Using Directional Antennas as Sensors to Assist Fire-fighting Robots in Large Scale Fires

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***Abstract*—Humans will replace human labor with new robotics technologies, especially where humans can be placed in danger situations or task domains. Evolving sensor and robotic technologies allow the transfer of humans from mundane, dangerous or difficult tasks, leaving robots to apply their specific capabilities to replace human's daily routines or hazardous tasks. Commonly, humans work in teams to resolve difficult scenarios, such as the aftermath of some natural or man-made disaster. Communication between each and every team member is critical to resolve relief efforts or remediation, in most disasters. This research presents robotic technology developed to remediate the long lead time to re-establish or develop network infrastructure in the case of a disaster situation. The specific application and test domain of this research, is with fire fighting.**

I. Introduction

As robotics technologies have advanced and become more ubiquitous, humans have tried to replace human labor with new robotics technologies, especially where humans can placed in danger simply by doing their job. Evolving sensor and robotic technologies allow the transfer of humans from mundane, repetitive, dangerous or difficult tasks. This leaves robots to apply their specific capabilities to replace human's daily routines or hazardous tasks, and allow the human to take on higher level tasks. Often, humans work in large or complex teams to resolve difficult scenarios, such as the aftermath of some disaster. The first order of business after a disaster is the re-establishment of communication to all pertinent parties to facilitate the relief and rebuilding efforts. To do this, communication between each and every team member is critical to resolve relief efforts in most disasters.

In a disaster area, where previously established networks are incapacitated or destroyed, autonomous mobile robots carrying wireless devices can be deployed to create end-to-end communication. In the event of an earthquake disaster, like Fukushima, Japan, rapid establishment of a wireless backbone is useful, because as it enables rescuers and first responders to communicate and to coordinate evacuation, containment and search-and-rescue missions effectively. The destruction of critical infrastructure will hinder or prevent relief efforts or seriously hinder remediation. The ability to re-establish critical network infrastructure is key in disaster recovery. Unfortunately, often the development of new infrastructure has a long lead time, but lives and critical tasks do not.

This research presents robotic technology developed to remediate the long lead time to re-establish or create new networks in the case of a disaster situation. The specific application and test domain, of this research, is with fire fighting in large structures. Specifically, the development of cooperative robotic technology that can be used to battle large-scale fires in plants, box-stores and other very large structures. These types of structures present a special set of dangers for fire-fighting personnel, due to common roof collapses and structural failure.

The specific motivation is the employment of fire fighting robots in extremely dangerous fire scenarios. For example, a recent very large-scale fire in Hoopeston, Illinois (USA) in July of 2013 [10] [11]. The fire occurred in a tire recycling plant, which was very large and contained thousands of tons of combustible, old rubber tires. As shown in Fig. 1, the fire was large and fire trucks could not approach the fire or disperse water very far into the structure. The building was 400,000 ft^2, as shown in Fig. 2. As the trucks cannot get the water into the structure, this presents a dangerous situation for the fire fighters as they must venture into the middle of a large burning structure, where there is very real danger of structural collapse. In the case of a collapse, there will be a high chance of injury or death to the fire-fighters.

Fig. 1. Inability for trucks to reach a large fire

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Fig. 2. Large-scale fire

To remedy the highly dangerous aspects of fire-fighting, robots have been proposed to fight these specific types of large structural fires. The robots allow the fire-fighter to remain outside of the structure and out of harm's way, for the most part. Fig. 3 shows the Dongil Field Robot *FIRO-M* Model [9] in the middle of the Hoopeston blaze. At this point, it is almost 100 meters into the center of the building. It is fighting a fire where no fireman will ever want to venture. In this case, the fireman had a direct line-of-sight to the robot. But, more could have been accomplished if there was a team of robots that could forge an electronic trail through the difficult terrain of the factory. This allows access to all places where the robot can go to put out the fires or look for survivors.

Fig. 3. Hoopeston, Illinois fire - July 2013

In Fig. 4, there are Purdue fire fighters and the *FIRO-M* robot. This is the proposed common team for any large fire. To integrate these heterogeneous team members, there must be a interface between them, which can be used in a dangerous situation where the main focus is on quelling the emergency. This is the main incentive for this specific research. The development of a reliable network interface between a fire fighter and the robot, so they can act as a team, in the midst of a dangerous and potentially lethal fire scenario. And, they can work using an interface similar to two human fire fighters. This reliable interface must be constant through the very difficult terrain of a complex structure, which is on fire.

Fig. 4. Firefighting robot and fire fighters

The organization of the paper gives the following section on the need for fire-fighting robots. Section III shows the theoretical elements of multi-robot network control. Section IV provides the realization, experiments, results and the proposal for use in linked structures for large-scale fires. Finally, section V provides the conclusion of this work.

II. Fire-fighting Robotic Networks

Typically, there are two possible options for the construction of an end-to-end communication link with autonomous fire-fighting robots. This work is an extension of previous work on tracking and following of robots [13], but applied to a specific fire-fighting domain. The first option involves planning robots' final positions prior to deployment of robots [1]−[4]. This planning should be designed for optimizing the communication link. Thus, this approach is better suited for static environments than dynamic environments and is more useful for scenarios where a rapid establishment of the network is required, because this way does not require a search task.

A second option involves deploying a team of leader-follower robots in a convoy [5]−[7]. This strategy is depicted in Fig. 5. With this option, multiple robots are employed, and only the leader computes navigation trajectories to create the network. The robotic followers do not require any planning and simply follow the leader or the precedent robot. Therefore, this approach is suitable more for dynamic environments because this way is based on classic sensor percept loops with state and not a completely pre-planned strategy.

Although directional antennas have many advantages, it remains a challenge to increase their accuracy for common use as a typical sensory device, similar to laser or ultrasonic sensors in the field of mobile robotics. One common type of directional antenna (the type used in this study) has a beam width that is conical in shape [12]. This broad beam width allows directional antennas to scan a wide area; however, it also yields a more coarse measurement resolution than a non-expanding beam-width, generated by a laser. In addition,

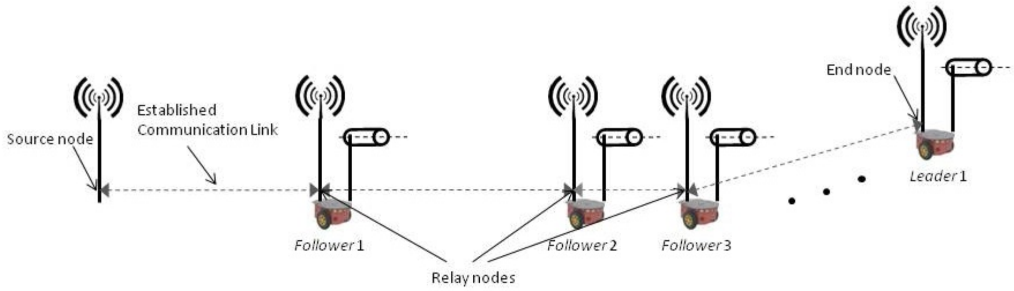

Fig. 5. The overview of a team of leader-follower robots to create end-to-end communication link.

because of the presence of walls and other objects that act as reflectors or scattering obstacles, the signals received by a directional antenna can consist of multiple copies of the same transmitted signal arriving via different paths. This effect gives rise to varying levels of received power, represented as sensor noise or uncertainty. The magnitude of this sensor noise is much larger than typical noise in other types of rudimentary sensors, it restricts directional antennas from being used as sensory devices. This necessitates some filtering of the received signal to remove potential interference.

Because of such inherent issues with directional antennas, we introduced a simple, but powerful bearing estimation technique that is called the Weighted Centroid Algorithm (WCA) in [13] [14]. The WCA is very efficient because it requires only one rotating directional antenna that measures surrounding radio signal strengths, and a little arithmetic composed of summation and multiplication of much lower degree data than other estimation methods.

III. Multi-Robot Network Control

This section describes the interaction between the basic robot control and the interaction required for tracking. The Adept Mobile Robots P3AT [8] is a four-wheeled robot; however, two wheels on the same side are physically interconnected with a rubber belt. For the simple control of this robot for the follower robotic system, differential-drive mobile robots with characteristics of non-slipping and pure rolling are considered. The robot can be then controlled to move to any posture by adjusting the velocity of the left wheel V_L and the velocity of the right wheel V_R. V_L and V_R are calculated with either Eqs. (1) or (2), depending on the current situation of the robot.

$$\begin{aligned} V_L &= v_1 + k_{p1}\widetilde{\Theta} + k_{d1}(\widetilde{\Theta} - \widetilde{\Theta}^{t-1}) \\ V_R &= v_1 - k_{p1}\widetilde{\Theta} - k_{d1}(\widetilde{\Theta} - \widetilde{\Theta}^{t-1}) \end{aligned} \tag{1}$$

$$\begin{aligned} V_L &= v_2 + k_{p2}\widetilde{\Phi} + k_{d2}(\widetilde{\Phi} - \widetilde{\Phi}^{t-1}) \\ V_R &= v_2 - k_{p2}\widetilde{\Phi} - k_{d2}(\widetilde{\Phi} - \widetilde{\Phi}^{t-1}) \end{aligned} \tag{2}$$

A follower robot can either use *bearing estimation* or *obstacle avoidance*. If obstacles are too close, the robot runs with the obstacle avoidance algorithm, activating Eq. (2) for the velocity control. Otherwise, it runs with WCA for bearing estimation, activating Eq. (1) for control. In Eq. (1), $\widetilde{\Theta}$ is the current estimated bearing obtained by Eq. (2) in [13], $\widetilde{\Theta}^{t-1}$ is the old estimated bearing, k_{p1} and k_{d1} are positive gains, and v_1 is the background velocity of the robot, set to change according to a value of the best *Received Signal Strength Indication* (RSSI) measurement from one scanning with a directional antenna, i.e., v_1 is calculated by

$$v_1 = -\omega_1 RSSI^* - \omega_2, \tag{3}$$

where $RSSI^*$ indicates the best RSSI measurement in one scanning, ω_1 and ω_2 are should be set to a positive value and $w_2 \leq |w_1 \cdot RSSI^*|$ for v_1 to be a positive value.

In the same way, in Eq. (2), $\widetilde{\Phi}$ is the current estimated direction obtained by Eq. (8) in [13], v_2 is a constant of the background velocity of the follower that we set to be low to avoid any dangerous situations (e.g., here we set v_2 to be 100, meaning 0.1 m/sec in a P3AT library), and k_{p2} and k_{d2} are positive gains.

For the robot stopping criteria, we use the following condition,

$$\begin{cases} V_L \text{ and } V_R = 0 & \text{if } RSSI^* \geq Threshold \\ V_L \text{ and } V_R \text{ from Eqs.(1) or (2)} & \text{else.} \end{cases} \tag{4}$$

In Eq. (4), depending on a value of $Threshold$, we can differ how close the follower can get to the leader or prevent the follower from getting too close to the leader. Actually, the received power at the follower from the transmitter at the leader can be given by [15]

$$P_{dBm} = \underbrace{L_0 - 10n \cdot \log\left(\left\|x^t - x\right\|\right)}_{Fading} - \underbrace{f\left(x^t - x\right)}_{Shadowing} - \underbrace{\varepsilon}_{multipath}, \tag{5}$$

where L_0 is the measured power at 1 meter from the transmitter, n is the decay exponent, and x^t and x are the positions of the transmitter and receiver respectively. If terms of shadowing and multipath are very small compared to a term of fading, they can be negligible. Then, we can roughly calculate P_{dBm} by pre-obtaining L_0 and n with experiments. Therefore, we can select a proper value of $Threshold$ with Eq. (5) for a desired motion of our follower system. For example, we identified through experiments that -15 dBm of $Threshold$ keeps the follower away from the leader at intervals of 1 meter in indoor environments and -20 dBm for outdoor environments.

IV. Results

In this section, we describe the realization, experiments and results. Then, we propose the usage of the technology in the area of large-scale fire-fighting.

A. Preparation for experiments

To test the proposed methods, we have developed a prototype of the leader-follower robotic system, shown in Fig. 6 and a field test of the system, shown in Fig. 7. The complete system consists of a leader and follower systems. Both systems use the same components, but the leader system has been simplified for this research to place the focus on the follower system. The follower robotic system is made up of the P3AT mobile robot, a laptop, a yagi antenna, Wi-Fi USB adapter, and a pan-tilt servo device. And, as the ultimate goal is end-to-end communication, we have installed two access points and a network switch. In the future, by using a network switch in the communication system, we will be able to easily add additional network devices or laptops to the established communication link between the robots. The leader robotic system is equipped with equivalent equipment as the follower with the exception of the yagi antenna and Wi-Fi USB adapter, for this test.

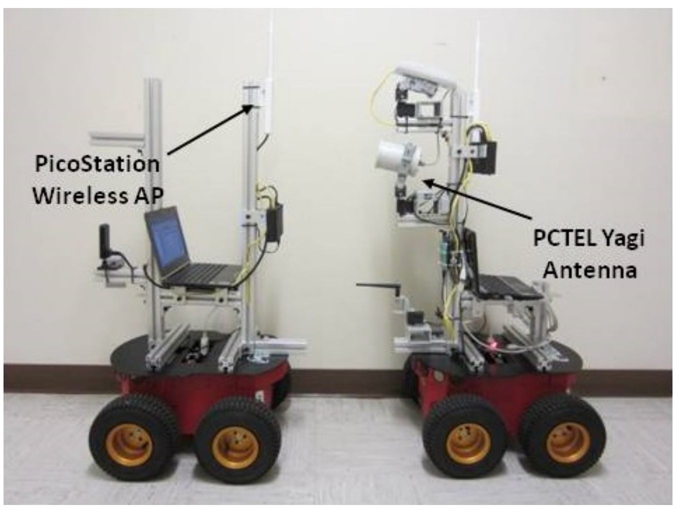

Fig. 6. leader-follower robotic system

For the bearing estimation, we installed a small, light PCTEL yagi antenna. This device resembles a can located on the lower right side of the system as shown in Fig. 6. This device has 10 dBi of gain, uses 2.4 GHz frequency range, and has $55°$ horizontal and vertical beam width at $1/2$ power. For the leader's transmitter which requires an omnidirectional antenna, a low cost, high performance, and small wireless AP (Access Point), Ubiquiti Networks PicoStation M2-HP is used. This AP is equipped with a 5 dBi omnidirectional antenna, and supports passive *Power over Ethernet* (PoE), which does not require an additional power code. Also, it runs with the IEEE 802.11g protocol with an operating frequency of 2.4 GHz, and produces up to 28 dBm output power. As this device was designed to be deployed either indoor or outdoor environments, it is ideal for applications requiring medium-range performance and a minimal installation footprint.

The laptop is connected by a serial connection to the P3AT, the pan-tilt device, and Alfa USB adapter. A pan-tilt device

Fig. 7. Field test of the leader-follower robotic system composed of the follower system

allows the directional antenna to be oriented in specific angle autonomously. In this paper, we employ a pan angle only. The directional antenna chosen has approximately $55°$ beam width vertically, and therefore there are few cases that our robot is deployed out of range. However, it should be noted that vertical beam-width would also affect wireless communication, in some cases.

For parameters needed in Eqs. (1)−(4), we set them as shown in Table 1.

TABLE I. Setting of parameters

Parameter	Value
$Threshold$	-25 dBm
k_{p1}, k_{d1}	1.0, 0.3
k_{p2}, k_{d2}	1.2, 0.6
w_1, w_2	10, 150

B. Experiments

In order to validate the prototype, we conducted three different field tests. We chose a large parking lot at Purdue University for these tests, as shown in Figs. 8, 10, and 12. This parking lot has many of the same obstacles that would exist in a large building structure.

The first test was designed to analyze the performance of the obstacle avoidance algorithm. The leader was manually controlled so that it moves straight to about 15 meters with a constant velocity at 0.2 m/sec. The follower was initially placed behind the building and the squared obstacle about the size of 0.5x0.5 meters when viewed from above. In this planned situation, the follower should avoid the obstacle and the side of the building in order to follow the leader successfully. Otherwise, the follower fails to achieve its goal.

In Fig. 8, the red lines indicate moved paths by the leader. The black lines indicate moved paths by the follower. These lines were drawn by referring to videos recorded during the test and odometer information from the robots. As shown in this figure, the follower could avoid the obstacle and the side of building without any contacts and follow the leader in the long run. Fig. 9 shows that a history of the measured best

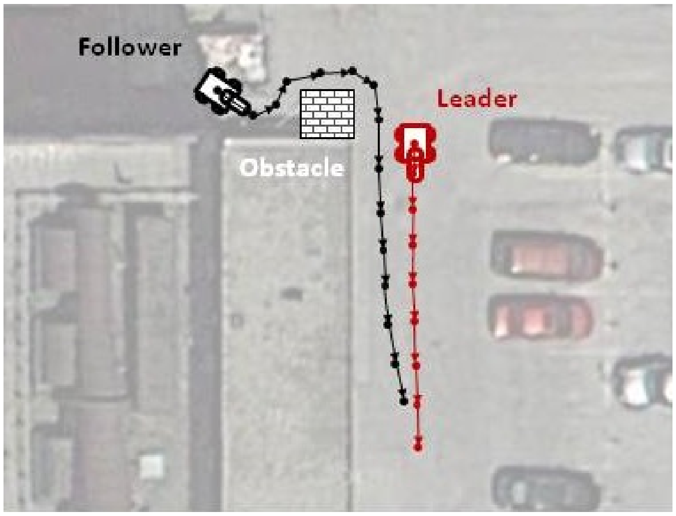

Fig. 8. Traces of the two robots

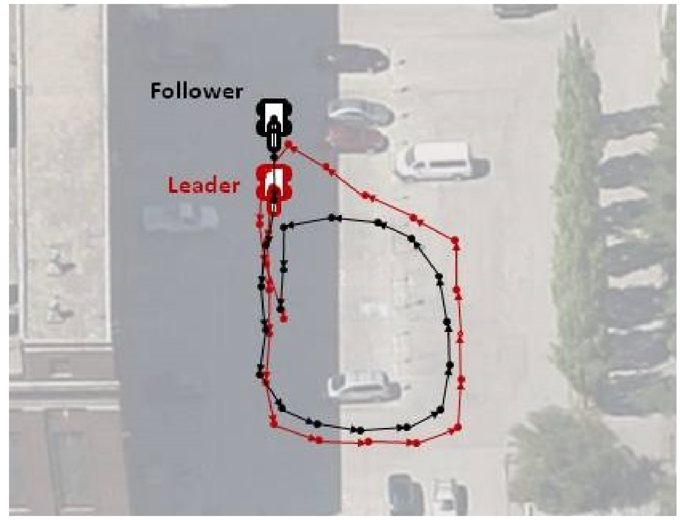

Fig. 10. Traces of the two robots

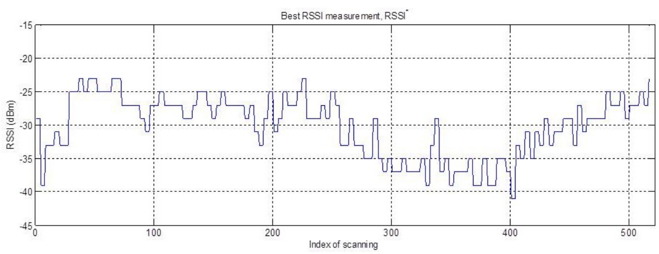

Fig. 9. History of the best RSSI

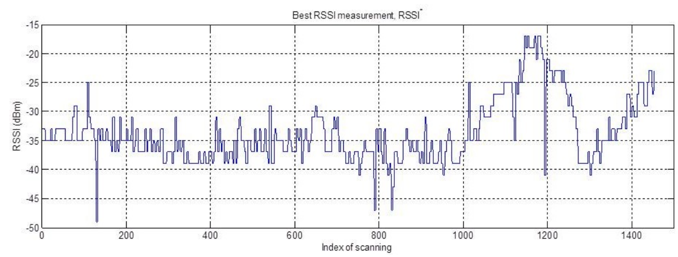

Fig. 11. History of the best RSSI

RSSI denoted with $RSSI^*$. As shown in the horizontal axis, approximately 520 times of scanning were performed during this test. During the first half of scanning, there were few decreases in measured RSSI as the leader and the follower were close to each other. While the leader bore off gradually and the follower focused on escaping from obstacles, measured RSSI became decreased up to about -40 dBm. However, as soon as the follower avoided the obstacles and became free, it resumed following the leader. After that, as shown in the end of the history in Fig. 9, the measured RSSI reached to the pre-defined threshold, -25 dBm, making the follower stop with a close distance to the leader.

Figure 10 and 11 shows the trace of the second test. In Fig. 10, the red lines show moved paths by the leader. The black lines show moved paths by the follower. As shown in this figure, the follower tracked way points that the leader produced relatively well during the entire test. It is shown that there are some noticeable gaps in the paths that two robots moved, but it results from the fact that the leader always moved ahead, resulting the follower changed its heading at a corner before it reaches the path that the leader moved. Figure 11 shows a history of the best RSSI measurements.

Figure 12 and 13 shows the trace of the third test. In Fig. 12, the red lines show moved paths by the leader. The black lines show moved paths by the follower. As shown in this figure, the follower tracked way points that the leader produced relatively well during the entire test, in the face of very sharp paths requiring almost a 180° turn. Figure 13 shows a history of the best RSSI measurements.

C. Linked Robots in Large Scale Fires

Employment of a linkage of follower robots is a natural application for the remediation of large-scale fire scenarios. In the case of the Hoopeston, Illinois tire recycling plant, which by size was 400,000 ft^2, the hottest areas of the fire were not in reach of the truck mounted ladder spray rigs. Nor were the hotspots in places where the fire-fighters dared to venture, for their own personal safety.

In Fig. 14, an aerial view of the Hoopeston fire wreckage is shown. Superimposed over it is a potential configuration of a series of follower robots with a *FIRO* fire suppression robot in the end position. The lead *FIRO* will drive through the wreckage, moving towards the desired hot spot placement. The follower robots will move into position behind the lead *FIRO*, to maintain a strong connection to the base station, exterior to the burning structure, away from mortal danger.

V. Conclusions

This research presents robotic technology developed to remediate the long lead time to re-establish new networks in the case of a disaster situation. The specific application and test domain is robotic fire-fighting, for use of fire fighting robots in the extremely dangerous fire scenarios of large structures, where communication capability is critical, due to the size of the building.

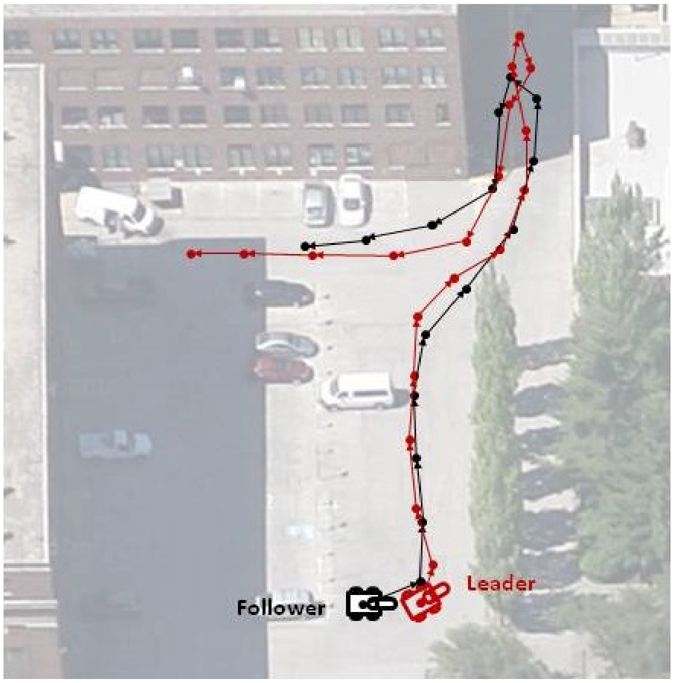

Fig. 12. Traces of the two robots

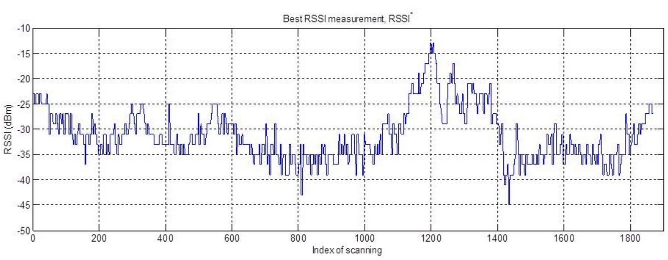

Fig. 13. History of the best RSSI

Although directional antennas have many advantages, it remains a challenge to improve accuracy enough to use them as typical sensory devices to build autonomously configured networks. This research provides techniques that extend and improve the basic capability of the directional antenna configuration into a more useful sensor, for use in many task domains and scenarios.

The results show promise for developing quickly configured networks that can penetrate buildings such as the one in Hoopeston, Illinois to place the robot in a position where it can provide the most relief.

Future work will fully implement the complete scenario on leader-follower teams which are networked. In addition, the follower robots will be extended to assist the leader robot in the logistics of pulling uncharged and charged hoses into a fire scenario. This will assist in navigating the tip-of-the-spear into the most needed places, but also provide water cooling to enhance the life of both the leader and follower robots.

Fig. 14. Firefighting robot linked to base station through a set of follower robots

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