# Dynamic Robot Networks for Search and Rescue Operations

*Ömer Çayırpunar*, *Bülent Tavlı*, *Veysel Gazi*

*Abstract—* **In this article we consider cooperative search by a team of mobile robots using dynamic (ad-hoc) network (communication topology). We implement the algorithm on a set of custom designed Akrep mini-robots and compare its performance with the performance of non-cooperative search. It is observed that in the experiments performed cooperative search is faster than non-cooperative search. The focus here is on the importance of the wireless ad-hoc communication/networking in cooperative multi-robot systems.**

*Index Terms—* **Multi-robot teams, communication network, cooperative search and rescue.**

## I. INTRODUCTION

Search and rescue operations have great importance under disaster situations like earthquakes or terrorist attacks. In such disaster relief missions search and exploration are the initial steps of a larger operation. Traditionally such missions have been performed by human teams; however there are intensive ongoing research efforts for developing multi-robots search teams to be deployed in such missions. Rescue robotics, or basically the use of autonomous robots in search and rescue operations, is a relatively new field of research. It is a part of the broader field of coordination of a group of mobile robots to achieve a specific objective/goal. In order to achieve cooperative behavior there is a need for effective (direct or indirect) communication methodologies. The use of network architecture is one possible form of direct communication and will be very essential in many applications for exchanging resources of information between the robotic agents in the team and the team and human operators. In particular, in search and rescue scenarios by combining the network system with an appropriate search algorithm an effective search can be achieved by the robots.

Recent technological advances in control theory, electronics, electromechanical systems, and communication/networking technologies are paving the way for the development and deployment of a large cooperating robot groups (swarms) [1]. Deployment of groups of relatively simple mobile robots has several advantages over a single complex (advanced) robot. These advantages include robustness to failures (the group may still be able to perform the job in case of loss/failure of one or more robots while in the single robot case the job will be aborted, moreover simple agents are less prone to bugs or failures compared to complex agents), flexibility (the group can re-organize/self-organize based on the situation or objective), scalability (based on the objective or task different number of agents can be deployed), an cost (simplicity leads to decrease in the cost of the overall system). Moreover, autonomous robots can assist humans in risky operations during search and/or rescue missions. Furthermore, robots can have the ability to work in environments which are dangerous to humans such as collapsed or unstable buildings, in fire or gas leakages, environments with high nuclear radiation concentration, deep under the sea, etc. Therefore deployment of systems of multiple cooperating robots will have a great potential in search and rescue operations in the near future.

The field on coordination and control of multi-agent dynamic systems (sometimes called swarms, swarm robotics, cooperative robotics, etc.) is a relatively new field that has become popular in the recent years. Since the pioneering work by Reynolds [2] on simulation of a flock of birds in flight (using a behavioral model based on few simple rules and only local interactions), the field has witnessed many developments. Several different approaches have been considered for swarm aggregation, navigation, coordination and control. While initial research has focused on centralized [3][4][5] and leader based [6] approaches, most of the research has been concentrated on decentralized ones due to their reduced computational complexity and robustness to failures. Such approaches include behavioral [7], artificial potential functions [8][9][10][11][12][13][14][15][16], virtual agents or virtual structures [17][18], probabilistic [19][20], and others [21][22][23]. There are also open-loop approaches using mostly game theory or optimal control for navigation [24] as well as works dealing with improving systems performance

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through adaptation and learning [25][26][27]. Some of these works use global information while others are based on local interactions and rules. Moreover, besides bio-inspired models, there are hard control-theoretic approaches as well. Nice surveys on recent advances and the state of the art in swarms can be found in [28][29][30][31] while recent special issues include [32][33].

It is obvious that it is difficult and even impossible to have global information and implement centralized controllers in systems consisting of large number of agents with limited capabilities. Therefore, recent research has concentrated on decentralized approaches. In such systems, as was mentioned above, the inter-agent communication and networking algorithms are of paramount importance.

In order for a decentralized system to be achieved there is still a need for development and verification of effective coordination and control as well as communication and networking algorithms and protocols. Communication in multi-robot systems can be classified as explicit or implicit communication. Implicit communication (sometimes also called stigmergy) is communicating through the environment. In other words, if the actions taken on (modifications made to) the environment by one agent lead to the change of the behavior of the agents (the other agents and the agent itself), this is a type of implicit communication. Simply stated, in implicit communication changes in the environment may represent some useful information. Explicit communication is the type of communication in which the robots directly pass messages to each other and/or to the human operator. In the context of multi-robot systems the definition of communication can be made as the transfer of meaningful information between one agent and another (or the human operator). This definition is very broad and can include all kinds of communication such as information obtained from the sensors (e.g., the position of a significant object), information about the robot itself (e.g., its movements), commands or task/service request messages, etc. A more specific and narrowed definition which includes some form of intentionality can be stated as “The intentional transfer of meaningful information between robotic agents.”

Communication/networking can enhance the performance of multi-robot systems from several aspects [43]. First of all, in the case the group of robots has to fulfill a specific goal the coordination between different agents becomes very necessary. For example, consider a mission that includes moving a large (and possibly fragile) object by a multi-robot team. Without communication and coordination the robots may try to push the object in different directions which can result in undesired consequences. Second, with communication the robots can exchange valuable information and significantly improve the performance. For example, in heterogeneous multi-robot teams sensory information inquired by a robot with a specific sensor could be exchanged with other robots that are not having this sensory setup. Similarly, a robot not being able to perform specific task can request that service from another robot that has that capability. Furthermore, different tasks (or objects) can be allocated to different agents thus achieving parallel (and therefore more efficient operation).

A group of mobile communicating robots constitutes by its nature a wireless ad-hoc network. In such a system there are many issues to be resolved for effective operation. First of all, since the agents will be simple, their communication capabilities (such as range, power, processing capability, etc) will also be limited. Therefore, in the case two agents that need to communicate are out of range, they will probably need to communicate through other agents. Therefore, beside the need for development of appropriate message structures and communication protocols, there is a need for development of effective/cooperative routing/networking and service discovery protocols as well. A recent survey on the main issues in mobile sensor networks can be found in [34].

Performance of a distributed robotic system using shared communications channels is presented in [35]. It is shown that for surveillance applications it is extremely important to coordinate the robots through wireless communication channels. Yet, the performance of the system is affected by the capacity of the links and the number of robots sharing the links. It is reported in [36] that adding simple communication capabilities to robots improves the predictability of the task completion times. In [37] a multi-robot coverage study is presented. It is shown that by allowing robots to communicate among them through wireless links better algorithms for the complete coverage problem can be obtained. In [38] it is shown through simulations that use of direct communication (through wireless links) can be beneficial for the effectiveness of the group behavior in performing collaborative tasks. In this study we also utilize communication links between the robots to provide better coordination as suggested by the aforementioned studies, however, the difference in our study is that we do not treat the communication paradigm as the utilization of direct communication link between entities only – instead we chose to utilize the wireless links among the robots as a dynamic network to provide a better coordination capability.

In this article we consider cooperative search by a team of mobile robots using dynamic communication network between the robots and the robots and the base station. The algorithm is implemented such that the communication link between the robot team and the base station is always up (i.e., broken links are dynamically repaired). We implement the algorithm on three custom designed Akrep mini-robots and compare its performance with the performance of individual-based non-cooperative search (i.e., without a network connection and cooperation between them meaning that all robots carry out the search themselves without being aware of the other robots). The success rates of these two search algorithms can be measured in terms of mission time that is the precise time passed to fulfill a common search. Our experimental results show that the networked strategy is faster and more successful than the individual search strategy with the performance metric chosen.

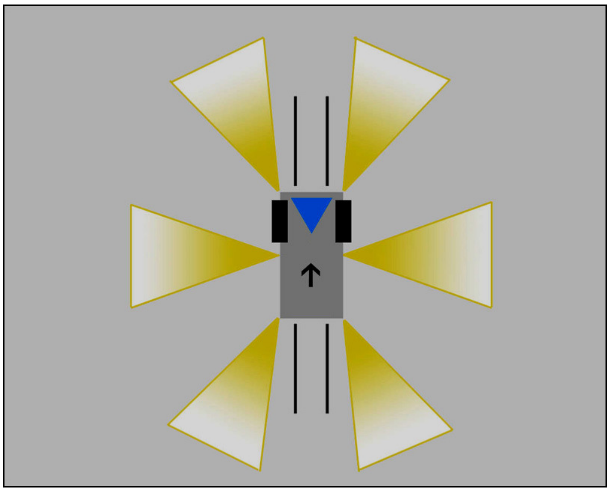


Figure 1. A schematic model view of the robot used in experiments.

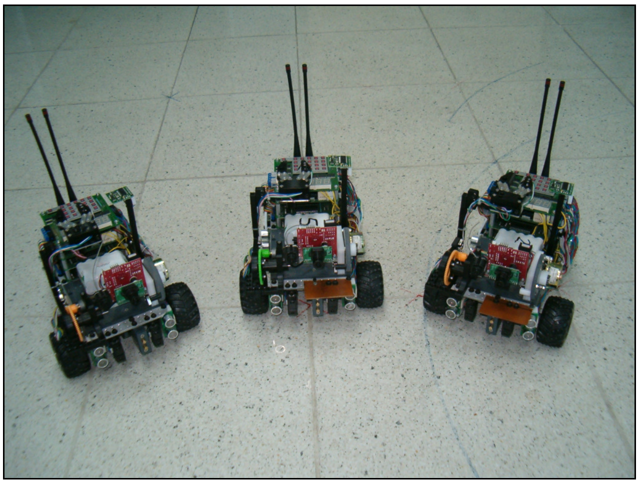


Figure 2. The Akrep series mini robots used in the experiments.

## II. THE ROBOT PLATFORM

Three Akrep series mini robots with two wheel differential driven mechanics are used in the experiments. The robots have 10 proximity sensors mounted on their sides and corners looking at different angles. **Figure 1** shows the schematic of the robot platform. The arrow in the figure shows the heading direction of the robot. The black lines in front and rear of the robot represent scaled measuring distances (ranges) of the infrared sensors, while the triangles/cones at the corners and the sides of the robot represent the (longer) scaled ranges of the ultrasonic sensors. The small triangle in the front represents the view angles of the camera, while the black boxes represent the wheels of the robot. The robots have built-in wireless communication hardware. Also they have an onboard camera module for video processing and a live cam for broadcasting video. There is also a two axis gripper to collect or grab small (non-heavy) objects. In addition there is also an electronic compass mounded on each robot. A picture of the robots used in the experiments is given in **Figure 2**.

The robots are equipped with Zilog Z80 microcontroller unit as their main processor. This unit has 32 KB EEPROM for application independent program library and 32 KB RAM for user programs and data. The clock speed of the microcontroller is 20 MHz. In addition, the robots have a PIC 16F877 based microcontroller card for sensor and communication interface. This card is used for background sensor readings and serial communication and passes the results to the main CPU (the Z80 microcontroller). Only the Z80 microcontroller can be programmed by the user while the program of the PIC microcontroller is fixed. We used C programming language and in particular the free SDCC (Small Device C Compiler) as software development platform. The features of the robot platform are listed in Table 1.

Table 1: Akrep mini robots hardware features

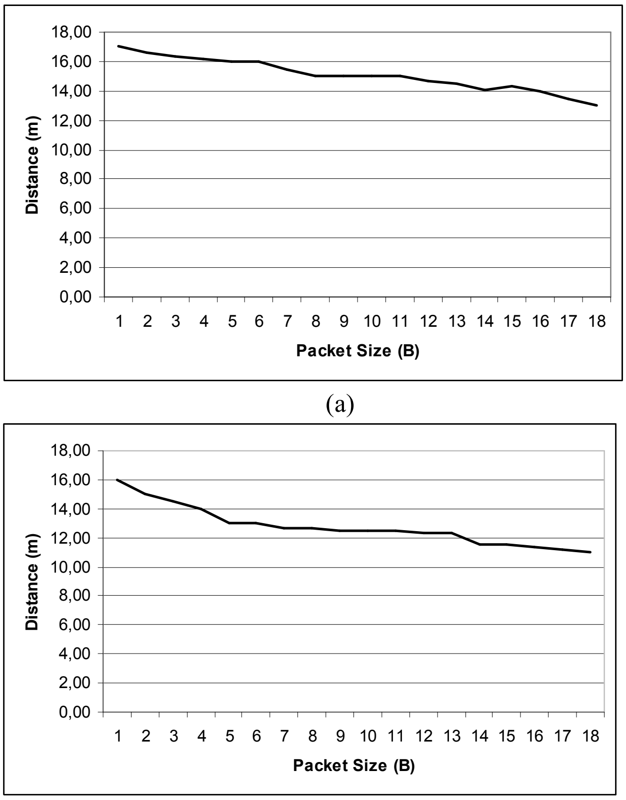
| | |
|---|---|
| Main CPU | 20 MHz Zilog Z80 microcontroller |
| Program Space | 32KB RAM, 32 KB EPROM |
| Peripheral Interface | PIC16F877 Based Sensor and Communication Controller |
| Proximity sensors | 6 Ultrasonic (Devantech SRF04) and<br>4 IR (SHARP GP2D02) distance sensors |
| Communication Module | 433 MHz Radio Transmitter and Receiver Module |
| Vision System | Robotic Camera Board (CMUCAM2) and Broadcasting Live Video Camera Module (Generic) both mounted on the same tilting platform |
| Locomotion | Differentially (stepper motor) driven mechanics |
| Gripper | 2 Axes Gripper in front |
| Orientation | Electronic Compass Module |

| Preamble<br>(3x55h)<br>(3 Bytes) | "Z"<br>(1 Byte) | "#"<br>(1 Byte) | Receiver id<br>(1 Byte) | Sender id<br>(1 Byte) | Data length (n)<br>(1 Byte) | Data<br>(1 to 18 Bytes) | Checksum (1 Byte) |
|---|---|---|---|---|---|---|---|

Figure 3. The communication packet format.

We have used 433 MHz transmitter and receiver pairs [39][40] for half duplex networking. The data rate is fixed to 4800 Bps. A packet structure and data error control system is used. The three robots and the base station also have different networking addresses on that structure, so that the data sent to a specific robot is received only by the corresponding robot and ignored by the other robots. Also data integrity is checked by arithmetic checksum in each packet in order to prevent faulty communication. Packet format is presented in **Figure 3**.

We performed several experiments in order to determine the characteristics of the transmitter receiver pair for different distances between them. The results from these experiments are shown in **Figure 4(a)** and **Figure 4(b)** for the static and the mobile cases respectively. The figures show that as the packet size increases the maximum achievable distance (i.e., packet error rate increases above acceptable levels) decreases. The minimum packet size is 10 bytes and the maximum packet size is 27 bytes which is limited by the hardware buffer. 9 bytes of the packet is used up for overhead (e.g., preamble, checksum etc.) and the rest is used to transfer the payload. Thus, for the minimum packet size (1 byte data plus the overhead) the maximum error-free distances are 17.0 m and 16.0 m for the static and mobile case, respectively. For the maximum packet size the maximum error-free transmission distances are 13.0 and 11.0 meters for the static and mobile cases, respectively. Since the transmit power is kept constant the received power decreases with increasing distance (i.e., due to spreading of the wave front and attenuation) usually.



(b)

Figure 4. Packet size versus distance graph of wireless transmission system of the robots (a) while they are steady in transmission, (b) while they are moving in transmission.

Figure 5. The corridor where the experiments are conducted.

The decrease in the received signal strength obeys an inverse power law, where the exponent is usually greater than two. Furthermore, no matter how high the received signal power is there is a non-zero probability that a bit (or a symbol) may be corrupted due to noise, which manifests itself at the checksum calculations. The higher the ratio of the received signal power level and average noise power, the higher the probability of bit error. With the assumption of independence between the bit error rate of separate bits the packet error probability becomes $(1-p)^N$ , where $p$ is the bit error rate and $N$ is the total number of bits in the packet [41][42]. Hence, as **Figure 4** shows the effective transmit distance reduces as the packet length increases (longer transmit distances result in lower received signal power and lower signal to noise ratio levels).

As it could be understood from the general characteristics of the upper and lower panels in **Figure 4**, mobility of the robots decrease the effective transmit range of the radios on them. The reason for such decrease is that the motors on the robots are sources of additional noise, which further reduces the signal to noise ratio of the received signals. When these sources are off (i.e., the static case) the signal to noise ratio is relatively higher than the mobile case.

The experiments are conducted within a 50-meter long corridor surrounded by classrooms and windows (see **Figure 5**). The object the robots are searching for is placed at various distances from the base station and the time from the start of the search to the instant at which the robots report to the base station that the object was found is measured. The two different search strategies employed in the experiments are discussed in the next section.

## III. SEARCH STRATEGIES

The objective of the search strategies is to search for a predefined object (an orange colored box for our experiments) by the robots and when it is found report back to the base station. The searched object represents an entity to be rescued in a disaster situation and at the beginning its position is not known exactly. Once the object is found by the robots the base station is informed about the position and the situation of the object. We compared two different strategies based on the time to find and report the searched object back to the base station.

### *A. Non-Cooperative Search Strategy*

In the non-cooperative search strategy the search operation is conducted individually by each robot. Once a robot locates and identifies the target object, it returns back to a sufficiently close distance to the base station to convey this information. The reason for returning back is that the distance between the robot and the base station is larger than the effective range of the radios. The flowchart for this strategy is presented in **Figure 6**. In the non-cooperative strategy the robots perform the search operation in

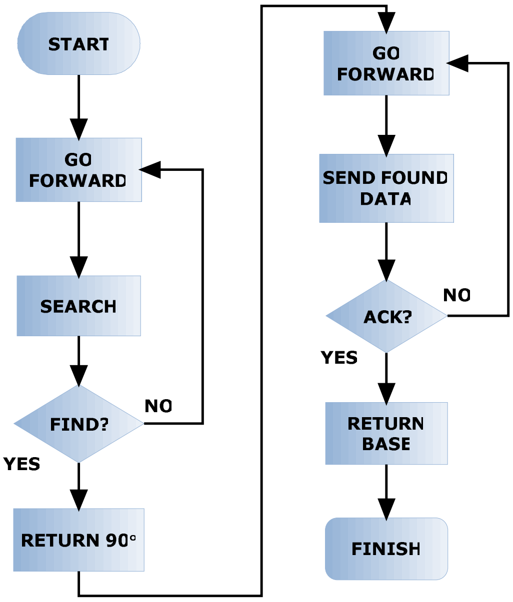


Figure 6. Flowchart of Non-cooperative search strategy.

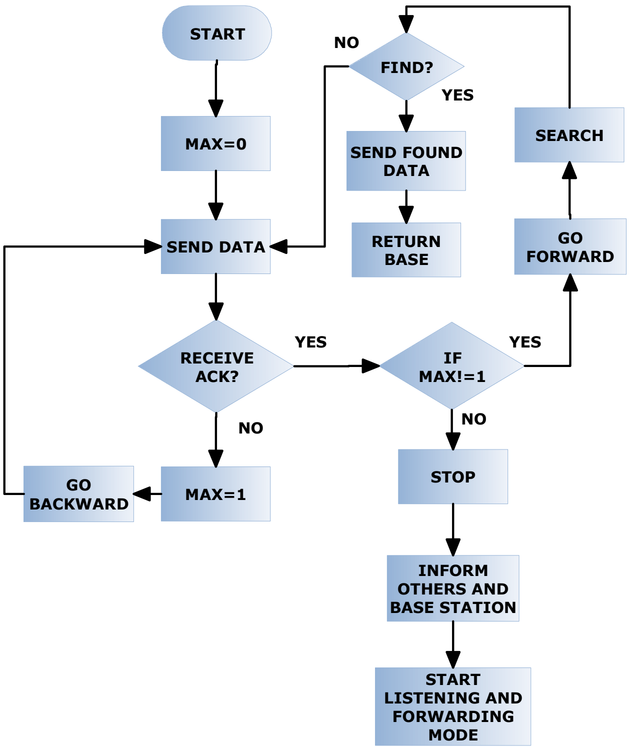


Figure 7. Flowchart of Cooperative search strategy.

two steps. In the first step the robot moves for a while and stops. In the second step it scans its surroundings through the camera mounted on top of it. This two-step behavior continues until either the searched object is found or an obstacle is encountered. Once the searched object is found the robot terminates the search procedure and returns back towards the base station to a distance at which it can communicate with it to report the information it acquired.

In **Figure 8** the mission completion time for non-cooperative search strategy is presented. It can be seen from the figure that it takes the robots about 250 seconds to find and report the object for the case in which it is located at about 20 meters from the base station, while it takes about 620 seconds to find and report the object for the case in which it is located at about 40 meters from the base station. As expected the mission completion time increases with increasing distance between the object and the base station (i.e., the area to be searched increases with increasing distance between the base station and the target). Moreover, the increase in the rate (of the time to find and report with respect to the distance) is almost linear. This is mainly due to the fact that the object is not hidden and there are no obstacles in between. Our objective here is to study the search time with respect to the distance and not the difficulty of the terrain (although such study can also be performed and included here as well).

### *B. Cooperative Search Strategy*

In the cooperative search strategy an active multi-hop wireless communication network connecting all the entities (e.g., the robots and the base station) is maintained. The reason for maintaining such a network is to share the information acquired by all the entities in the network. Hence, once a search robot locates the object while searching, it does not need to wait to report until it can traverse all the way back to a sufficiently close distance to the base station.

Since the effective communication range of a wireless transceiver is limited, therefore time/position varying special care is taken to avoid broken links between the robots. The flowchart for the cooperative search strategy is presented in **Figure 7**. Once the search operation is started by the base station one of the robots starts its search as if there are no other robots around it (like the non-cooperative search strategy). During the search operation the robot continuously monitors the link between itself and the base station. If the link is active it continues in its normal mode of operation. If it detects a faulty communication, this is interpreted as a link failure due to the overextended communication distance. Hence, the robot goes back towards the base station to activate the broken link. Once the link is reactivated the robot goes back in the reverse direction in finer steps to avoid an abrupt link breakage. After a certain number back and forth movements it concludes that the limit of the effective transmission radius is reached. (The experimentally obtained characteristics of the transmission channel were discussed in the preceding section.) At this point this robot starts listening and forwarding mode as shown in **Figure 11** and the entities in the network are informed of the situation of this robot and a second robot (initially positioned near the base station) takes over the job of the previous robot as the active search agent (see **Figure 10** for a conceptual schematic) and continues to search from the point left by the previous robot. Hence, the previous robot starts to act as a relay to the base station to keep the communication link between the active search robot and the base station. Once the second robot reaches the maximum effective communication distance to the first relay node, it stops searching and starts to act as the second relay for the base station and the third search robot. In our experiments we used three robots, however, for larger distances and more (available) robots this strategy can be extended to larger scale search operations. The general idea of the cooperative search strategy with dynamic networked communication is presented in **Figure 10**.

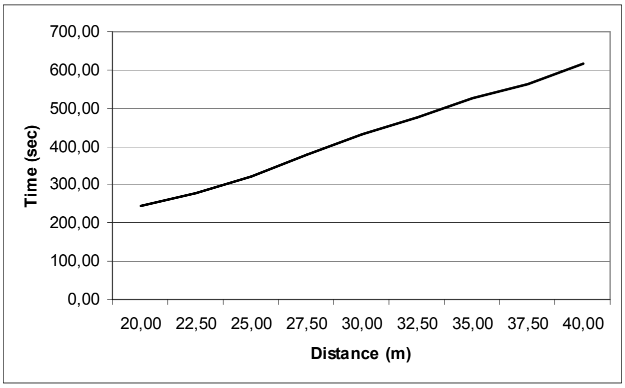


Figure 8. Mission completion time for non-cooperative search strategy.

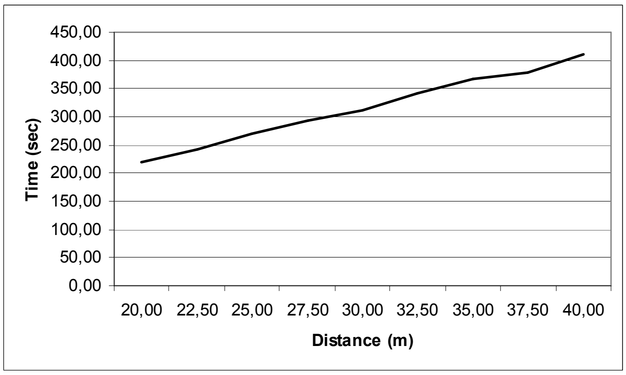


Figure 9. Mission completion time for cooperative search strategy.

The most important advantage of the cooperative search strategy is to shorten the reporting time to the base station when compared to the non-cooperative strategy (i.e., once an object is identified it can instantly be reported back to the base station through the ad-hoc wireless network maintained by the robots acting as relays). **Figure 9** presents the mission completion time for the cooperative search strategy. As discussed in the previous subsection the mission completion time increases (again almost linearly) with increasing distance between the base station and the object. As can be seen from the figure the mission completion time for case of 20 meters distance of the object from the base station is about 225 seconds, while it is about 410 seconds for the case the object is located at about 40 meters from the base station. This shows that for the 40 m object distance the mission completion time for the cooperative search strategy is about 30 % less than the mission completion time of the non-cooperative search strategy. As the distance and the number of robots increases this may increase even further.

The above result shows the effectiveness of the cooperative search strategy and the importance of communication for that purpose. There might be many applications where the communication links to the base station should be kept always on, which may be critical for the performance of the system. However, we would like to emphasize here that we do not by no means claim that the strategy discussed will be more effective in all applications, terrains, and situations. Nevertheless, the study complies with previous results on cooperative search while stresses the importance of dynamic wireless ad-hoc networking in multi-robot systems.

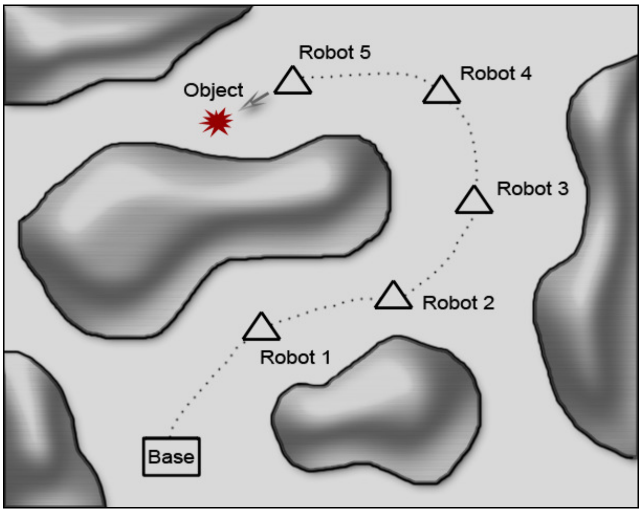


Figure 10. Illustration of the cooperative search strategy.

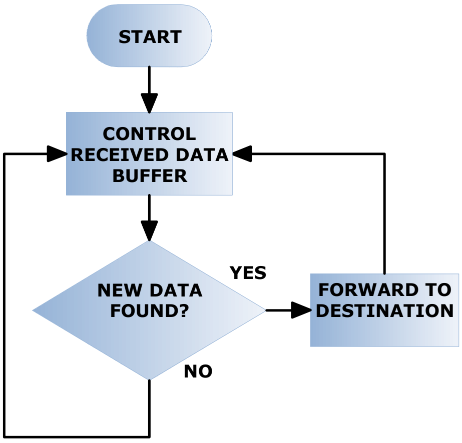


Figure 11. Flowchart of the listen and forward algorithm of the cooperative search strategy.

## IV. CONCLUDING REMARKS

We have presented a cooperative networked dynamic search strategy which can be used in search and rescue operations. That strategy combines the aspects of individual search with networked communication. The results of individual search and the results of networked dynamic search are compared with respect to their measured mission time. For the experiments performed the networked search has better timings for larger distances to the searched objects.

During the experiments there is a great amount of external electromagnetic noise caused by electronic devices in the building such as the wireless access points located in floors and cell phones. That noise interferes with the communication and sometimes breaks of the network link. As a result the measured maximum communication distances are slightly smaller and the measured times are longer than expected. In a less noisy environment the results will be more accurate and more efficient. In addition with the use of more advanced wireless communication hardware the communication between the robots can be more robust.

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