Development and Evaluation of a Novel Robotic System for Search and Rescue

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Abstract. Search and Rescue robotics is a relatively new field of research, which is growing rapidly as new technologies emerge. However, the robots that are usually applied to the field are generally small and have limited functionality, and almost all of them rely on direct control from a local operator. In this paper, a novel wheeled Search and Rescue robot is proposed which considers new methods of controlling the robot, including using a wireless "tether" in place of a conventional physical one. A prototype is then built which acts as a proof of concept of the robot design and wireless control. The prototype robot is then evaluated to prove its mobility, wireless control and multi-hop networking. The experimental results demonstrate the effectiveness of the proposed design incorporating the rocker-bogie suspension system and the multi-hop method of "wireless tethering".

Keywords: Search and rescue robot, rocker-bogie system, wireless control, multi-hop network.

1 Introduction

Disaster scenes such as a collapsed skyscraper, an earthquake in a densely-populated area or a collapsed tunnel are not exclusively fatal at the time the disaster strikes. Search and rescue (SAR) services must operate quickly and efficiently, as the first full day immediately after poses numerous risks to life from unstable rubble to fires spreading through ruins. This is not only dangerous for the potential survivors but also for the rescue workers [4].

Many robots have been proposed over the past years into the field of SAR to reduce the risk to human life, but these robots face many limitations; cost of repair or replacement if damaged, scenarios where GPS location is unavailable, unsuitable traction method for a specific type of terrain, poor communications with base station, and general efficiency of conducted search [23].

Searching under rubble for survivors is often a battle against time but is crucial to survival of any person trapped in voids under rubble. However, there is no single tactic that is efficient enough to employ on any given disaster scenario that ensures a thorough search, given the complexity and uniqueness of building collapse patterns. The prevailing methods for localising trapped people remain physical searching, audible callingout, search cameras and fibre optics/borescopes, thermal imaging, electronic listening devices and canine searching [24]. These methods have advantages and disadvantages, but the main problem is the need for rescue workers to stand in the proximity of or on unstable debris. This poses risk to both survivor and rescuer.

Extensive research has been done to implement robotics into SAR to help the trapped people survive in hazardous environments. However, the choice of SAR depends on the nature of disaster [13]. Natural disasters generally affect a wide area and the victims are largely dispersed. Unmanned Aerial Vehicles (UAVs) and Unmanned Surface Vehicles (USVs) have the potential to be employed in such scenarios.

Manmade disasters, however, pose different challenges; they are generally more concentrated, and thus the focus is often less on surveying the full extent of the damage but rather to search the remaining rubble or wreckage. Damaged infrastructure such as electricity and gas are important to monitor due to their risk to the life of buried survivors. Unmanned Ground Vehicles (UGVs) are likely to be the most useful form of robotic rescue vehicle, due to the small and enclosed nature of voids remaining in rubble after a major collapse [23].

The motivation for this paper stems from the need to reduce human loss in a major crisis, both for survivors of such incidents and for the rescue workers. Also, the speed of recovery time is important for survival time. In theory, robotics can solve these problems by replacing rescue workers in hazardous situations and in large numbers to find survivors more quickly, however, in practice, few such robots have been consistently used in the field. Thus, this paper aims to develop a novel robot that can bridge the gap between the development stage and field use, and thus help to save more lives. This paper presents (i) a literature review on the current methods and robots used/proposed in SAR in collapsed disaster scenarios, and on multihop wireless networking; (ii) a design of a SAR robot system; (iii) development of a prototype for the proposed robot system; and (iv) experimentation and control of the proposed robot system to demonstrate the effectiveness.

2 Related Works

Canine units were heavily used for search and rescue during the 9/11 incident due to their ability to detect human presence through scent [1, 24]. However, this is detrimental to the health of both dog and handler [6]. Human cognition on its own is not reliable enough to adequately detect human remains or live, buried persons when seen by a typical small-scale robot which has only a camera on it and is purely user controlled. Instead, robots must be redesigned to provide intelligent assistance, including the ability to tell the robot’s orientation, surrounding temperature and some level of image processing [2].

Several kinds of UGV were deployed to the world trade centre (WTC) on 9/11 such as Inuktun micro-VGTV, Inuktun micro-tracks, Foster-Miller Solem, Foster-Miller Talon, iRobot Packbot etc [19]. They were used largely to investigate voids that were 1m in diameter, too small for human and dog to fit, and voids with a 2m diameter that were still burning. One robot was lost in the rubble when it lost wireless communications and stopped, and the safety tether broke on retrieval. It was noted that thermal imaging was unusable in the WTC rubble due to the overall heat from the fires of the surroundings

[19, 23]. The main problems were poor communications inside the rubble, difficulty recovering robots and thus the need for a safety tether, waterproofing, and lack of usability of thermal imaging. These vehicles were deployed at other disaster scenes, and it was found that the ultimate cause of failure for them was poor track design (particularly on the smaller micro-UGV) [19, 23].

Robots for SAR should be small enough to fit small voids of ~1m diameter and it must be mobile and flexible. On the other hand, it needs to be large enough to traverse debris and obstacles present in a disaster site. Further, selection of SAR robots depends on the available logistic support as large robots require large vehicles to transport it to the disaster site whereas small robots can be carried on cars or by people [19].

Researchers have proposed various types of robots that could be evaluated for SAR applications. The examples include wheeled robot, tracked robot [30], legged robot [28], capsule-type robots [9, 10], robot with visco-elastic joint [15], hybrid legged-wheeled robot [12, 17, 31], hybrid legged-capsule robot [32], snake-like robot [20], crawler-robot [11, 25], swarm robots etc.

Many off-the-shelf tracked vehicles [7, 21] are widely used such as in bomb disposal but legged and snake-like robots show promise. Wheeled platforms' [16] capability in SAR is limited, due to the inability to overcome obstacles and steep ramps [23]. Arm-like manipulators [21] are a common addition and allow interaction with the environment, as well as the possibility for different camera angles. This addition, however, has its drawback that it increases the likelihood of damaging the robot due to added complexity. Serpentine [20] robots have a sophisticated structure to implement and legged [29] robots are challenging in their design compared to wheeled or tracked robot; however, their mimicry of biometric principles make them very effective at traversing difficult terrain [23].

For decades now, the NASA Mars Exploration Rover has been utilising a tried and tested wheeled platform, the rocker-bogie suspension system [3, 22, 18]. They are designed to overcome rough terrain, and they must function for long periods of time without failure.

The research was also done on wireless communications, particularly on multihop wireless networking for robot control. Tardioli [26] proposed a multihop solution to solve the problem of poor point-to-point wireless control of a robot. The nodes for the mesh network were pre-placed, in such a way that when a robot equipped with a SLAM device for mapping follows a path around a square corridor [26]. This work is a proof-of-concept of the usability of multihop networking for the direct control of a robot, as well as real-time processing of telemetry received from the robot.

Timotheou and Loukas [27] presented a scenario where a multihop network was established using multiple robots as nodes, creating a wireless network for the robots to communicate and to create a communication link at the surface for the trapped survivors. [27]. Here each node is attached to a robot and some robots are forced to remain close to the base station to provide the connectivity between the base and the rest of the network. Thus, the utility of the robots providing the backbone of the network is drastically reduced since they are forced to remain stationary to maintain connectivity.

The main points taken from this literature review are (i) SAR robot is a relatively new research area, and there is currently little in the way of standardised design; new designs and research is welcomed and needed. (ii) Robots are needed where rescue workers and canine units cannot access for health and safety or logistical reasons [6]. (iii) The use of robotic SAR can reduce the number of on-scene rescue workers, which will reduce the number of people with respiratory problems due to rescue tasks [23]. (iv) Robot designs that are useful for SAR have a small form factor, must be weatherproof and suitable for loose and hazardous terrain including high-temperature tolerance, have a camera with a feed to operators, and are ideally easy to set up and use [23]. (v) A big problem with robots searching rubble is communications; limited wireless signal under fallen debris and a tether can limit the travel of robot and potentially catch on debris or break [23]. (vi) Rocker-bogie suspension is designed to be simple and durable as well as able to overcome significant obstacles, and thus may be a better alternative to tracked vehicles which have more points of failure [3, 18, 22]. (viii) Multi-hop networking is a viable method of wireless communications with SAR robots. (ix) The use of swarm robotics with multihop networking can result in robots forced to remain largely stationary nodes to maintain connectivity, thus the utility of these robots is greatly reduced compared to their potential, and the resources put into making these “tether” robots could be saved by instead using small, simple repeater nodes that are dropped in the wake of a single robot [27].

3 Design of the Search and Rescue Robot System

3.1 Proposed overall design

In this paper, we consider a wheel-based UGV robot, wirelessly controlled utilizing multi-hop, with a rocker-bogie suspension system. This is a new approach to SAR robotics. Block diagram of the complete system is shown in Figure 1(a).

The robot utilises multi-hop networking to overcome the obstacle of poor wireless connectivity in collapsed rubble, particularly involving reinforced concrete structures. This paper presents a functioning mobile rocker-bogie robot and implementation of multi-hop nodes for wireless communication. Wireless control of the robot is performed using a MATLAB user interface.

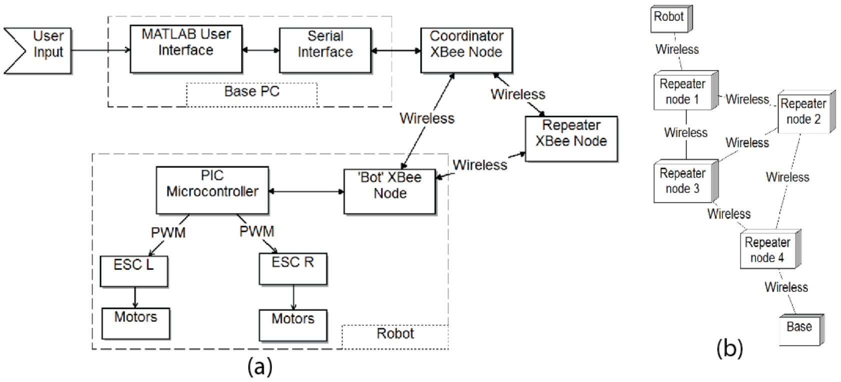


Figure 1: (a) Block diagram of the complete system (b) Network model for multi-hop network

3.2 Robot body design

The robot body (Figure 2 (a)) was designed in a 3D CAD software DesignSpark Mechanical and then it was 3D printed. The robot body features a box-shaped body, left hollow for housing the electronics and battery, and a door that swivels around a pivot mounted on the top. The two halves of the robot body were designed to be held together using the main axle holder on either side of the body, which serves the dual purpose of holding the body together and strengthening the holes in the body through which the main axle passes. On the top of the body is the bar which differentially connects the arms of the robot on either side, a key component of the rocker-bogie suspension. Finally, the arms themselves are made up of three-wheel mounts (which clamp onto the motor for each wheel), the 'shoulder' which mounts onto the main axle and has a mount to connect to the differential bar, the pivot for the rocker and the rocker itself. The robot body design is inspired by the design of EPFL's Space Rover [5] and NASA Mars Exploration Rover and rocker-bogie suspension system [14].

The key design specifications for the robot design were that it should be small, specified as no larger than half a metre in any dimension, and have a sizable ground clearance so as not to snag on large debris. The robot occupies an area of 37x27cm and has a ground clearance of 8 cm with the 9cm diameter soft wheels fitted. This ground clearance could be further increased by fitting larger diameter wheels.

3.3 Multi-hop networking

Multi-hop networking is constructed by having the robot drop small repeater nodes as it roams deeper into the rubble, providing a wireless "tether" for the signal to return to the surface through. It increases both the signal quality and the chances of a signal making it from robot to base station when compared with the point-to-point long-range transmission. This also removes the limitations of a physical tether, by removing the possibility of catching the tether and thus trapping the robot.

UML of Figure 1(b) shows the concept of multi-hop networking, showing how a signal is received by the base station from the robot even if the robot has no direct connection to the base, and even if some nodes are also out of range of the base or the robot.

ZigBee was selected for the network protocol as it natively supports mesh networking. It has better range than Bluetooth but less range than wifi. However, it consumes less power than wifi and is more geared towards embedded systems.

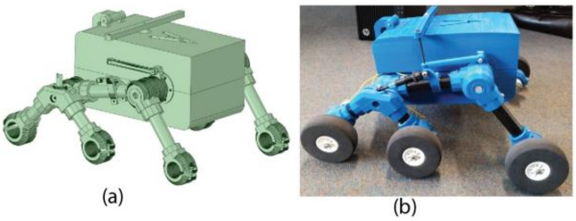


Figure 2: (a) Design of the Robot Body (b) Prototype of the Search and Rescue Robot

4 Development of the Robot

The first part of the development of the robot was printing the outer shell. The full body (Figure 2 (b)) was 3D printed out of ABS, except for the pipes between the motor mount points and the rocker/bogie and shoulder joint, which were cut out of PVC plastic piping to save cost and for ease of cutting.

A PIC microcontroller is used to handle incoming commands and control the motor circuits. The code and embedded circuit for the PIC was designed in Proteus, allowing for the code to be written and tested without the need for building test circuits, eliminating any potential faults caused by circuitry for debugging code. ZigBee was chosen for low power multi-hop networking. The specific type of XBee module which supports ZigBee mesh networking natively is the series 2 line of modules.

The motors were chosen to suit the purpose of the robot; 133rpm geared motors with a gear ratio of 1:75 was selected for their high torque. This is an advantage when the wheels are intended for use in a rocker-bogie suspension system, as the key method of surmounting obstacles is using the torque of the motors to push the robot against the obstacles and force the front most wheels up and over. This means that the motors are likely to be at risk of reaching their stall current often. The specific model of motor selected has a 5.5A stall current rating and given that there are 3 motors per side the current consumption was likely to be very high. Thus, a pair of high current Electronic Speed Controllers (ESCs) were selected with a max output current of 45A and includes a Battery Elimination Circuit which supplies a 5.6V, 2A output for powering the control circuit and thermal protection.

The XBee modules were configured to implement the ZigBee mesh network. For XBee modules to work together effectively, there are several important parameters to check and configure. Firstly, they must all be series 2 XBee modules, as only series 2 modules support mesh networking. Secondly, they must all support use of the same protocol.

5 Experiments and Evaluation

The completed prototype robot can move forward, reverse, and turn. Two types of wheels are used: foam wheels and rubber wheels where rubber wheels have higher friction coefficients. The rocker and bogie mechanisms rotate freely, even with the weight and wires of the motors in them, and the addition of a damper on the bogie prevents it from hyper-rotating, helping it to keep a grip on the ground with all six wheels. Following subsections, A to E presents various experiments.

5.1 Free standing, small obstacles test

The robot is capable of surmounting flat obstacles of 8cm height with little difficulty. Due to having six powered wheels and a great range of motions for each rocker arm, if the undercarriage of the body was caught on an obstacle at or under this height there was always at least 1 wheel in contact with the ground to push/pull the robot off the obstacle.

With the rubber wheels, the robot is more likely to grip loose obstacles and go over them than to simply push them as with foam wheels. This is beneficial as pushing loose obstacles can exasperate further obstacles or create insurmountable piles.

Lots of loose small debris is likely to be scattered around collapsed or partially collapsed buildings, so being able to handle small loose obstacles without pushing or slipping is an important capability.

5.2 Slope test

The robot was tested (Figure 3 (a)) with two types of wheels (foam and rubber) and with varying slopes. A successful climb is defined as the robot reaching the top of the slope and not sliding down. The experimental results are provided in Table 1.

Table 1: Experimental results for slope test (Yes=Successful climb and No= failed to climb)

	Foam Wheels		Rubber Wheels	
Slope	Low Speed (0.5 m/s)	High Speed (1 m/s)	Low Speed (0.5 m/s)	High Speed (1 m/s)
20°	Yes	Yes	Yes	Yes
25°	Yes	No	Yes	Yes
30°	No	No	Yes	No
35°	No	No	No	No

The slope test demonstrates that grip strength of wheels contributes towards the performance of the robot. The robot has better performance with rubber wheel compared to the foam wheel as rubber wheel has a higher friction coefficient. It demonstrates that a low speed combined with a high torque of the motor is an efficient way to enable the robot to climb without slipping, as reinforced by the NASA study of a rocker-bogie system [8]. It demonstrates the ability of the robot to function in non-flat scenarios, a high likelihood in unstable/collapsed structures. It also demonstrates that the grip of the wheels failed before the robot was unbalanced enough to tip over backwards.

5.3 Obstacle test: Loose rubble/outdoor environment

The robot was tested in a variety of outdoor scenarios, including over loose rubble, over plant material and over a single large step. Every scenario was tested forwards and backwards, to highlight the difference between using either end of the rocker-bogie system as the front.

The first test was over the loose stone and plant debris on an uneven surface (Figure 3(a)). The debris was made up of loose rocks on the ground, of a maximum of approx. 8cm in diameter. The plant debris was made up of long sticks (approx. 60 cm max). The robot was able to pass over the uneven surface in both directions. The loose rubble was also surpassed in both directions; however, the longer twigs were susceptible to beaching the robot by trapping it between wheels. In some, but not all attempts, moving the robot back and forth dislodges it. A standard brick was added to the rubble. The robot was unable to traverse the brick head-on without maneuvering carefully either around it or so that only one leg of the rocker-bogie mounted it. On a direct approach, the robot was beached on the leading edge of the brick.

The next test was over plant material, over a low carpet of long grass (Figure 3(b)). The robot managed to go a short distance in the long grass, however, it never managed to fully traverse the terrain without getting beached as the soft leaves were pushed down away from the wheels. The wheels also failed to grip the soft leaves. The main conclusion drawn from this test was that the wheels used are too slick for softer, moist terrain.

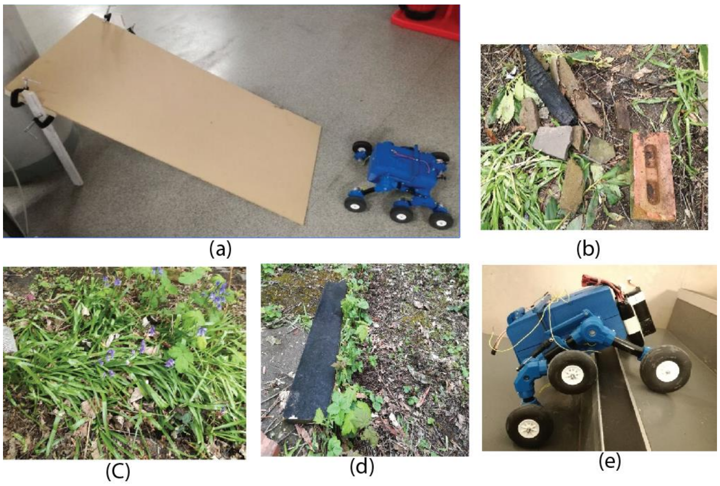
The final outdoor test was over a single, large step in outdoor conditions (Figure 3(c)). The step was initially 8cm in height, increased to 10cm using two wooden boards. The robot succeeded in scaling the step in the forward direction at 8, 9 and 10cm heights; however, in the reverse direction, it failed at scaling the 10cm height.

The conclusion from these outdoor tests show that the rocker-bogie system behaves as designed, and the motors can provide enough torque; however, the robot needs larger, grippier wheels to keep it further off the ground and grip the floor better.

5.4 Obstacle test: Staircase

Steps of the stairs are 14cm (Figure 3(e)). The robot can pull itself up onto the step, but when rearmost wheels contact the step, the robot loses its balance and tips backwards. Attempts to add counterweights to the front were not enough to prevent this (as shown in Figure 3 (e), the robot is seen with counterbalances on the front, at the point of tipping) and this combined with the slipping backwards on the slope test demonstrate balancing issues with the robot design. The robot was tested at faster and slower speeds in both directions to confirm that this was the case, and in each test, the same result occurred. In the reverse direction, the robot tipped quicker and was unable to scale the leading wheel over the step. Revision of current design should see the main axle mounted closer towards the centre of the body.

Stair climbing is a critical ability for search and rescue reconnaissance robots, as partially collapsed or even completely collapsed buildings are likely to have a completely or partially intact stairwell, and with no human intervention possible the robot must be able to overcome such an obstacle with ease and stability. Stairs are regularly used as a test bench for SAR robots and this problem must be overcome before the chassis design can be considered for more rough terrain testing.



(a) (b) (C) (d) (e)

Figure 3: (a) Slope test setup (b) Loose Rubble used for testing (c) Long grass used for testing (d) Step used for testing (e) Staircase obstacle test

5.5 Testing the Multi-hop network

Three nodes were used to demonstrate the multi-hop network. The hardware version of the nodes was XBee24-ZB (Figure 4 (a)). Each node was loaded with the latest ZigBee firmware version. Each node was set up to be able to recognise each other and talk on the same local area network. ZigBee protocol uses a PAN ID to define the local area network; a coordinator establishes the PAN, and routers search for PANs nearby, joining if they are set up to have a matching PAN ID and the coordinator is not gatekeeping other nodes from joining. When the network was tested, all three nodes could join the same PAN.

Once all three nodes were set up in API mode, a test set up was created to ensure that the nodes would be forced to utilize multi-hop networking for the coordinator to reach the 'bot' node. First, the coordinator and router node, which have RPSMA connectors for high-gain antennas, had their antennas removed to shorten their range for the test.

The 'bot' node uses a whip antenna, which has a shorter range than the other two by default. The ranges for each node type was measured by transmitting a broadcast message repeatedly with only 2 nodes connected until no more messages were received. This test was done in an open space with line-of-sight between nodes, in a room containing computers and desks. The reliable range of an RPSMA node (without antenna) to the whip antenna was found to be roughly 8.5m, and between 2 RPSMA nodes were within 2m. The nodes were then placed so that the router was in the range of both nodes, but the coordinator was not in range of the 'bot' node. The connectivity of the network was checked using XCTU's Network Working Mode, which allows each node to scan the network and draw a graphic map showing the connectivity and even signal strength between nodes (Figure 4(b)).

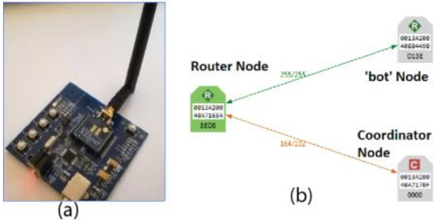


Figure 4: (a) XBee node with RPSMA connector with antenna (b) Screenshot from XCTU Network View

The network view (Figure 4(b)) confirmed that the nodes were connected in the proper configuration. To ensure that multi-hop routing was being used, the router node was turned off and a transmit request frame was created in the XCTU terminal at the coordinator node. The frame was sent in a repeating pattern, with the 'bot' node set as the destination address. With the router off, the frames were not received by the 'bot' node. When the router was turned on, the 'bot' node began receiving frames, thereby proving that the protocol had automatically routed the frame through the router (Figure 4 (b)).

5.6 Power consumption of the robot

The robot was powered by an 11.1V 1000mAh Li-Po battery, typically used and designed for radio-controlled hobby vehicles. This was chosen for its ability to handle high current outputs, and its compatibility by design with the selected ESCs. Each motor has a no-load current of 0.35A, so 2.1A for the wheel system in total, thus consuming 23W of power. The stall current for the motors is 5.5A at 8.8kg/cm of torque, resulting in peak power consumption of 366.3W at the stall. On very rough terrain or aggressive climbs each motor can consume 2A each on average, so 12A in total, which is 133.2W of power. The ESCs have a max continuous current of 45A, and a max burst current of 340A, so the motors are effectively unlimited in their current consumption.

This reflects the motor usage at top speed. The upside of using ESCs is that they reduce power consumption at lower speeds, and as it drives the motors using PWM pulses it is more efficient than regulating the output voltage.

Typically, the robot is used at half of its top speed to better navigate the terrain, so it can roughly double the battery life this way. Finally, the PIC micro has a typical run current of 11uA and the Zigbee of 150mA when transmitting, consuming 55uW and 495mW respectively. Thus, accounting for a small amount of current to power the ESCs the robot does not consume much energy and will run for approximately 5 hours on a 1000mAh battery when stationary.

The robot's battery life was tested by placing it on a pedestal where the wheels did not contact the ground with a fully charged battery, and the motors are driven at full speed continuously until their performance was severely degraded. The robot lasted just under 30 minutes, which reflects the no-load current of just over 2A total when supplied by a 1Ah battery. Hence, for long term use in inaccessible conditions where the battery cannot be replaced, Li-Po batteries of 3000mAh or greater would be optimal.

6 Conclusions

In this paper, a new perspective on SAR robotics was presented through research into the field. A robot design was proposed and built, which drew its influence from other fields of robotic exploration, namely interplanetary exploration. The developed prototype robot based on Rocker-bogie system works and moves as intended. The experimental results show that Rocker-bogie system is viable for surmounting smaller obstacles and dramatic slopes, but the performance was hindered by grip strength of wheels, positioning of the robot's centre of balance. Thus, the robot must be rebalanced by shifting the main axle and re-examined before it can be tested on more rugged obstacle tests. Rubber-based, larger wheels perform better than firmer, slicker, smaller foam wheels. Bigger, more grippy wheels and lower speeds are the best methods to ensure the robot can surmount most obstacles it encounters.

The proposed robot incorporates multi-hop networking, with a method of distributing repeater nodes behind the robot as it travels to form a wireless "tether" replacing a hard cable tether. This multi-hop network has the capacity as is the nature of ZigBee for other router nodes to be added, thus in theory expanding the network to be as big as the coordinator node can handle.

Overall, the work done in this paper is a proof of concept of the full proposed design, and a good base for future work to expand on and grow towards a possible solution to making the use of SAR robots more affordable, streamlined and efficient, and thus increase chances of discovering survivors earlier with less risk to rescue workers' lives.

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