SBIR Phase 1 Final Progress Report

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Project: Smart Communications Infrastructure for First Responders

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List of Terms and Abbreviations

TX: Transmitter

RX: Receiver

RSS: Received Signal Strength

UGV: Unmanned Ground Vehicle

SCB: Smart Command Block

IMU: Inertial Measurement Unit

GPS: Global Positioning System

ROS: Robot Operating System

OpenCV: Open Computer Vision

Abstract

This report summarizes the findings of the work performed under this SBIR Phase 1 Project. The objective of this SBIR is to develop a multi-robot system capable of autonomously deploying and maintaining a portable and temporary communication infrastructure to provide coverage for emergency responders at the scene of an incident. Ability to effectively communicate is extremely important for emergency responders because of the need to be able to effectively transfer voice, video, and data for effective incident management. The problem with most communication technologies is that they require the use of a communication infrastructure to function properly. This poses a challenge to emergency responders trying to use communication capabilities because deploying a communication infrastructure a-priori, or during emergency response is impractical for various reasons including cost, deployment time, and lack of manpower at a scene. The approach we are pursuing is to deploy a portable and temporary communication infrastructure at an emergency scene using a group of robots that work in concert to set up network access points to provide coverage to all emergency responders at a scene. This system will be capable of moving around the scene to ensure that each responder has access to a communication link at all times. Therefore, the system in development will enhance the communication capabilities of emergency responders by deploying a temporary communication infrastructure with minimal human participation. This SBIR Phase 1 effort focused on proving the feasibility of the proposed approach and on building the key pieces of the system so the full development can be pursued with additional funding.

This Phase 1 effort proved that the proposed approach is feasible by achieved the following milestones:

1) Obtained and tested a proof of concept prototype of a mobile system capable of deploy the temporary network infrastructure

2) Designed a multi-robot control approach that optimizes coverage at the scene

3) Developed a block diagram for a fully operational system to be developed in Phase 2.

These milestones will now allow us to pursue additional funding to complete the implementation and evaluation of the system.

Section 1

Significant Key Findings

Key Finding 1: We designed and tested a radio transceiver and the control system for navigation based on a single communication signal. This showed that guiding a robot using the proposed radio sensing approach is feasible. The success rate on fields tests in different building and diverse configurations was 80% as expected from the proposed feasibility metric. The failed cases were in large concrete building with low TX power. Systems with higher power are available and will be used in these types of challenging scenarios.

Key Finding 2: We designed the multi-robot control algorithm to control the navigation of multiple robots providing radio coverage to multiple communication signals. This showed that using multiple robots to provide communication coverage to transceivers inside a building is feasible. We performed 60 simulations with random building sizes between 15 x 15 meters and 30 x 30 meters, random first responder motion and different combination of TX and RX, and we obtained successful behavior in 88% of the tests, higher than the proposed feasibility metric. These results were obtained for simple channel models. More complete channel models will be pursued as the project advances to Phase 2.

Key Finding 3: We obtained a block diagram for a fully operational system and identified its key components considering the possible impact of the proposed approach on emergency response. This has shown that the key technologies to develop this project are available, and that the final system to be fully developed in Phase 2 will operate according to emergency responders needs and will not introduce new hazards to the emergency scene. The challenge will be to find the right trade-off between the system intelligence and the algorithmic complexity and hardware cost. We will work closely with our First responder consultants to design the least expensive yet useful system possible.

Translation of Findings

The findings during this Phase 1 effort will allow us to fully develop, implement, and test the proposed concept in the field. These findings have allowed us to verify that the proposed approach to deploying a smart, portable, and temporary communication infrastructure is feasible. The tests performed during this Phase 1 have been simplified so that we can address different feasibility challenges. Extensions in the level of autonomy, RF channel modeling, and system implementation will be pursue in Phase 2 so that a full system is implemented and tested.

Outcomes/ Impact

Reliable communications are key to first responders' safety when entering a scene. This project has taken us one step closer to being able to implement and deploy a system that increases the reliability of communications in emergency response. Future research that will derive from this project will be performed towards achieving the goals of being able to provide reliable communications and support first responder localization being developed with the support of various other agencies (e.g. DHS).

Section 2 – Scientific Report

1. Background for the Project

Reliable wireless communication capabilities for emergency responders are key to successful operations [1-5]. However, most communication technologies have severe limitations when applied during emergency situations [1]. In particular most communication solutions have problems maintaining the transmission quality in dense urban environments [1]. This problem is mainly due to the limited penetration of radio signals into large structures. One approach to addressing this limitation is to set a communications infrastructure that provides complete coverage to all personnel at the scene. Technologies that use of some type of infrastructure include: repeaters, Wireless Local Area Networks (WLAN), Wireless Mesh Networks (WMN), Bi-Directional Amplifiers (BDA), Ultra Wide Band modulation (UWB), Power Line Communications (PLC), and Radio over Heating, Ventilation, and Air Conditioning systems (RF-over-HVAC) [1, 6]. Two approaches for deploying an infrastructure are currently available: 1) Set the infrastructure a priori (applicable to all technologies), and 2) set up the infrastructure manually during emergency response (applicable to all except PLC and RF-over-HVAC). Both approaches are impractical because of cost, regulatory issues, deployment time, lack of manpower at the scene [1].

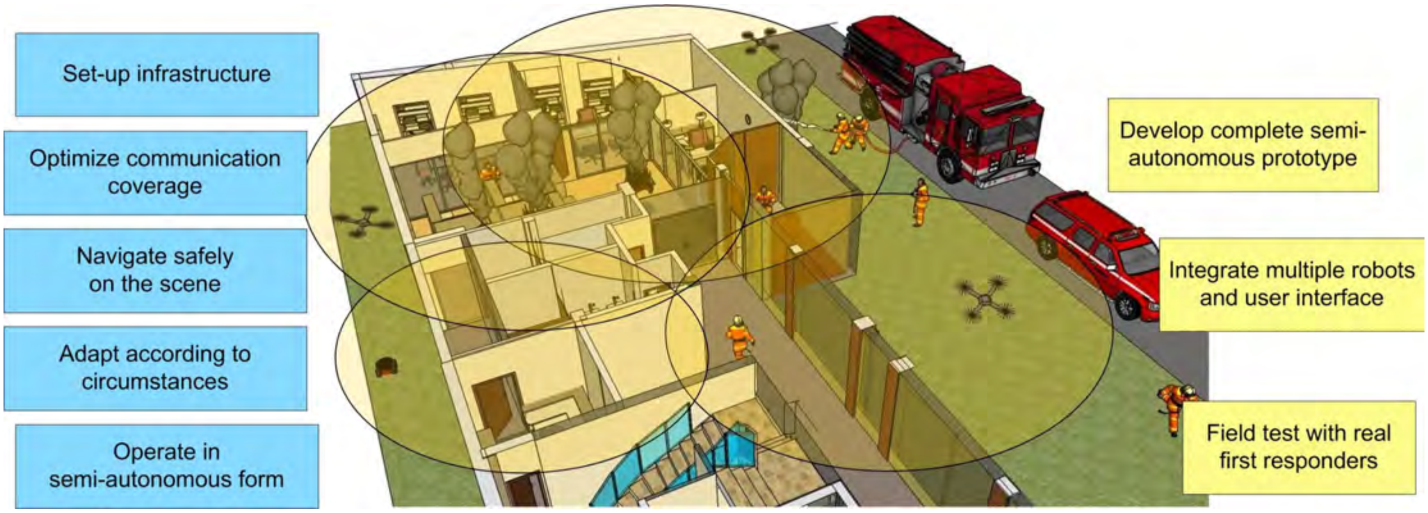


Figure 1: Multiple robots move around the scene providing communications coverage (light orange circles over-layed on the building) to first responders in the building. The blue blocks on the left summarize the characteristics of the system. The yellow blocks on the right indicate the objectives for Phase 2.

This SBIR project is focused on developing a multi-agent system that is capable of autonomously deploying and maintaining a portable and temporary communications infrastructure to provide coverage to emergency responders on the scene. The proposed system (Figure 1) consists of several robots that work in unison with each other and the emergency responders to deploy network access points that enhance the communication coverage to all responders at the scene. The proposed system will be capable of adapting to the dynamics of any emergency scene by using the mobility of the robots to change the position of the communication access points in coordinated manner. The motion of the robots will be controlled such that the quality of communications between all the responders at the scene, the robots, and the command center is optimized. Therefore, **the innovation of this project is the ability to create and maintain a communications infrastructure in a highly dynamic environment by using a group of autonomous robots.**

The proposed system will act in a semi-autonomous manner: The robots will obey simple language-like commands (e.g. Deploy, Retrieve, Ensure Communication), while the real-time control needed to achieve the specified behaviors will be completely autonomous. So, in a typical emergency situation, the robots will move to an initial configuration as soon as they are deployed. Then the robots will use communication quality data to update their location improving the radio coverage for emergency responders. Once the emergency situation concludes, the robots will go back to the command center after receiving the retrieval command.

The intended end product of this project will be the multi-robot system capable of deploying a temporary and mobile network infrastructure. The core innovation of the proposed system is the radio sensing capability and the control algorithm that uses the communication signal quality to control the motion of the robots. The final system will be developed in this Phase 2 by integrating multiple navigation techniques (GPS [63] and maps [54], ranging [55 - 57], stereo vision [63, 65]) with the communication-based motion planning developed in Phase 1 obtaining a semi-autonomous ground robot platform capable of moving to optimize communication quality. Then this will be integrated with other robot replicas, a user interface and the cooperative control policies developed in Phase 1 and early Phase 2 to obtain the complete system.

Alternative solutions to deploying a network infrastructure for emergency response have important capacity limitations. Alternatives include Ad-hoc networks, Medium Frequency (MF) and Very Low Frequency (VLF) radios. Ad-hoc networks are self-organizing networks where every node may be used to transfer information between the origin and the destination. So, deploying an Ad-hoc network during emergency response would be as easy as having each emergency responder carry an Ad-hoc transceiver. The drawback of this approach is that the capacity degrades as more nodes are added to the network [1, 6], which limits their application in high data rate transfers like video. MF and VLF radios work on frequencies that travel better across obstacles, which improves their penetration capabilities in cluttered environments. The drawback is that these radios provide narrow bandwidths, limiting high data rate transfers as well [1].

This SBIR proposes the following innovations in contrast to ongoing research on robotics, cooperative systems, and self-organizing networks:

- The proposed system is semi-autonomous, which requires less human supervision than tele-operated systems available in the market [7 – 9] and research Labs [10 - 12].
- The proposed system will use communication quality measurements to plan and execute the motion of the robots deploying the network infrastructure. Few results with similar approaches [13 – 17]. Most of the previous results propose generic solutions to achieve cooperative behavior without focusing on a particular application [18 - 34].
- The proposed system should be considered a capability enhancer for self-configurable networks [6, 35] rather than an alternative. This is especially true in the newest WMN, which can be seen as a combination of infrastructure-based, and Ad-hoc networks [6].

The proposed system will impact emergency responders' operations by improving the communications coverage and reliability for any type of information exchange:

- Emergency responders will be capable of deploying a temporary and mobile network infrastructure with minimal human participation due to the semi-autonomous nature of the proposed system.
- The proposed communication system will be dynamically responsive to situational changes due to the ability of the robots to use communication quality as feedback for self-configuration. This will improve the overall reliability of emergency responder’s communications.
- The proposed system will be adaptive so that robots can be added or removed on the fly. Note that a minimum number of robots should be used for optimality but multiple systems will be able to interact

in large-scale emergencies, addressing the interoperability issue of multi-jurisdictional incidents.

- The proposed system will work with various communication technologies common among emergency responders [36 – 38]. For example, the proposed system will improve the capabilities of K&A's video transmission system [36] by enabling the deployment of repeaters and mobile IP video systems.
- The ability to automatically set access points will eventually facilitate commanders to track and locate emergency responders inside a structure using RF-based tracking systems under development [39].

During Phase 1 of this SBIR project, the implementation of the proposed approach has proven feasible. A proof of concept system of a single robot capable of measuring a received radio signal and moving to improve its reception capabilities has been implemented. Simulation studies single and multiple robots have been performed showing that the use of multiple robots to provide radio coverage to first responders provides an improvement over using a single static receiver (RX). Finally the main components of the full prototype have been specified obtaining a block diagram of the system to be implemented in Phase 2.

2. Description of the Innovation

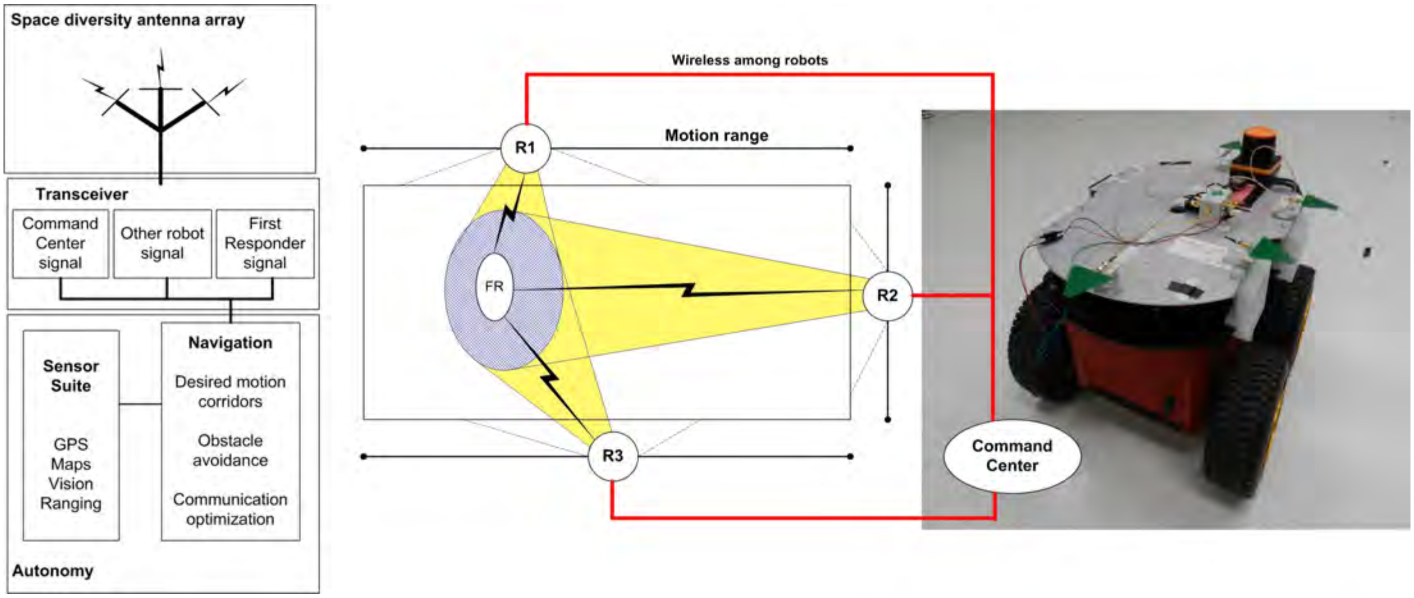


Figure 2: Key innovations of the proposed system. The robot architecture (left) uses a radio transceiver with an antenna array to help the system determine the origin of the signal. The information from the transceiver and the sensor suite (GPS, maps, ranging, and vision) is used by the optimization-based navigation system to drive the robots. The robots move around the building (center) establishing communication among various units at the scene, triangulating first responders' approximate positions, and moving according to the communication performance. A picture of the proof of concept platform developed in Phase 1 with an array of four log-periodic antennas is shown on the (right).

The innovation of this project is to use a multi-robot system to deploy and maintain a communications infrastructure for emergency responders at an emergency scene. The robots will use the communication quality to position themselves in locations that maximize radio coverage. The key components that will allow the system to accomplish this goal are:

- A transceiver that will allow each robot to measure communication quality in the network.
- A cooperative approach that uses space diversity to estimate the possible location of emergency

responders inside a structure and direct the robots in a direction that improves overall communication.

- An optimization-based approach [13, 34, 40 - 48] for each robot that uses proportional fairness to ensure that all first responders receive balanced coverage.
- A control architecture that will use inputs from various sensors [49] to develop simplified motion plans and ensure safe navigation while optimizing communication quality.

The transceiver that will provide each robot with the capability of measuring the quality of service will consist of an antenna array and a radio transceiver with quality of signal indicators. The antenna array provides space diversity to divide the covered area around the robot in sectors. This allows a single robot to measure changes on the quality of signal around it to determine an approximate location of a moving transmitter (TX). The radio transceiver will communicate with emergency responders, other robots, and the command center, and will provide quality of signal indications (e.g., received signal intensity, bit-error rate) to the control algorithms. The control algorithms will use the quality of signal to control the robots' motion.

The cooperative approach to control multiple robots will use signal strength measures from multiple robots around the building to help the system move the robots towards the areas where emergency responders are located, even if not all the robots receive the signal from such responders. This approach will not provide enough precision to track or locate an emergency responder. It will help the multi-robot system to determine the direction of motion that the robots should take to improve the communication performance and increase the communication reliability for all first responders moving inside. The advantage of this approach is that is uses space diversity (both from each antenna array on the robot, and the different locations of the robots) to locate signals of interest and their approximate origin.

The optimization-based approach will be used to maintain communication links among emergency responders, robots, and the command center by improving the overall communication quality for all emergency responders without losing links. This is currently implemented using a proportional fairness approach where the robots attempt to balance the communication coverage so no first responder has a poor signal as a consequence of other first responders receiving more attention from the system. Additional goals like safe navigation and power efficiency will be implemented as modifiers to this motion control goal such that the architecture and the software are as simple as possible.

The control architecture will allow the robots to act semi-autonomously. This architecture will have different modes of operation, which will specify different behaviors for the system. The modes of operation will change according to commands received from operators and events occurring at the emergency scene. Therefore, the robot operators will only need to provide commands to the system while the robots execute the specified behaviors on their own. The behaviors will include, but are not limited to deploying the system, communication assurance, and retrieval. Each of these modes will be developed in Phase 2 as part of the autonomous navigation tasks. The mobile robots in the proposed system will be equipped with various sensors including inertial navigation systems [50, 51] and GPS receivers [52, 53] and a map database [54] for robot localization, and range sensors [55 - 57] and a vision system [65] for obstacle detection. The control architecture will take the GPS and map information an generate preliminary motion corridors where the robots will be allowed to move, and the robots will use obstacle avoidance capabilities and the communication aware motion planning to move safely inside these motion corridors safely while providing reliable communication coverage.

3. Specific Aims and Summary of Findings

The Phase 1 effort was planned to prove the feasibility of developing the proposed system. The intention was to develop the key components of the system to show they could be assembled in Phase 2. There were three specific aims planned, which were proven to be feasible during Phase 1:

Objective 1 - Obtain the radio transceiver and the control system for navigation based on a single communication signal. The completion of this objective showed that guiding a robot using the proposed radio sensing approach is feasible. The specific measure of success proposed in the Phase 1 proposal was test the robot in 20 trials and show that a robot moves around a 4000 square foot single story ordinary construction building according to the received signal quality 80% of the time. The approach we actually took was slightly modified. We tested the system for 20 times after the control law was designed and the system showed the desired behavior. 4 times was tested in Marhes Lab. at UNM programming the robot to move directly towards the TX. 6 times was tested in Marhes Lab. programming the robot to move parallel to a wall and attempting to maximize the received signal. 4 times was tested outside at UNM campus where buildings have thick concrete and metallic walls. Finally 6 times, was tested at K&A headquarters programming the robot to move parallel to a wall and attempting to maximize the received signal. We believe this approach gave us a better understanding of the system behavior and more testing variety compared to the original approach. The system successfully behaved in all tests 16 out of 20 tests. The failed tests occurred at UNM campus. However, we were able to determine that the problem was that the power output of the Zigbee transceiver used for the tests was too low for propagation through thick walls and we will address this issue in **Phase 2** by using higher transmitted power systems like K&A proprietary system or Wifi systems.

Objective 2 - Design the multi-robot control algorithm for navigation based on multiple communication signals. The completion of this objective showed that designing a control algorithm capable of driving multiple robots that provide coverage to multiple emergency responders at a scene based on measures of the communication signal quality is feasible. The specific measure of success was to simulate 50 different configurations varying number of robots and emergency responders, building sizes, and communication configurations, and obtain an optimal behavior in 80% of the tests. We performed 60 simulations with random building sizes between 15 x 15 meters and 30 x 30 meters, random first responder motion and different combination of TX and RX (between 2 and 4 TX and 1 and 3 RX), and we obtained that in 53 cases (88%) the smart infrastructure was better than fixed nodes at a command center location.

Objective 3 - Obtain a block diagram for a fully operational system that identifies its key components, and considers the possible impact of the proposed approach on emergency scenes. This has shown that the key technologies to develop this project are available, and that the final system to be fully developed in Phase 2 will operate according to emergency responders needs and will not introduce new hazards to the emergency scene. The specific measure of success was to show that a working prototype of a fully operating system can be implemented in Phase 2. We obtained a system architecture based on off-the-shelf robots equipped with most of the desired sensors. In addition we will integrate additional sensors initially using professional robotic parts and then pursuing cost reductions with lower cost sensors and proprietary software to be developed in **Phase 2.** We also listed open source libraries and source code available for the implementation we will pursue during **Phase 2**.

4. Methodology and Detailed Results

PROOF OF CONCEPT ROBOT WITH SPACE DIVERSITY TRANSCEIVER (MILESTONE 1)

The key component in the proof of concept developed during Phase 1 is the RF sensing system. We used the concept of antenna diversity differently from its typical use in communication systems. Four directional antennas (log-periodic) were placed on top of a mobile robot to be able to determine the approximate direction of the origin of the signal. All antennas were connected to a radio transceiver through and RF-switch that selected one antenna at a time to determine the received signal intensity through that antenna. By iteratively selecting one antenna at a time the robot was able to determine the direction it should move to increase the the intensity of the received signal.

Figures 2 and 3show the platform used for testing. The MobileRobots Pioneer P3-AT is a differential drive unmanned ground vehicle (UGV) with an on-board computer and interface to connect several sensors such as Laser Range Finders, GPS, IMU. In this particular work the only sensor used on the robot is a XBee ZigBee node. This small, low-power module works as a transceiver and allows the creation of mesh networks. Two XBee were used in the experiments: one as a TX to simulate an exploring first responder and one as a RX installed on the UGV. The RX XBee on the robot is connected to a RF switch that selects one of four different ports. Each port is connected to a log-periodic directional antenna (Figure 3 right).

Figure 3: Proof of concept prototype. This platform was used to test the antenna diversity sensing system and the motion planning for communication coverage.

The motion planning for the robot was implemented in the following way.

- At each iteration the robot was programmed to switch between the four antennas and read the Received Signal Strength (RSS);
- The smallest RSS was selected and, depending on the position of the relative antenna, the robot was moved in the environment toward the maximum of the gradient of the signal.

Figure 4: Motion sequence of the robot with the antenna array transceiver on top approaching the origin of the signal.

The robot was moved for a predetermined amount of time and when stopped to avoid instability. The above iteration was repeated in a loop. Several types of experiments were performed:

- At the Marhes lab at UNM. Both the TX and the RX (robot) were positioned in the same room without obstacles blockage. The robot was expected to move towards the fixed TX.
- At the Marhes lab at UNM. The TX and the RX (robot) were positioned in the different rooms. The wall dividing the rooms was not even (metallic closets, doors). The robot was expected to move parallel to the wall increasing the received signal.
- Outside at UNM campus. The TX and the RX (robot) were separated by thick concrete and metallic

walls. The robot was expected to move parallel to the wall increasing the received signal.

- At K&A headquarters. The TX was located inside or outside the building always separate by at least one wall while the robot was moved along a hallway. The robot was expected to move parallel to the wall increasing the received signal.

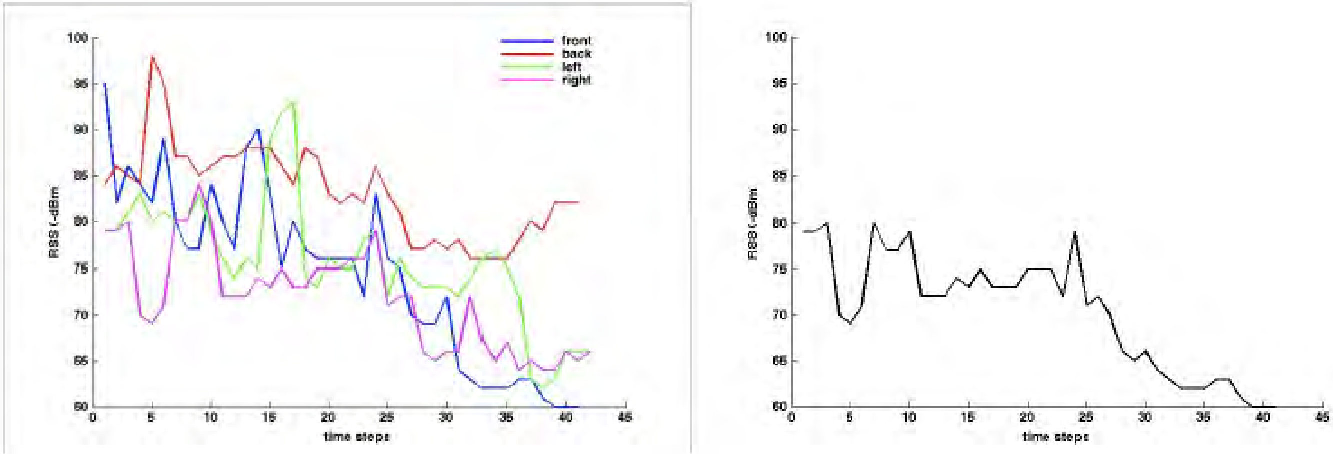


Figure 5: Signal strength (in -dBm) received by each antenna (left) and maximum signal strenght received among the antennas in the array (right) corresponding to test in Figure 4.

Most of the tests were successful. Only the tests performed outside at UNM campus were not successful. This was due to insufficient power on the Zigbee transceiver to penetrate thick concrete and metal walls. The figures below illustrate the results we obtained. Figures 4 and 5 showcase the test where the robot moves toward the origin of the signal when both transceivers are in the same room. Figures 4 shows a sequence of the motion of the robot approaching the origin of the signal. Figures 5 shows the RSS received through each antenna (left) and the maximum signal strength chosen by the robot at each iteration. As expected, the RSS increases as the robot approaches the origin of the signal.

Figure 6: Motion sequence of the robot with the antenna array transceiver on top approaching an optimal reception location.

Figures 6 and 7 showcase one of the tests where the robot moves parallel to a wall looking for an optimal reception location, while the TX is located outside or in a different room separated by at least a wall. Figure 6 shows a sequence of the motion of the robot towards an optimal reception location. Figure 7 shows the RSS received through each antenna (left) and the maximum signal strength chosen by the robot at each iteration. As expected, the RSS increases as the robot approaches the optimal point of reception.

MULTIPLE ROBOTS COVERAGE (MILESTONE 2)

In this part of the work we used Matlab simulations to develop and validate the control approach that allowed multiple robots moving around a building to provide coverage to first responders moving inside. To simplify the problem we focused on rectangular buildings, and robots moving parallel to one of the external wall of the building. The motion of the TX inside was random, only constrained by the boundary of the building. We explored two propagation models: standard path loss, and modified path loss for indoor environments. The only difference between them is that the latter has more signal attenuation than the former. The TXs moving inside had a fixed transmitted power. The RXs outside had four antennas with an idealized radiation lobe of a 60 degrees-cone (similar to the developed prototype) that allowed the robot to determine the approximate direction of the origin of the signal relative to the robot location and orientation.

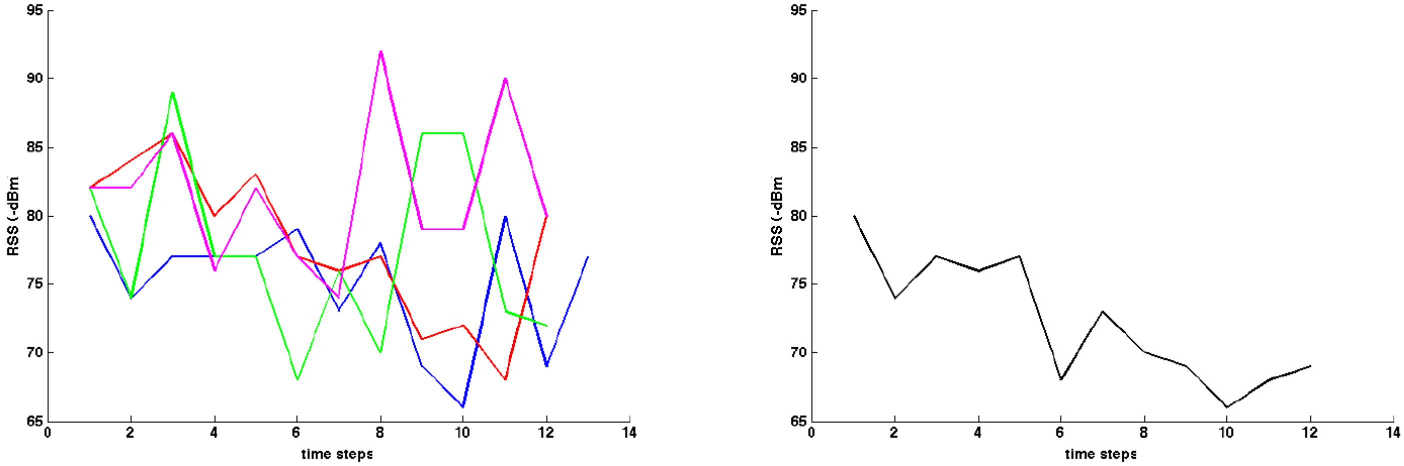


Figure 7: Signal strength (in -dBm) received by each antenna (left) and maximum signal strength received among the antennas in the array (right) corresponding to test in Figure 6.

The performance function depends on the signal received by each robot in the system. We assumed that the communication between the robot and the command center (both outside the building) is reliable. The control of the robots was developed using proportional fairness principles previously explored for control of robots and networks [46 - 48]. The idea is that each receiving robot locates itself in a position that allows it to balance the coverage among all TXs inside the building so that no TX receives less coverage.

The work performed in Phase 1 covers the most critical part of the proposed system, the communication aware motion planning. However, **Phase 2** will still need to be focused on development of the deployment and retrieval approach for the robots, and on the search for communication signals once deployed. In addition, extensions for the work on communication-aware motion planning will be needed in **Phase 2** in order to make the control more realistic. These extensions will be pursued by adding probabilistic modeling to the communication and sensing model of the system [14, 15, 58]. These extensions are:

- Relax assumption of existence of a 100% reliable communication channel between command center and every robotic access point.
- Include multi-path effects in the channel model.
- Include modeling indoor obstacles that make communication less uniform.

As pointed out above, the final approach was tested with varying numbers of robots and first responders moving in rectangular buildings of random sizes. The result was that 88% of the time the system behaved better than compared to fixed nodes. This is an encouraging result, which satisfies our feasibility metric. The figures below showcase the types of result we obtained in this part of the work.

The illustrated simulation has four TXs moving inside a rectangular building, and three mobile RXs moving parallel to three walls of the building. To determine if the approach provides any improvement compared to standard system we also simulated the performance of the same motion pattern for the TXs, and fixed the three RXs in a location that emulates a reasonable commander's post (x=0,y=0).

Figure 8 shows the performance of the system over time (blue circle markers) compared to the same number of fixed RXs at the command center location (green cross markers). As expected, the performance of the mobile system is superior to the system with static RXs all the time.

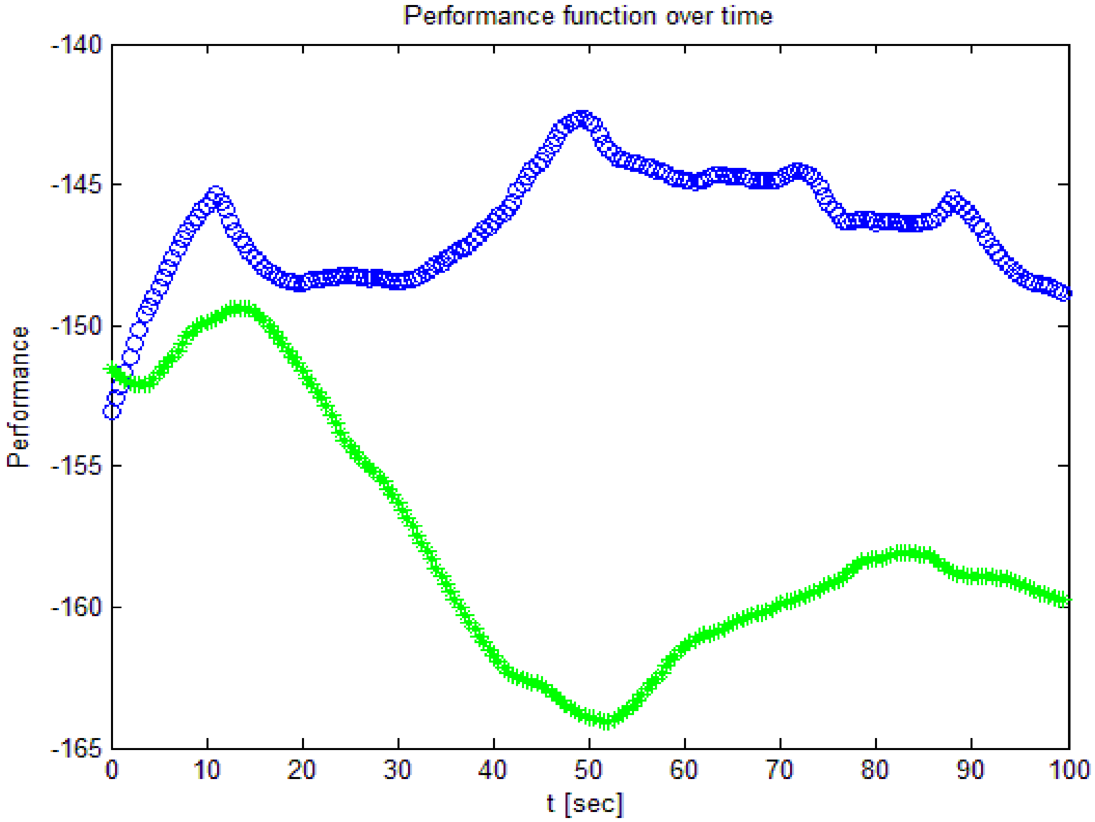


Figure 8: Performance of the mobile system (blue circle marker) compared to an static RXs (green cross marker)

Figure 9 shows the detailed XY trajectories of the TXs and mobile RXs in four snapshots corresponding to 25 seconds of motion in each snapshot for a total of a 100 seconds test. Note that by carefully inspecting the timing in Figures 8 and 9, one can see that the static system performance largely depends on the location of the TXs inside the building, while **the mobile system is able to obtain even performance over time regardless of the location of the TXs**. For example looking at the snapshots on the bottom of Figure 9, most of the TXs are located far waya from the command center location at (0,0). During this time (the last 50 seconds of the simulation) Figure 8 shows a larger difference between the performance of the static system and the performance of the mobile system, which is not the case for the first 25 seconds (top left in Figure 9) where the TX are closer to (0,0).

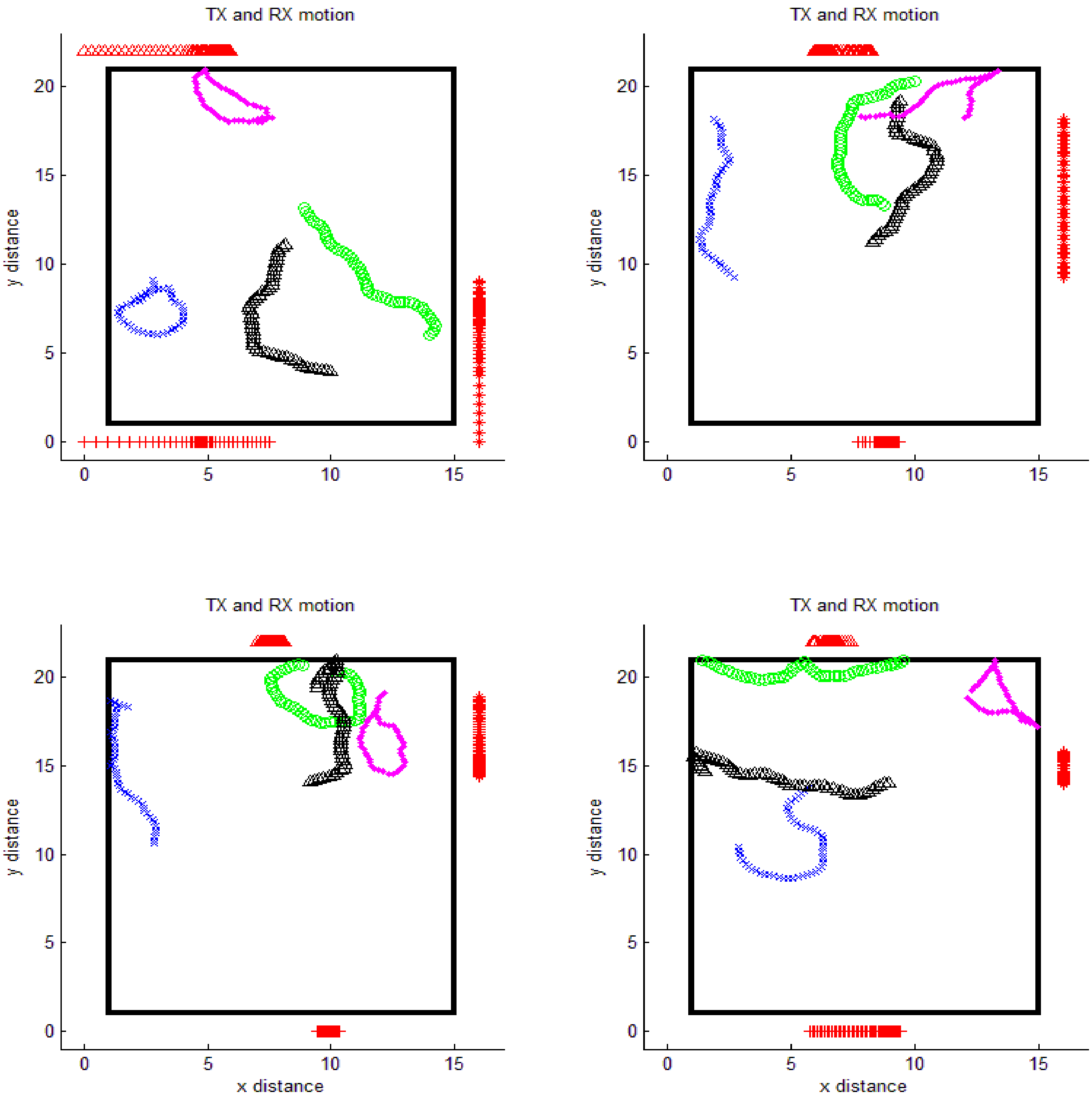


Figure 9: Trajectories of four transmitters inside a building and three RXs outside. The transmitters inside move randomly, while the RXs outside use proportional fairness-like policies to chose their location. Top left corresponds to 0 to 25 sec, top right to 25 to 50 sec, bottom left to 50 to 75 sec, and bottom right to 75 to 100 sec.

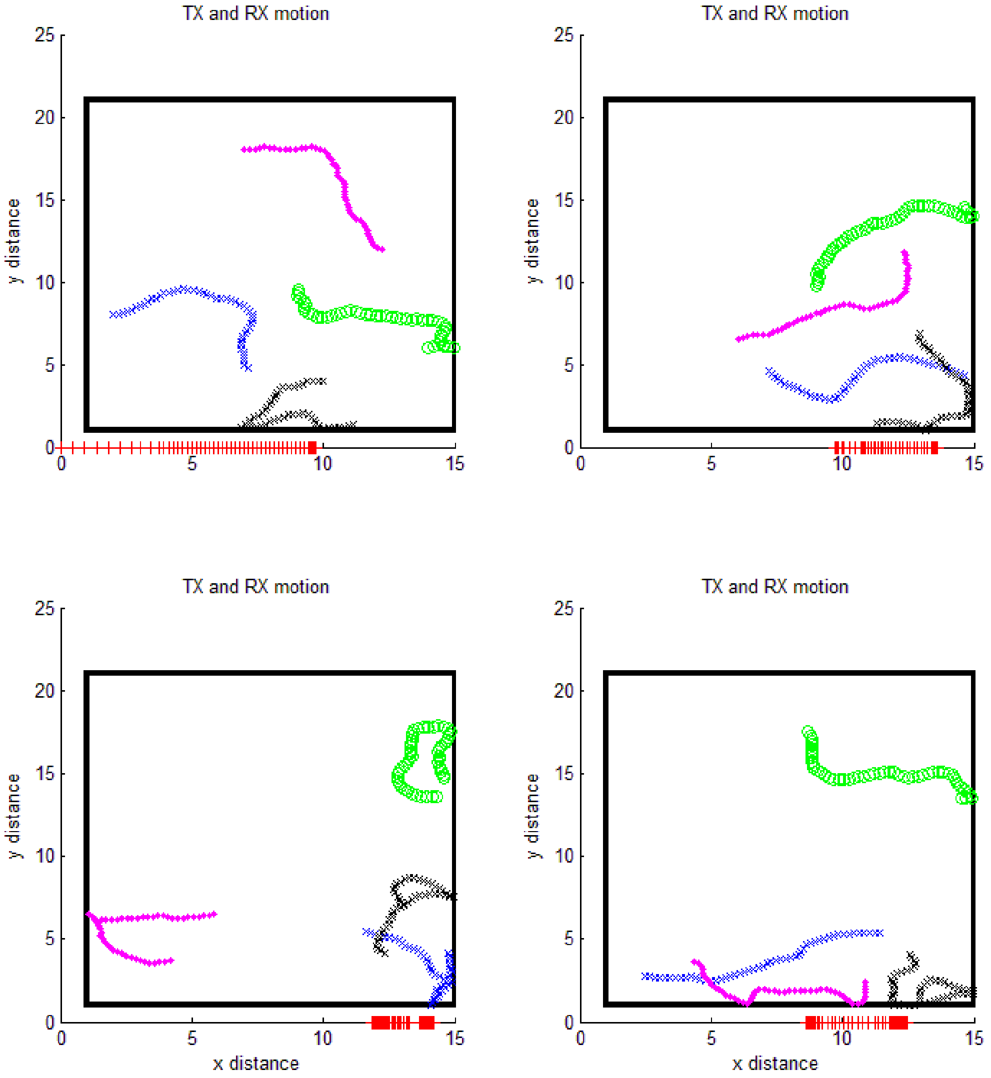


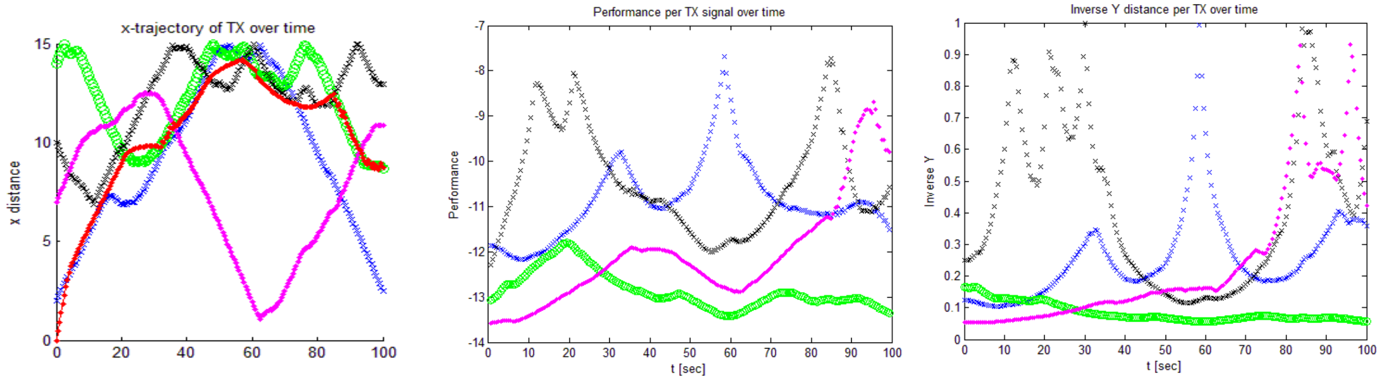
Figure 10: XY trajectories of four TXs moving inside a building and one mobile RX moving along the X axis on the bottom. Top left corresponds to 0 to 25 sec, top right to 25 to 50 sec, bottom left to 50 to 75 sec, and bottom right to 75 to 100 sec. It can be seen that the robot moving outside the building tends to track the TX that is the farthest in the Y dimension as a result of the proportional fairness-like policy.

A more in-depth analysis of the system can be performed if considering a single robot optimizing coverage for multiple TX moving inside. In this particular case we show a single robot providing coverage to four first responders moving inside. There are two special features of the system that this test highlights:

- The robot has a tendency to track the TX that is the farthest from it in the uncontrollable dimension. For example if the robot moves along the X axis, then the Y distance between the robot and the TX is uncontrollable because it depends entirely on the trajectory of TX moving inside. Then the robot tends to track the trajectory of the TX that is the farthest from it because of the proportional fairness policy.

- The performance function for a single robot tends to track the distance between the robot and the TX in the uncontrollable dimension. This indicates the the robot is maximizing the communication.

These two features can be observed in the following plots. Figure 10 shows the XY trajectories of the TX and the moving robot. The robot tends to move closer in the X dimension to the TX that is farther away in the Y dimension (Magenta dots in the first plot of the sequence, and green circles in the remainder plots). Figure 11 (a) shows the X trajectories of the TXs and RX over time. Here we can also note that the robot (Red cross) moves to catch up with the magenta dot trajectory in the first quarter of the trajectory (which which is further away in Figure 10). Then the robot's X trajectory moves closely to the green circle trajectory (which is farther away in Figure 10). Figure 11 (b) shows the performance of the received signal of each TX, which is closely related to the plot of the inverse of the Y distance in Figure 11 (c). These observations support suggest that the robot is acting optimally within the motion constrains that it has i.e. moving in along the X axis only.



(a) (b) (c)

Figure 11: (a) X trajectories of all TXs and the mobile RX over time. Red cross (RX) tends to track green circle (farthest TX) most of the time. (b) Performance over time corresponding to each TX. (c) Inverse of Y dimension value over time. (b) and (c) show to be related confirming that the mobile RX is acting optimally within motion constraints.

SYSTEM ARCHITECTURE (MILESTONE 3)

The system architecture will include a Smart Command Block (SCB) and a number of robots corresponding to a typical urban application (3 to 4 for a rectangular building). The functions of the SCB will include supervising the robot system, interfacing with the incident commander, and obtaining preliminary information about the incident to facilitate the operation. The robots will be designed to satisfy the main goal of enhancing communications, and will have a system that guarantees safe and reliable navigation. The system diagram is shown in Figure 12.The SCB will consist of:

- A high precision GPS receiver, that will help determine the overall location of the system, which combined with mapping information will provide a highly accurate starting point to the multi-robot system, and the information of the building (coordinates, size) that requires communication coverage.
- A Stereo Vision system, that will determine the overall outlook of the scene, obtain additional information about the building, determine feasible deployment paths for the robots, and help on the robot localization while they are on line of sight.
- A communication system that will be capable of communicating with both the robot and the first responder.

- An intuitive user interface the will allow a person to supervise the system and gain access to the system information.

Note the SCB will take advantage of the power available in a car or firetruck to run the most sophisticated and complex processing tasks to release the robotic system of those task and therefore increase the operational time of the whole system.

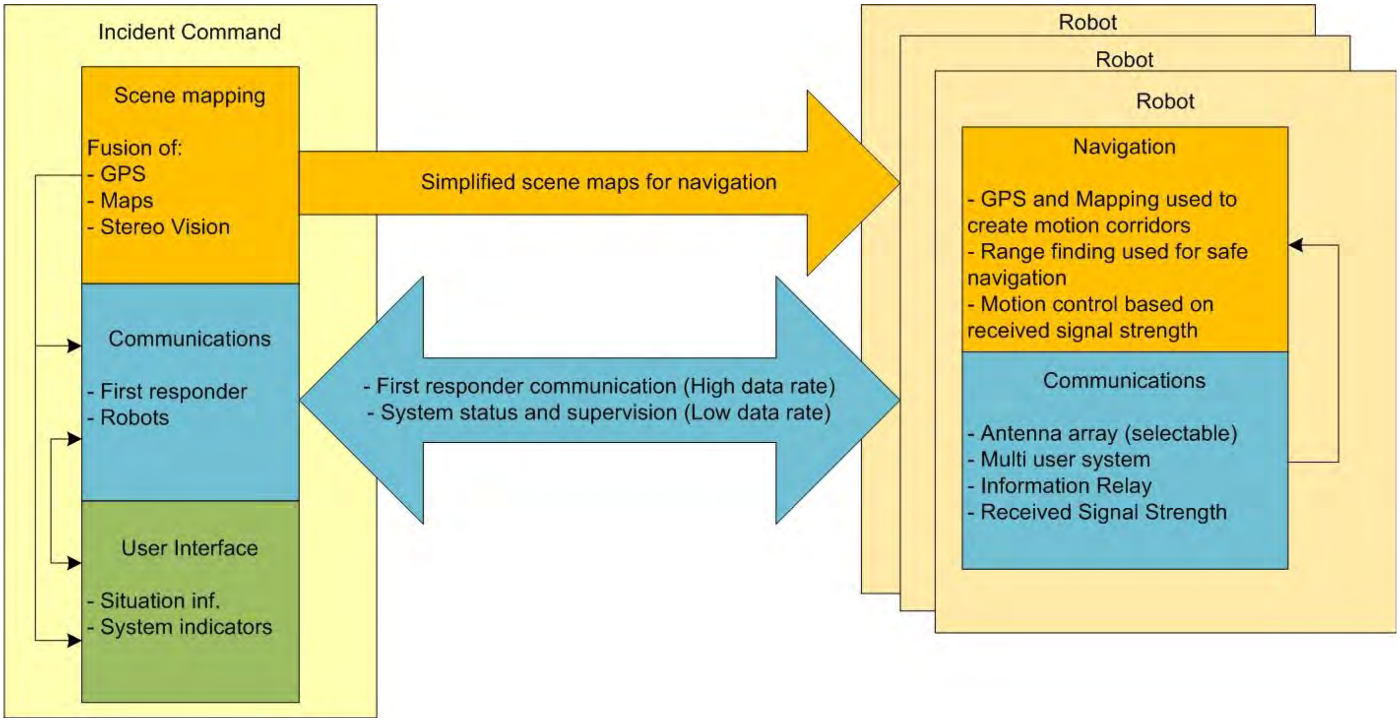


Figure 12: The multi-agent system architecture. On the left the incident command block consists of three main blocks: The scene mapping, the communications, and the user interface. On the right, each robot consist of a navigation block, and a communications block.

Each of the robots will consist of a **motion platform, a navigation block, and a communication block**:

The motion platform is frame of the robot and low-level control electronics. We selected the Dr. Robot Jaguar platform [59] for our prototypes, and also the frame and wheels of this robot for the final product. This is because it is a good trade-off between cost, commercialization path, and development support. Other platforms that were explored include the Adept MobileRobots Pioneer [60], the iRobot PackBot [7], the ReconRobotics throwable robot [61], and the platforms from Robotic Group Inc. [62].

- Adept MobileRobots provided more sophisticated support for development (included autonomy software) but a fully equipped platform was much more expensive ($40,000) and would not have been viable for commercialization.
- The iRobot Packbot was even more expensive ($65,000), provided little support for development but has presence in the Military market that could potentially make it attractive for commercialization. This commercialization alternative will be explored later in the project and probably with additional non-SBIR funds.

- Finally ReconRobotics and Robotic Group Inc. provided little or no development support, which would make it too challenging to develop a fully working system in this **Phase 2** effort.

The selected platform from Dr. Robot provides development support for several software platforms including the Robot Operating System (ROS [63]), which we plan to use during **Phase 2.** This platform also provides a full set of sensors (IMU, GPS, Camera), and options to add more sensors (Laser Range Finders, Stereo Vision), which makes it flexible enough for development within a reasonable cost ($8,000) for a full platform with the basic sensors. In addition it is also worth mentioning that we selected a ground robot instead of a flying robot because flying robots have limited battery life (10 to 20 minutes [64]) compared to hours (by conserving energy) of a ground robot.

The navigation block will consists of IMU (inertial measurement unit [50, 51]) a GPS receiver [52, 53], a ranging solution (Sonar [57], and laser range finder [55], XBOX Kinect [56]), and vision [65]. The navigation block will download motion corridors from the SBC unit in order to determine prefer motion paths. Then it will use its own GPS, IMU, and vision to navigate along those corridors, while avoiding obstacles using its ranging sensors. The IMU, GPS, and basic cameras are already available in the selected platform. We will add the ranging and vision solutions using the ROS [63], and Open Computer Vision (OpenCV [65]) libraries to facilitate the development.

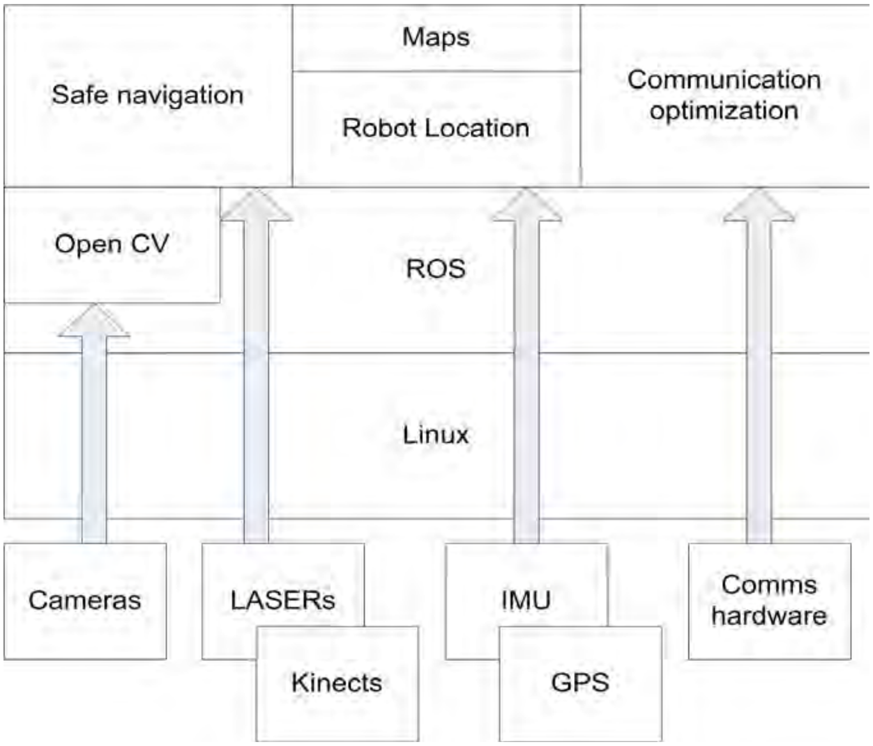


Figure 13: Hardware/Software stack for each robot. The robots will use the Robot Operating System that runs on Linux. The final computing platform will be a single board embedded computer interfaced with various sensors explained above. The vision-based obstacle detection will use Open Computer Vision (OpenCV) libraries. The supervision software will include safe navigation, robot location, and communication optimization.

The communication block will have dual functions in the system: 1) relay information between first responders and the command center and 2) provide information to the navigation system about the desired motion plan for communication purposes. The information that will be transferred to the navigation system will manly be RSS. This information is directly related to the quality of the information to be decoded. This information is readily available in K&A analog video system, and will also be accessible (via software) on the digital communication system in development at K&A Wireless.

The list of parts that was selected for the robots in the system is shown on the table below. This table shows the parts for both types of robots to be build during Phase 2, and a note about which parts are included in which version of the robot.

The hardware/ software stack for each robot is shown in Figure 13. The robots will use the Robot Operating System that runs on Linux. The final computing platform will be a single board embedded computer interfaced with various sensors explained above. The vision-based obstacle detection will use Open Computer Vision (OpenCV) libraries. The supervision software will include safe navigation, robot location, and communication optimization.

Figure 14: K&A Command center receiver already in the market.

The SCB unit will use similar hardware for the cameras and communication interface. In addition it will use a high precision GPS receiver [52] and cell-phone electronics to have access to precise location and environment information. The user interface will be similar to our Receiver Command Center already commercialized (Figure 14). The software stack will be similar to the robot software as well. Mounting alternative for the antennas and cameras will be explored in Fire trucks, and other emergency response vehicles.

Part	Detail	Prototype robot	Low cost robot
Dr. Robot Jaguar 4x4	Complete platform includes frame, motors, GPS, a 9 DOF IMU and a camera [59]. Also sold as frame and motors only.	Complete platform	Frame and motors only
OEM Garmin GPS	High precision GPS for OEMs [53]	Not included	Included
VectorNav IMU	9DOF IMU board [51]	Not included	Included
MicroStrain GPS aided IMU	High precision GPS aided IMU including Kalman based data fusion [50]	To be evaluated	
2 x Hokuyo URG-04LX Scanning Laser Rangefinder	Used for front and back obstacle avoidance. Each has a angular range of 240 degrees a linear range of 4 meters [55].	Included	Not included
2 retail webcams	Used for stereo vision with additional software processing [65] (regular retail cameras)	Included	Included
2 Microsoft Kinects	Used for obstacle avoidance. The objective is that the low cost unit will only use Kinect for obstacle avoidance since laser range finders that are more expensive) [56]	Included	Not included
Single board computer (PC-104)	Used to control the robot [66]. The initial prototypes will use a regular laptop instead of a single board computer to ease prototyping and troubleshooting.	Not included	Included
Standard laptop	For control of prototype robots. Need Linux and ROS [63] installed.	Included	Not included
K&A Communications suite	Analog wireless receivers (existing), Wifi/UWB digital transceivers (in development)	Included	Included
Microcontroller-based interface board and USB HUB	To interface computer with communication suite IMU, and all USB sensors [67]	Included	Included
Maxbotix LV-MaxSonar-EZ1 High Performance Sonar Module	Sonar sensors for lower cost obstacle detection [57] (To Replace laser range finder and Kinect)	Not Included	Included

5. <u>Discussion and Conclusions</u>

In this report we have summarized the findings obtained during the Phase 1 effort. The main objectives were planned to show that the proposed approach to deploying a smart and temporary communications infrastructure for first responders is feasible. These objectives were:

1. Obtain and test a proof of concept prototype of a mobile system capable of deploy the temporary network infrastructure

2. Design a multi-robot control approach that optimizes coverage at the scene
3. Develop a block diagram for a fully operational system to be developed in Phase 2.

These objectives were accomplished and the detailed results have been explained in this report.

An array of antennas was mounted on top of a Pioneer robot available at MARHES Lab. at UNM. These antennas were connected to a Zigbee radio that communicated with another Zigbee radio set at different locations in the Lab, at K&A Headquarters, and outside. Then the Received Signal Strength in each antenna was used to determine the direction the robot should move to improve the signal showing that it is feasible to optimize the communication quality by moving the robot according to the signals received in its transceiver. This completed Objective 1.

A multi-robot control approach was designed and tested in simulations to show that multiple robots carrying receivers with antenna arrays can be driven around a building to improve the communications coverage to transmitters moving inside. The approach was to develop a motion planning algorithms based on proportional fairness principles so that robots look for locations that provides balanced coverage to all transmitters moving inside. The results were compared to fixed receiver placed in a command post location. This showed that using mobile receivers helps improve the overall performance, while the performance of the fixed receivers is largely dependent on the proximity of the transmitters to the receiver's location. This completed Objective 2.

The complete system block design has been specified, and the main components have been identified. This includes robots, sensors, software blocks, and software tools and libraries to be used. This block level design and parts' list will be used in Phase 2, in conjunction with the findings from Objectives 1 and 2 to develop and implement the complete system. This completed Objective 3.

This work will be continued during Phase 2 with the complete implementation of the proposed system. It will also continue with extensions to the muti-robot control approach that consider more realistic models of the channel in order to make the system perform optimally and robustly in a real application.

Section 2 – Publications

No publications have been submitted related to this award.

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