude this paper in section V.

II. Related Work

A. *Routing in Mobile Ad-hoc Networks*

Routing algorithms can be classified into reactive, proactive and hybrid approaches. *Dynamic Source Routing* (*DSR*) [3] is a typical example for a reactive algorithm. The route to be taken by a data packet is only determined when required. The source node tries to localize the destination node within the network topology by flooding the network with a route request. In contrast, when using proactive protocols like *Destination-Sequenced Distance-Vector Routing* (*DSDV*) [4], routes are proactively built up and maintained even if no data packets are being transmitted. Hybrid protocols like the *Zone Routing Protocol* (*ZRP*) [5] employ proactive techniques for the neighborhood of a node and reactive protocols for routing over larger distances. Each of these approaches has various strengths and disadvantages affecting features like traffic volume, scalability, and latency.

Position-based routing utilizes the position data of network nodes to increase scalability and efficiency of the network. Position-based routing algorithms [6] avoid both the flooding of the network to search a destination as well as the proactive exchange of routing tables. Instead, neighboring nodes regularly exchange so-called beacons (or hello messages) containing their geographical positions. Using this neighborhood information, messages can be efficiently delivered to the destination by a so-called greedy forwarding strategy: A data packet is simply forwarded to that neighboring node which is geographically closest to the destination. It can be shown that there is a high probability of successful message delivery if the average node density is sufficiently high [7]. If the greedy forwarding fails, a recovery strategy, as for example suggested in [8], can be applied to reach the destination. The major disadvantage of position-based routing protocols is the fact that the geographical position of the destination node must be known in advance. However, that is no problem in this case, as the node offering the desired service has to be localized anyway. The geographic position of the discovered service provider can be transmitted as part of the response to the client.

B. *Location Services*

When using position-based routing, the position of the destination node has to be determined before a communication link between two nodes can be established. For this purpose so-called location services are employed. In literature various approaches are suggested which in principle could also be applied to the problem of service discovery. If the existence of a hash function is assumed which could map service descriptions to globally unique IDs (the way mobile nodes are usually identified in the network), on first sight the search for a service and the search for a mobile node do not differ significantly from each other. However, it can be questioned whether it is reasonable and possible to map service descriptions to alphanumeric IDs, as substantial disadvantages regarding the flexibility and complexity of service requests are involved with this reduction [9]. Even more serious are two main differences between the localization of services in a network and the localization of nodes in a network. A service will normally not be unique within the network. There will be replicas of services especially in large networks, and different service providers will offer overlapping sets of services. Furthermore it is reasonable to assume that a node will not only offer a single service but a number of services. Considering the *Grid Location Service (GLS)* [7] as example, one of the most mature approaches for location services, we show how these two properties prevent a direct application of location service solutions to the problem of service discovery.

GLS assumes that each node has a globally unique ID. The nodes are assigned to geographic cells which are hierarchically ordered such that four cells form a cell of the next order. In every order, a node A recruits that node S as server for its position data, whose ID S_{id} is numerically closest to its own ID A_{id}. If a node B wants to contact node A, first B has to determine the geographic position of A. For this purpose B sends a request to that node C among its set of known nodes whose ID C_{id} is closest to the one of A. The search request is forwarded in this way – it moves along a path of IDs which approaches A_{id}. It can be shown that a position request will always arrive at a node that knows the position of the searched node A if there is no mobility in the network, if no nodes fail and if there has been sufficient time for all nodes to recruit their position servers. However, if we examine this approach under the two aspects that nodes could offer more than one service and that multiple equivalent services could exist in the network, the application of this approach would have two major disadvantages. Firstly, the traffic would increase significantly, as every service offered by a node would have its own distinct ID, meaning that the announcements of every single service of each node have to be forwarded to their own specific servers. Secondly, due to identical IDs all equivalent services in the network would be managed by the same position servers. Multiple instances of a service would not contribute to the robustness of the system should the respective location servers fail.

C. Position-based Service Discovery in MANETs

The problem of service discovery in mobile ad-hoc networks in general is still open. In this review we focus on proposed solutions which exploit the position information of the nodes like our solution. A two dimensional overlay structure is suggested in *Lightweight Overlay for Service Discovery in MANETs* (*Lanes*) [9]. Announcements of newly available services in the network are propagated in vertical direction. Nodes that receive such an announcement cache and forward them. As all nodes in a vertical lane possess the same information about services available in the lane, search requests can be directed towards arbitrary nodes in neighboring horizontal lanes if the searched service is not available in the own lane. A similar approach is applied in *Geography-based Content Location Protocol* (*GCLP*) [10]. In difference to Lanes, services are propagated to all four cardinal points. If multiple equivalent services exist in the network, only the geographically closest service is forwarded. Search requests are also forwarded to all four cardinal points.

One disadvantage of the Lanes approach is the costly maintenance of the lane structure when nodes move, as the structure is based on single nodes and not on groups of nodes. Nodes that are in motion, particularly nodes that move across the network, will cause a high traffic volume. On the one hand, the node has to join, leave and store the data of the lanes it crosses. Even more costly however, to achieve consistency in the vertical lanes, the locality property [11] is neglected. In worst case, every lane that is visited by the moving node will propagate information about the node along its whole length. Especially in large networks, where presumably always a subset of nodes is in motion, the network as a whole will not settle down. The main advantage of this approach is that it is totally decentralized. This analysis is, to some weaker extent, accordingly valid for the GCLP approach. The locality property is also neglected, in worst case service announcements are also propagated along the whole length and width of the network.

A recent example for a home region-based approach is *Rendezvous Regions* [12]. The network is geographically partitioned into rectangular cells called rendezvous regions. Resources available in the network use a globally shared hash function to determine their home region where they store information about their current position. Within such a rendezvous region a number of elected servers are responsible to answer requests of nodes searching for the location of resources mapped to this rendezvous region.

The main strength of Rendezvous Regions is its very low-traffic service announcement and look-up mechanism. The main disadvantages are a consequence of the use of the hash function. As service requests have to be mapped to a region, only semantically weak requests of low complexity are supported [9]. Moreover, the locality property is neglected, as services could be mapped to arbitrarily distant rendezvous regions. This also means that even close-by clients and service providers may require arbitrarily distant look-ups to discover each other. Like in the case of GLS, multiple services per node increase the number of messages and multiple equivalent services in the network do not necessarily increase the robustness of the system as they are all mapped to the same rendezvous region. In case of network partitions, a rendezvous region may become unreachable, thus preventing a successful discovery even if suitable service providers are still in the reachable part of the network. In case of partitions or empty regions, the authors of the paper suggest the use of multiple hash functions to provide substitute regions. However, that would in turn increase the traffic volume and thus undermine the main advantage of this approach. Finally, the operational area cannot be dynamically extended or shifted as the hash function requires a strict pre-determination of the area.

III. Approach

In mobile ad-hoc networks nodes possess physical mobility. Thus, the network topology is much more dynamic and can be highly instable. Nevertheless communication protocols should be suitable even for the worst case – when all nodes are constantly in motion. Furthermore, communication links in mobile ad-hoc networks are wireless. To bridge large distances, multi-hop connections are used. This can be necessary because of the limited range of radio links, for energy-saving purposes, as the required transmission power increases at least quadratically with the distance, or to avoid collisions in the radio traffic. Consequently, communication over large distances is expensive, slow and, due to the dynamics of the network topology, instable. For this reason, we put a high emphasis on the locality property – the solution should preferably resort to local communication links [11].

Regarding the network model we assume that all nodes in the network have an omni-directional antenna and the same transmission range. All links are bidirectional, if node A can hear node B, then node B can also hear node A. Further, we assume that the wireless nodes are roughly in a plane.

A solution for service discovery in multi-robot systems

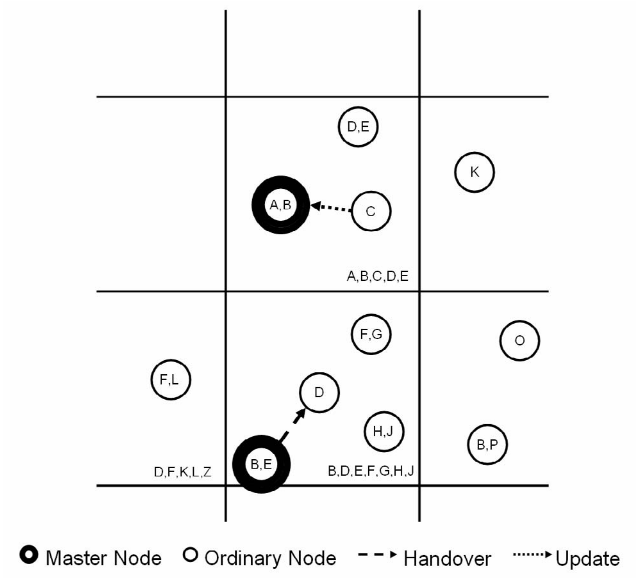

Fig. 1. The services available in a cell are listed in the lower right corner of the cell. In the upper middle cell, the node offering service C is sending an update massage to its master. In the lower middle cell, the master is leaving the cell and chooses the node offering service D as successor.

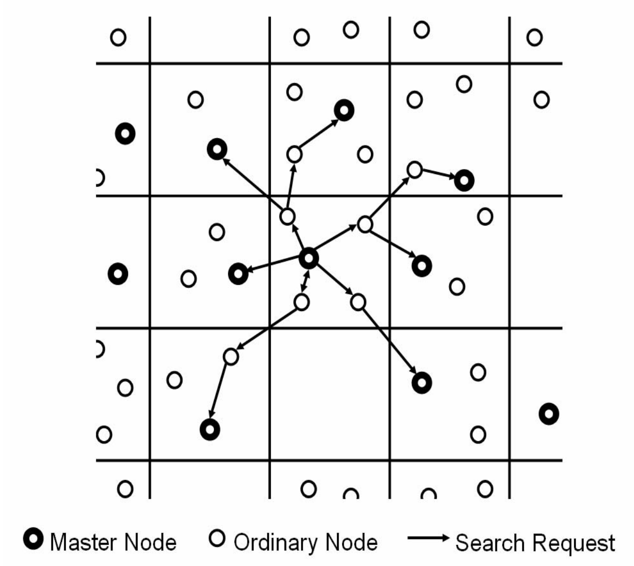

Fig. 2. The lower left node in the middle cell sends a service request to its master. The master forwards the search request to the first order neighbors.

cannot be studied without considering the routing protocols in such networks. We use a position-based protocol as robots eventually have to know their positions within their environment and relative to other robots to navigate and collaborate. For our solution we assume that all nodes know their own positions within a common coordinate system. This information could be provided by global navigation satellite systems like GPS in outdoor environments. A number of suitable positioning systems have been proposed for indoor environments, for example based on RFID tags [14] or maps in combination with sonar sensors [15].

Beside the points above, we have the following additional requirements to our solution:

- Robustness: A network of mobile robots can be very dynamic. Nodes will fail, log off the network or leave the radio range, and new nodes will join the network. The absence of single nodes should not decrease the success rate of search requests of the network as a whole significantly. New nodes are to be integrated quickly.
- Scalability: The developed solution should be able to integrate and service hundreds or even thousands of nodes.
- Compatibility: A smooth integration with wired networks should be possible so that so called "wired-cum-wireless environments" can be built. This will enable our solution to exploit existent infrastructure, if available, to increase scalability and throughput of the network while decreasing resource consumption of the mobile nodes.
- Efficiency: The transmission bandwidth in wireless networks is usually lower than in wired networks. And the probability of collisions increases with node density. The developed solution is to be resource efficient, particularly regarding the radio bandwidth.

IV. Solution

A. Cell Structure and Master Nodes

A cell-based grid forms the basic structure of our solution (see Fig. 1). The position data of the robots are used to assign them to geographic cells. Every cell has a master node (if there are nodes in the cell). When constructing the grid and at low densities the first active node in a cell assumes this role. The fixed cell structure has the advantage that the selection of master nodes is faster, requires less traffic and can be executed depending on local necessity since not the whole network needs to be involved in the election process. Information about nodes in an area is associated with the cell and not with the current master of that area. If a master node leaves a cell, the information remains in the cell, together with the majority of the nodes and does not wander with him. This requires a handoff mechanism if a master leaves his cell or the entire network, or if the master decides that he cannot fulfill its role for other reasons, for example due to low energy reserves. Instead of executing a complete election procedure within the cell, we suggest that the master node chooses his successor based on data available to him like the geographic position of the other nodes in the cell or their membership duration at the cell. For example, a node close to the center of the cell would be preferred as successor since it can be more easily contacted by other

TABLE I
HANDOFF MESSAGE

Successor Node ID
Successor Node Pos.
Node Table
Service Table
Pending Searches

TABLE II
HELLO MESSAGE

Own ID
Own Position
Master ID
Master Position

TABLE III
UPDATE MESSAGE

Own ID
Own Position
Service List

TABLE IV
INTRA-CELL SEARCH

Search ID
Own Node ID
Service Description

TABLE V
INTER-CELL SEARCH

Search ID
Own Cell ID
Destination Cell IDs
Service Description

TABLE VI
INTER-CELL REPLY

Search ID
Destination Cell ID
Service Provider Node ID
Service Provider Position

A compilation of the most relevant messages in the protocol. Only fields directly related to the service discovery protocol are shown, other fields, e.g. for the routing algorithm, are omitted for clarity.

TABLE V II
COMPLEXITY COMPARISON

	CSD	Lanes	GCLP	Rendezvous Regions	GLS
Setup Costs per Service	O(1)	O($\sqrt{n}$)	O($\sqrt{n}$)	O($\sqrt{n}$)	O(log(n) $\sqrt{n}$)
Total Setup Costs	O(m)	O(m $\sqrt{n}$)	O(m $\sqrt{n}$)	O(m $\sqrt{n}$)	O(m log(n) $\sqrt{n}$)
Update Costs per Service	O(1)	O($\sqrt{n}$)	O($\sqrt{n}$)	O($\sqrt{n}$)	O(log(n) $\sqrt{n}$)
Costs per Search Request	O(n)	O($\sqrt{n}$)	O($\sqrt{n}$)	O($\sqrt{n}$)	O($\sqrt{n}$)
Memory Requirement per Node	O(1)	O($\sqrt{m}$)	O($\sqrt{m}$)	O(1)	O(log m)

n denotes the total number of nodes in the network, m denotes the total number of services available in the network. The upper part of the table gives the costs of the respective operation in terms of the number of nodes involved in the operation, which is a measure for the traffic generated. The last row gives the memory requirement per node depending on m.

nodes and needs more time to leave the cell. A handoff message denominates the successor node. It also contains a table of the available nodes in the cell including their positions and offered services, and a table of pending searches (Table I). For the position-based routing algorithm neighboring nodes regularly exchange hello beacons containing their positions. These beacons are also used to propagate information about position and identity of the own master within the cell (Table II). If the failure of a master is detected, for example through the absence of these regular updates, the node which first declares itself the successor becomes the new master. In case of conflicts a simple resolution strategy can be applied, for instance based on the geographic distance of the competitors to the cell center. Finally, we would like to point out that the cell structure makes it easy to exploit heterogeneity among the network nodes by favoring more powerful nodes when nominating a master. In particular the integration of dedicated wired nodes becomes easy, which can serve as immobile permanently available master nodes.

B. *Discovery Process*

Now we take a look at the search process. A new node appears in the network, for example because a robot has just been activated, and wants to use a service. Using its position data it can assign itself to a geographic cell. If there is already a master in that cell, shortly after activation the node will receive the position and identity of its master via hello messages from its neighbors. If there is no master in the cell, our node becomes the master itself. In the following we consider the more general case that there is already a master M in the cell. M knows all available services in his cell. Depending on the cell size nodes possibly cannot be contacted by their master through a single hop. Thus, nodes have to regularly, for example time- or event-triggered, contact their master to transmit their current position. Along with their position data they also send an overview of the offered services (Table III). The searching node sends a request to M, who first checks the table of available services in his cell to answer the request right away. As all nodes in a cell know their master and vice versa, a search request (Table IV) can simply consist of a search ID to be able to match requests and arriving replies, the ID of the requesting node and a description of the required service. If M does not find the required service in his cell, he sends requests to the masters in neighboring cells up to a certain distance (see Fig. 2 and Table V). The search ID is used to correctly assign replies to previously issued requests. The source cell ID is used to route a reply back to the originator of the request. The destination cell IDs specify the cells to be queried for the service described in the service description field. Inter-cell communication is based on cell IDs as the master nodes might change during the process. Since all nodes share a common coordinate system, it is sufficient to provide a cell ID to route a request to the destination cell by geographic forwarding. Upon arrival the nodes in the respective cell will forward the request to their master as they will know his location. To ensure an efficient distribution of the search messages, position-based multicasting can be employed. In [16] a multicast protocol is suggested that extends position-based unicast protocols such as GPSR by integrating rules for the splitting of multicast packets based only on local information. Furthermore, depending on the average number of service replicas available in the network or if nodes know that a service is available in the direct neighborhood and thus expect a low search diameter, an expanding ring search can be conducted. The first requests are only transmitted to the direct neighbors. If the search requests at the direct neighbors fail, new requests are issued to the second order neighbors. This expanding search is conducted until the request has been successfully answered or until a maximum limit of search steps has been exceeded. If a service has been successfully localized, the position of the service provider is send to M (Table VI) and forwarded by M to the requesting node in his cell.

C. Complexity Comparison

As you see in Table VII, the approaches presented in section II require O($\sqrt{n}$) steps for both service announcement and lookups, whereas our solution requires a constant number of steps for announcements but O(n) steps for service lookups. Our solution is specifically designed for scenarios like large-scale robot networks characterized by highly dynamic network topologies and high service announcement-to-lookup ratios. Mobile robots will be regularly in motion, in difference for example to sensor networks, resulting in highly dynamic network topologies. On the other hand, the physical interaction of the robots with each other and their environment, as opposed to the digital interaction in computer networks, decreases the rate of service requests, since it will take orders of magnitude more time to actually physically execute a task than to locate a service. The advantage of our solution is the minimization of the influence of node movement on the overall network by keeping the effects of changes strictly local. The proactive component of the solution, the grouping of nodes in cells, both ensures scalability of the solution and additionally stabilizes the network as this way not all node movements but only the crossings of cell borders trigger major changes.

V. Conclusion

Service discovery enables robots to discover and exchange generic services in open, heterogeneous, large-scale networks. We are convinced that service discovery will be an essential component for a successful large-scale deployment of robots in disaster scenarios. We presented a service discovery protocol specifically optimized for robot networks. The protocol exploits position information of the robots to increase scalability and efficiency of the solution. In difference to other protocols, it takes into account the high dynamics of robot networks by minimizing the effects of node movement on the overall network. Furthermore, the solution supports dynamic extensions or shifts of the operational area, semantically strong service descriptions, and seamless integration of existent infrastructure. Multiple instances of equivalent services in the network can be fully exploited to increase robustness of the system and to ensure proximity of clients and service providers. The overall system has no single points of failure.

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