Performance of the Improvements of the CAESAR Robot

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Abstract: *Robots are able to enter concealed and unstable environments inaccessible to rescuers. Previous Urban Search And Rescue (USAR) robots have experienced problems with malfunction of communication systems, traction systems, control and telemetry. These problems were accessed and improved in developing a prototype robot called CAESAR, which is an acronym for Contractible Arms Elevating Search And Rescue. Problems encountered with previous USAR robots are discussed. The mechanical, sensory and communication systems that were used on CAESAR are briefly explained. Each system was separately tested by performed experiments. Results of field tests and the robot performance experienced during a disaster scenario that was created are discussed. The capabilities of CAESAR are explained in these tests to determine if some of the problems experienced previously are solved.*
Keywords: *CAESAR, USAR Robot, Field Testing*

1. Introduction

Robots are required for search and rescue purposes. They should be able to access concealed places and environments to which fire fighters and rescue personnel cannot gain access. Three hundred and forty three firefighters died at the World Trade Center during the September 11 attacks in 2001 (Casper & Murphy, 2003). Sixty five of these rescuers died as a consequence of searching in confined spaces that later flooded (Casper & Murphy, 2003). Rescuers often enter areas that have unstable structures, unknowing of the fact that there are no live victims to rescue. Robots could save the lives of victims and be first responders. Rescue workers have about 72 hours to retrieve victims due to survival constraints (Stormont & Berkemeier, 2003). Several hours are lost when rescuers are unsure of a building's stability. After a disaster the structures are often unstable and rescuers need to evacuate until the rubble has stabilized. Routinely the rescuers have to evacuate when a body part of a possible survivor is found (Naudet et al., 2002). Robots can stay in the unstable area and continue searching for survivors. In the future robots could possibly also be used to access mines after an accident, prior to rescue workers (Kleiner, 2006).

Urban Search And Rescue (USAR) Robots were first extensively tested at the collapsing of the World Trade Center site in 2001 (Greer et al., 2002). The University of South Florida was involved in these rescue attempts. The advantage of these robots above the rescue members was the immediate entry into the areas of disaster.

Several problems were identified at the World Trade Center as well as at the testing grounds of the National Institution of Standards and Technology (NIST). The robot's traction system malfunctioned due to its low melting point (Greer et al., 2002). More research was needed for the robots to withstand the harsh conditions of a fire (Wiens, 2006). Other issues observed were, unstable control systems, chassis designed for narrow range of environmental conditions and limited wireless communication ranges in urban environment, as well as unreliable wireless video feedback (Calson et al., 2004).

Autonomous robots for USAR applications are not feasible as operators of robots are to work as a team, each contributing unique skills and capabilities (Scholtz et al., 2004). Tasks of USAR robots include searching for survivors, inserting special sensors into the environment, collecting visual data of structural damage, carrying radio transmitters, carrying small amounts of food and medication to the victims and transporting rescue tools (Murphy, 2000). Certain objectives that USAR robot developed that should prevail are, the ability to move in rough terrains, climb rubble and stairs, have high mobility and stability, consist of high integration modules, be radio-controlled, light-weighted, small and portable (Changlong et al., 2008).

Robots such as the ATR X-50 (Ray et al., 2007), uses 2.8 GHz Wireless TCP/IP networks. It has an overall weight of 84 kg, with dimensions of 950 x 650 x 350 mm and can move on inclines with a 15° - 20° angle. Infrared range finders were used for obstacle detection and it has an on-board CCD camera. Suggestions for a more compact robot are made (Ray et al., 2007). The VGTV-Extreme has

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a tipping point of about 15° in the event that it should climb over obstacles (Micire, 2008). Even though small robots are desired for USAR operations, larger stair-climbing robots are preferred (Murphy & Stover, 2008).

Field tests performed by the Center for Robotic Assisted Search and Rescue (CRASAR) at different disaster scenarios indicated the different advantages and disadvantages of robots. Robots are able to enter places that humans cannot enter. These environments could be concealed, extremely hot and toxic. The safety and effectiveness of rescuers are the most crucial in disaster scenarios. The rubble terrains were a challenge to the robots. Extreme heat within the pile of rubble caused the softening of the robot tracks and caused failure. The Foster-Miller Solen robot was abandoned as the density of the terrain interfered with the wireless network control. Robots are able to assist with five different tasks, namely "confined space search and inspection, semi-structured search, victim extrication, transport of medical payloads and monitoring." The average time that a robot was utilized, was 6 minutes and 44 seconds. Robots such as the MicroTracs had to have a secondary operator next to the robot's point of entrance feeding the tether or rope. This resulted in this operator being in direct danger should there have been collapsing of the unstable environment (Casper & Murphy, 2003). A tether has the disadvantage of being a hindrance for a successful operation, as it gets tangled and dragged (Murphy & Stover, 2008).

Research contribution is required in the area of USAR robots and Mechatronics, which is an integration of the mechanical, electronic and computer systems. The contributions that have been focussed on in the research are the improvements of the mechanical system, communication system and sensory system to provide a platform for further development in USAR robot research. The underlying theoretical principles and designs that have been used are briefly explained. The National Institute of Standards and Technology (NIST) have specifications for the performance of search and rescue robots. Tests that have been performed on the individuals systems are explained to determine the limitations and whether the specifications of solving some of the problems associated with USAR robots were successfully accomplished. A field test was then conducted in a created and controlled scenario developed by the local fire department training facility.

2. Mechanical System

The power to weight ratio of the robots needs to be examined by implementing a complex and efficient gearing system to maximize battery life. This will allow for manoeuvrability over uneven terrain. (Greer et al., 2002)

Further studies in the failure of USAR robots were researched and proved to be due to effectors and control systems that caused the most common of physical failures. Slippage was the more common failure rather than errors. Robot reliability in the field environments is considered to be low. Research has also shown that the maintenance of robots must be accomplishable in the event of expected failures. Results of tests performed on 13 different robots confirmed, "limited mobility, problems which need to be addressed." (Calson et al., 2004)

The rubble pile at the World Trade Center was massive and there were confined areas only possible to access by small robots. Because of fires, robots responding to these scenarios would have to be highly heat-resistant. (Messina & Jacoff, 2006) Climatic conditions like flooding and slippage hazards also added to the risk for rescuers. (Greer et al., 2002) USAR robots are required to be water-resistance, as the electronic components can be damaged by the moist of the environment or by sprinklers (Murphy & Stover, 2008).

A tracked robot was developed with arms in the front and rear supporting the CAESAR (Contractible Arms Elevating Search And Rescue) robot with climbing over rough terrains and obstacles. These arms can also be contracted to allow manoeuvrability in concealed areas. With the benefit of the symmetrical design, CAESAR is able to continue with a search operation in the event that it tips upside down. The CAESAR robot is shown in Fig. 1.

CAESAR's size was determined by the internal components and the required modules. Fig. 2 shows the internal layout of the different modules.

A stress and deformation analysis was performed on the mechanical parts, and software simulations verified the design for the different terrains. The design allows for the robot to continue with searches should it tip upside down.

As shown in Fig. 2, two motors are used for a differential drive system, while the other two motors are used for the flipper arm orientation. A closer view of the flipper arm assembly is shown in Fig. 3.

Fig. 1. CAESAR robot being tested on rubble

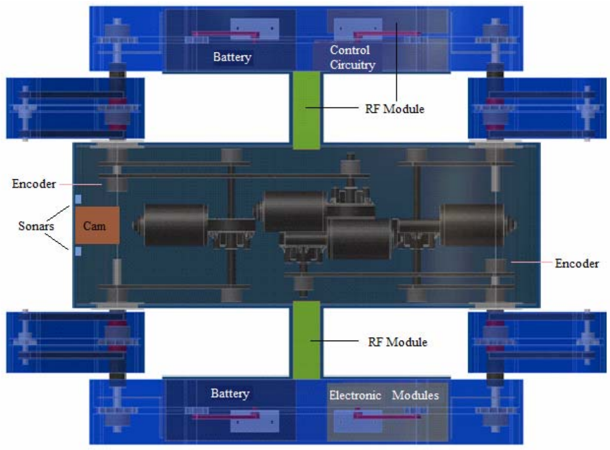


Fig. 2. Layout of the internal modules, which include the electronic components, motors and drive system

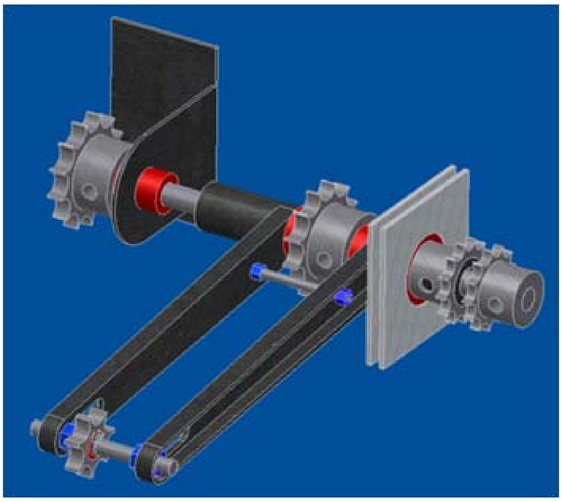


Fig. 3. A closer view of the flipper arms assembly

The flipper arms assist the CAESAR robot to have 4-degrees of freedom (DOF). These DOF allows the CAESAR robot to push itself over obstacles if required. Fig. 4 shows the different degrees of freedom, being forward and backwards, turning, the up and down movement due to the front flipper arms and the up and down movement due to the back flipper arms.

The body is made from Kevlar and phenolic resin, which both are able to withstand high temperature

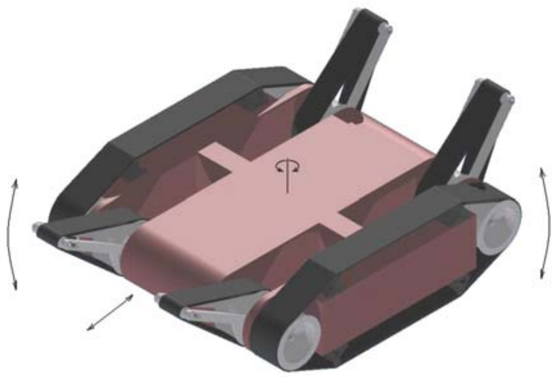


Fig. 4. The degrees of freedom of the CAESAR robot

environments of at least 300 °C. Aluminized Kevlar has been added to the outside, allowing heat to be reflected away from it. The composite body allows for the protection of the internal components from heat, falling rubble and unstable environments. As all heat sensitive components and modules are sealed within the composite housing, they are protected from the heated environment.

3. Communication System

Problems were identified regarding the communication with the robots (Remley et al.,2007). Communication protocols concepts and suggestions for robot applications have been documented for the "further development of protocols for robot communication" (Harmon & Gage, 1980). These concepts only investigated certain factors for the transport and content layer, but require "higher content layers to represent task dependent information" (Harmon & Gage, 1980). The IEEE 802.11b link used on the Packbot allowed for 200 m Line Of Sight (LOS) and about 2 rooms distance communication for Beyond Line Of Sight (BLOS) scenarios. Interference from other equipment using the 2.4 GHz frequencies decreased the quality of operation. Solutions for the handling of signal jamming and other radio traffic are desired. (Lundberg et al., 2007)

Two-way voice communication with a victim is important as this is one of the first steps for first aid assistance (Greer et al., 2002). Two-way voice communication capabilities proved to be important and effective for USAR attempts at the 2005 La Conchita mudslides, as the robots used were not appropriate for these types of rescue scenarios (Murphy & Stover, 2008). Results of tests performed on 13 different robots confirmed, "unreliable wireless communication which need to be addressed." The recommendation resulting from these studies is that information needs to be filtered for failure of data (Calson et al., 2004).

Communication is solved with the use of UHF frequencies and preferably 5W transmission power from the transmitters (Stopforth & Bright, 2008). UHF frequencies have been used as the signals are able to penetrate building materials, the antenna size is small enough to fit in the robot chassis and power efficiency is better than Wifi frequencies. In conjunction to this, the Robotics Communication Protocol (Stopforth et al., 2008) is used, which was developed to allow reliable packet communication of a single frequency and limited bandwidth. The communication system consists of a programmable Radiometrix TR2M module, a Motorola MCX-100 radio's power amplifier final stages and a programmable integrated circuit, which acts as an intelligent router, implementing the Robotics Communication Protocol (RCP). The RCP router relays the data from the application layers to the physical layer, which is the TR2M module, but adds and removes the excess headers required for reliable communication. The application layer is either the motor or sensor control module.

The RCP is a packet protocol that allows for communication between stations using a single frequency. Each station has a callsign, therefore allowing a robot to react to instructions only specifically indicated to itself. All other stations ignore instructions not meant for it. Furthermore, the RCP allows for the prevention of interference that might occur when one station is out of range of a robot or a control station.

Eggbeater antennas were used at the control station, thus allowing omni-directional communication, irrespective of the location and orientation of the CAESAR robot. Video transmissions of thermal images were done on UHF frequencies, but authorities limited the output power to 1W, to allow the principle to be tested. Audio communication is possible between the robot and control station, while two-way data communication is possible for control and telemetry.

The communication system permits instructions and data transfer between the robot and control station. This transfer of instructions allow for the manual control of the robot and to give commands to which direction it should move to. The semi-autonomous system is achieved with the on-board sensory system.

4. Sensory System

The initial aim in a disaster scenario is the location of causalities and the detection of dangerous situations such as gas leaks, live wires and unsafe structures. The identifications of such dangerous areas could save the lives of rescuers and victims (Greer et al., 2002). A thermal camera proved to be both important and effective sensor for USAR attempts at the 2005 La Conchita mudslides, as the robots used were not appropriate for these types of rescue scenarios (Murphy & Stover, 2008).

Tests performed at the NIST indicated that the video feedback did not supply an indication on the steepness of inclines. The need for sensors to gauge the slopes is suggested to be beneficial (Scholtz et al., 2004). It appeared that the state of each module within the robot influenced the robot's overall performance. Mass produced sensors have proven to be the more reliable than custom-designed sensors (Calson et al., 2004).

Control interfaces are required that will enable the operator to control the robot as desired. A future suggestion for research is the development of a better control interface for multiple robots. (Nourbaksh et al., 2005) Remote viewing of video feedback is essential and multiple observations stations are suggested, as this would enable other rescue members to also observe the video and have the advantage of observing dangers or victims (Murphy & Stover, 2008). The operator should have higher authority than the robots, and robots should be capable of accepting instructions. This problem prevents the operator from reacting instead of pro-actively controlling of the robot (Balakirsky et al., 2007).

The rescuers did not trust the robots that were used for the USAR scenarios. FLIR cameras are not portable on the VGTV, MircoTracs and Solem robots. Rescuers wanted air quality meters attached to the robots. These gas meters proved difficult to attach to the robots and readings were only possible once the robots returned from a search. Another suggestion that was made was that the robot and user interface needed to be usable with minimum training and that all researchers involved with rescue events have the sufficient training (Casper & Murphy, 2003).

Sonar sensors allows CAESAR to perform object detection. CAESAR has semi-autonomous abilities that permit the flipper arms to move to the best orientation depending on whether objects are detected and the angle of inclination and orientation of the mechanical body. To determine the angle of inclination, a weighted shaft was developed that was inserted into the encoder. The weight is always pulled towards gravity. As the robot climbs an inclination, the weight would moved from its zero position, and the angle could be determined. This configuration is shown in Fig. 5.

This local artificial intelligence allows for semi-autonomous system, leaving the controller to focus on the control and victim location. This control and localization is achieved by sending the necessary instructions to the robot to proceed to areas of interest and to be able to view any heat patterns that might be dangerous or be an indication of human life. The onboard computation is real time as it is interrupt driven should the sensors detect a critical change. The instructions from the control station are sent only when required.

Gas sensors were also included onboard. These sensors include Figaro's CO, CO_2, H_2S, methane and O_2 sensors.

Each gas concentration could have an unsafe or dangerous factor for victims and a dangerous factor for the rescuers or robot. The control station indicates the safety factor in the environment dependant on the individual gas concentration. Furthermore, an overall safety indication is given using a developed model (Stopforth et al., 2010) that uses data fusion of concentrations of all the gases.

5. System Integration

A block diagram of the system integration is illustrated in Fig. 6.

Fig. 5. Weighted Shaft used to determine the angle of inclination

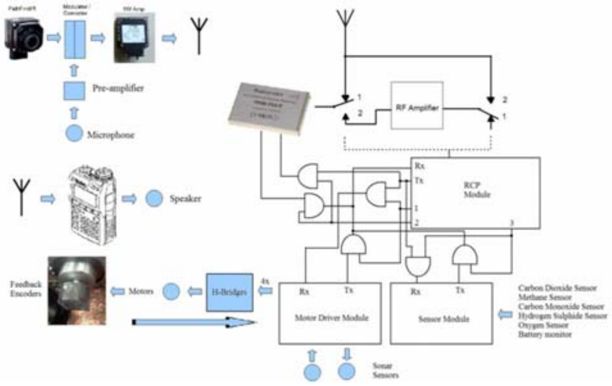


Fig. 6. Block diagram of system integration

The thermal camera and audio input is connected to a video transmitter. This signal is amplified to 1 W output power to the antenna. The transmitted signal allows for video and audio reception at the control station. A radio is used for the reception of audio within CAESAR, which is transmitted from the control station. The instruction is sent from the GUI interface to the RCP module, which adds the headers for the data packets. Packets are sent to the TR2M modulating module and then the RF amplifier.
The signal is received via the TR2M module within CAESAR, which gets sent to the RCP module. Packet headers are removed and the data is sent to either the motor driver module or the sensor module. These modules respond to the instructions. Information about the environment is send back to the control station, should this be requested.
Sonar sensors are connected to the motor driver module for obstacle detection. The motor driver module reacts to the obstacle detection and transforms the flipper arms. The angle of the flipper arms is determined by the angle of orientation of the CAESAR platform. This is achieved by sending the signal to H-bridges which drive the motors. Feedback encoders allow for the detection of the angle of the flipper arms.

6. Communication Tests

Tests were performed using the RCP protocol and it was found to be reliable for the mobile robot application (Stopforth, 2010). Packets were rejected when they were not meant for that specific station or when the checksum of the packet was not correct. It responded with the appropriate packets and routed the data to the application modules and visa versa. Due to the limited memory of micro-controllers the EEPROM was used for the storing of arrays. It was determined that, depending on the amount of memory available, the length of the data field was proportional.
With the UHF frequencies used, a limited reflection of the radio waves of building materials was experienced. The useful advantage of this is that it allowed the radio signals to be reflected between stations where previous contact would not have been possible. This permits further beyond line of sight communication.

The observation was that with the increase of RF power the electronics within the control station did not behaved as required. After numerous tests it was discovered that the radiation emitted from the amplifier stage caused interference with the rest of the system. A Faraday cage was developed around the RF circuitry to shield the emitted radiation.
Using the egg-beater antennas proved to give a lower performance compared to the communication between two vertical antennas. This lower performance was expected, as the signal interception is less, but it did allow for video, data and audio communication irrespective of the orientation of the antennas in the robot.
Video transmission tests were also performed and a good signal of audio and video was received. The thermal camera also revealed heated areas and it made it possible to identify human features in dark and dense smoke environments.

7. Gas Sensory System / Control System Tests

The gas sensors exhibited a dramatic increase of the gas concentration under testing. Detection was almost instantly and the increase in concentration was determined within a second.
The gas sensors were monitored to determine the consistency of the output concentrations in a nonfluctuating gas environment. These monitored concentrations are shown in Fig. 7.
In Fig. 7 the temperature and battery monitoring are also displayed. These sensors demonstrated a constant output. CO_2 gases fluctuated about 165 ppm, while H_2S fluctuated about 40 ppm. CO fluctuated about 35 ppm while methane fluctuated about 30 ppm.
The gas concentration levels are viable as about 0.2 % of the atmosphere consists of CO_2 and other gases. Chauvenet's criterion statistical analysis was performed on the readings to determine the validity. All readings were acceptable.
The control station consisted of a Graphics User Interface (GUI) on a computer system. This allowed easy control of the robot, video capturing and the ability to perform

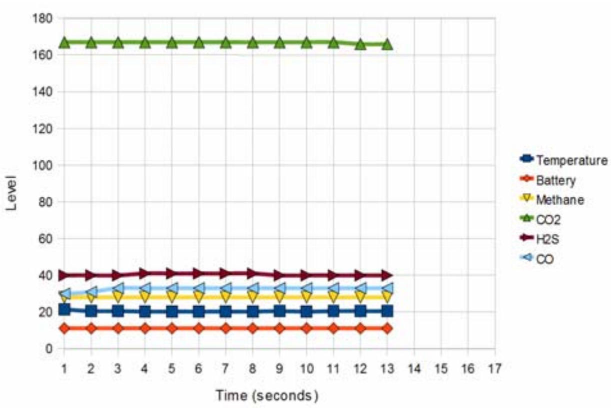
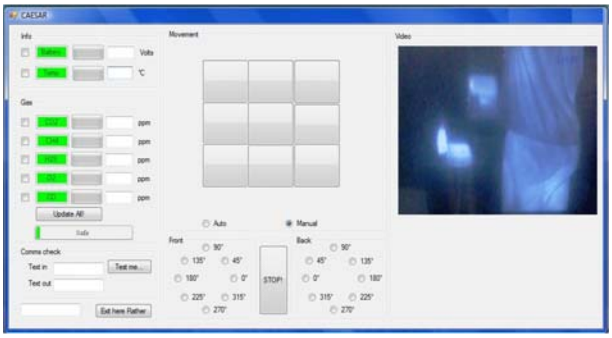


Fig. 7. Gas concentration levels indicated by the gas sensors in a constant gas environment



(a)

(b)

Fig. 8. (a) GUI for the CAESAR robot (b) Example of color indication for warnings

mathematical calculations due to the processing power. This GUI is developed to allow multi-agent robots to be controlled from a single system. Rescuers don't need to be familiar with different interfaces, as all the robot's controls are similar with a selection of unique instructions that are only feasible for a robot.

This interface was also developed for the First Encountered Assisting Robot (FEAR) (Stopforth et al., 2010). Fig. 8 shows the GUI for the CAESAR robot. The gas concentration levels are indicated with battery and internal temperature data. Flipper arm orientation selection is revealed, depending on whether the manual or automatic mode is selected.

The AI that was incorporated with the GUI system revealed an unsafe and probable dangerous environment for humans. A danger probability for the robot is also indicated. The environment danger information assists the rescuers with decisions of further rescue attempts.

8. Traction System and Transformability Tests

CAESAR has an overall weight of 56.5 kg, which is in excess of the predicted 25 kg. The weight at initial tests was 25 kg, but the addition of the overall payload, the protective layer and the phenolic resin to bond the protective layer added the additional 31.5 kg. Weight could be reduced with the layering and manufacturing of the composite material in a single stage, as the amount of phenolic resin used for bonding is reduced. The composite body was tested in temperatures up to 300 °C. A butane gas torch flame was applied to the body to determine the durations of protection with higher temperatures should a flash fire or explosions occur. The aluminized Kevlar started burning after a second, while the rest of the Kevlar construction started showing signs of disintegration after five seconds.

The drive system efficiency was found to be 95 % and flipper arms efficiency was determined to be 86.67 %.

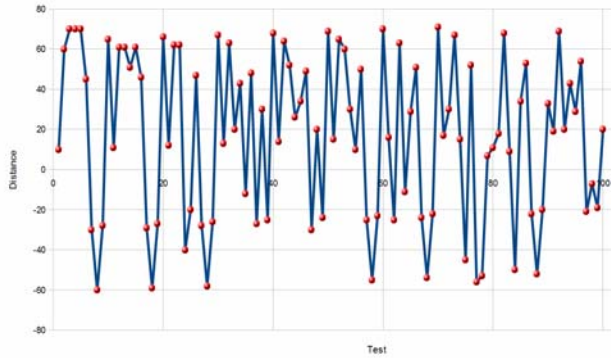


Fig. 9. Results of repetitive tests to determine the deviation from the original position after a 360° turn

This is required to determine the loss in the system. The calculations for these efficiencies are in Appendix A.

The CAESAR robot was tested on different terrains to determine the feasibility of the traction. The silicone pads decreased slippage on smooth and oily surfaces while the chain-type tracks allowed grip for climbing over obstacles. The accuracy of the CAESAR robot turning 360° was tested. 100 tests were performed on smooth concrete and the results are shown in Fig. 9.

As observed from Fig. 9, the maximum deviation was less than 70 mm. This would indicate that a 70 mm space is required around the CAESAR robot to allow for a successful turn in a concealed area. Chauvenet's criterion statistical analysis was performed on the readings to determine the validity. All readings were acceptable.

Different weights were placed onto CAESAR's chassis and the velocity was observed. The results of the tests are shown in Fig. 10.

The initial velocity was the weight of the robot chassis, which is 56.5 kg. As the weight increased, the velocity decreased. Traction was still possible up to 164 kg, after which the weight prevented the chain tensioners to keep the chain under tension, and therefore slippage occurred at the sprockets.

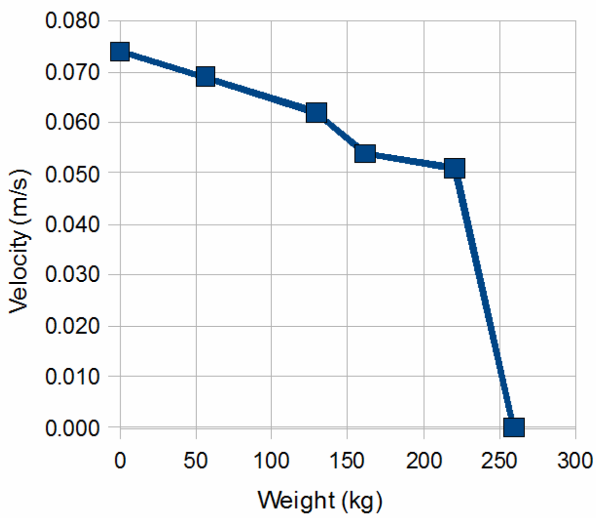


Fig. 10. The velocity vs weight relationship

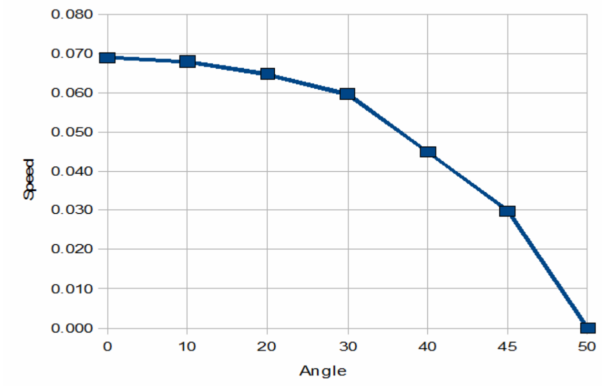


Fig. 11. Angle of inclination vs the Speed of motion

The flipper arms were also tested with different weights on the robot. Elevation is possible with the weight of the robot chassis, but anything more than this was not possible.

It is suggested that not more than 50 kg payload be added to CAESAR's chassis, as this could cause failure to traction. This payload is obviously only needed to be moved over a terrain where elevation is not needed due to the restriction of the flipper arms strength. The ability for an addition of a payload is useful as it allows the rescuers to send additional equipment into the disaster scenario. The equipment could either be to assist the rescuers or to assist the victims when located.

Transformation with the flipper arms assisted the CAESAR robot maneuver over an obstacle that had a gradient of 30° or less for long distance climbing, while 45° slopes were ascended for shorter distances. This gradient for the respective distances was considered acceptable for the environment where such rescues would occur. A comparison of speed vs the angle of inclination on a rigid terrain is given in Fig. 11. This analysis is dependent on the terrain surface as loose obstacles can cause slippage for short time periods.

These flipper arms were also able to assist the CAESAR robot by pushing it over an obstacle by rotating the arms down under the chassis before contracting them to the homing position.

The overall dimensions of the CAESAR robot, to determine the confined space it could enter, is:

- Height of composite chassis: 150 mm
- Length of robot excluding extended flipper arms: 730 mm
- Length including the extended arms: 1090 mm
- Width: 700 mm
- Height with arms at 90°: 395 mm
- Height including the side tracks: 364 mm
- Height from the ground to the top of the composite body: 250 mm

9. Field and Scenario Testing

After the separate tests proved to be successful, a series of integrated system tests were performed. These consisted of creating similar scenarios that could be encountered and a test at the local fire department training facilities.

The setup time of the robots was too extensive at the World Trade Center and the human to robot ratio for transport and controlling was not consistently at 1:1 (Greer et al., 2002). Setup times exceeding 5 minutes are considered to be vital time lost for the search (Micire, 2008). Upon arrival at the controlled disaster site, the setup for the robot usage was required. The human to robot ratio for the loading and carrying of the CAESAR robot is 2:1, but the human to robot ratio to control the robots with the GUI is 1:n, where n is the number of robots that need to be controlled. The weight and size of the CAESAR robot is more than the pursued goal, but it is able to contain all the modules and components required. In total, the setup time came to 2 minutes and 34 seconds, of which 52 seconds were spent on waiting for the PC to boot up and the software to load.

Communication with the data and audio modes were successful with 5W transmitted power. It was possible to send data to the robot through the built-up environment. Interference was reduced with the dedicated UHF frequencies and the RCP. Audio reports from the acted victims stated it to be clear and the readability as good. The audio from the victim was dependent on the video reception. With the 1W transmission power for the video feedback, it was found that the video clarity and signal strength was weaker within the built-up area compared to the audio transmission from the control station.

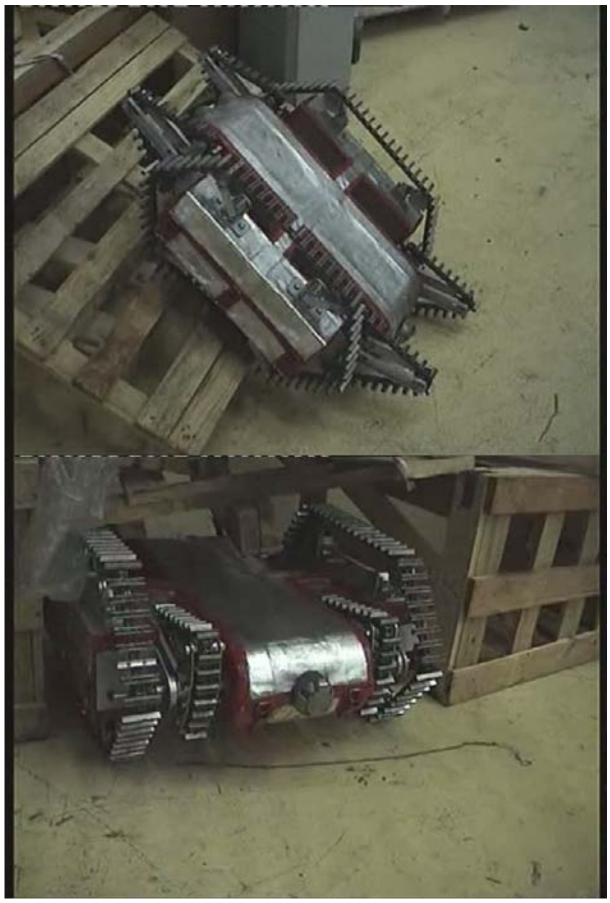


Fig. 12. CAESAR robot climbing obstacles and entering a confined space

Fig. 14. The flame from a normal camera compared to a thermal camera

The egg-beater antennas presented reliable communication between stations irrespective of the orientation of the robot. Transmitters with 5W output allowed Line Of Sight (LOS) and Beyond Line of Sight (BLOS) communication. It was found that the 1W transmission power for the video communication limited the distance for reception through the built-up area. The egg-beater antennas were mounted to the trailer with fishing rod suction cups. Higher elevation of the antennas will increase the distance of communication.

The traction system permitted traction on rough and smooth surfaces. With the contracting arms, it is possible to climb inclines and go through confined spaces where rescue workers are not able to enter. This is seen in Fig. 12 and Fig. 13.

The tracks allowed movement in eight different directions. These directions allow for a gradual or sharp turn and assisting with easy maneuverability. With the usage of lead-acid batteries, CAESAR was able to lift itself for a time period of about 10 minutes. After this time period, CAESAR still had one hour of power to climb over obstacles and move across the terrain.

The scenario test demonstrated that the composite body construction allowed for protection of the internal components when objects fell on the CAESAR robot due to unsecured structures. Tests performed in the fire environment proved that the heat was reflected away from the chassis and therefore prevented internal temperatures increasing unnecessarily. The chassis and tractions system did not soften or malfunction in the heated environment.

Video from the thermal camera displayed information and detail about the environment that the normal camera was not able to reveal. Fig. 14 shows a video comparison of the fire ignited. The thermal camera image reveals the rising of the heated gases, which was not visible with the normal video footage.

As the smoke was increasing, it was not possible to view the lighted exit areas. Eventually the flame was not visible, but the thermal camera was able to still indicate the flame.

As the CAESAR robot was in motion in the high dense smoke environment, the normal camera's display was limited but the thermal camera was able to reveal objects in the surrounding area. The thermal camera also indicated heated walls and areas that could be dangerous for the rescue personnel, which was once again not visible with the normal camera. The thermal camera also made it possible to locate victims as shown in Fig. 15.

Fig. 15. The moving head of an injured victim was noticeable with the thermal camera

Smoke rises as it gets generated, keeping the visibility lower to the ground. As the weight of CO2 is heavier than air it descends. The CAESAR robot immediately detected an increase of CO2 which gradually increased as the smoke filled the room. Fig. 17 shows the gas concentration levels over the testing period in a room 5 x 10 x 3 m.

The CO_2 concentration increased drastically. After 10 minutes, the concentration level increased more gradually, as the room was filled with smoke and the fire was decreasing in size.

From a time period of 15 minutes, it was observed that the CO_2 concentrations decreased, as the fire died. After 24 minutes the concealed room was opened and the smoke and gases escaped.

Methane levels increased slightly as time passed, which is possible depending on the materials being burned by the fire. The AI implemented by the GUI indicated the unsafe and dangerous levels by changing the background color from green to either orange or red respectively. The danger probability was also indicated and was shown as being unsafe for humans as the CO_2 levels were over 2000ppm. The unsafe level is considered to be 500 ppm, which was reached within a minute. A dangerous level is considered to be 4000 ppm and this was not reached. US fire departments reach a burning building within 5 minutes after a fire has started. At this stage the CO_2 concentration would have already reached 2000 ppm, which is unsafe for humans and therefore the victims

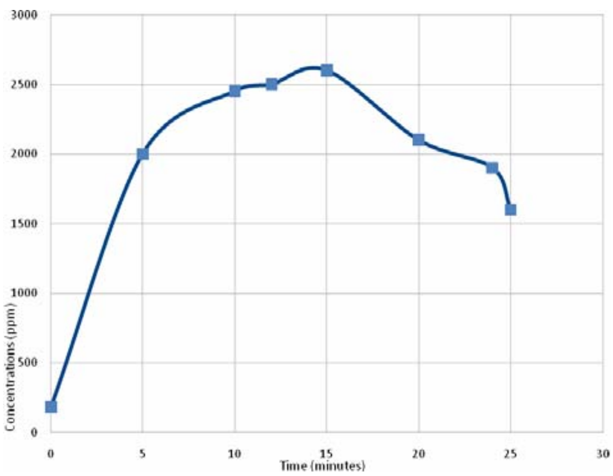


Fig. 17. CO_2 concentration vs time

would find it difficult to exit the building. A robot that could locate victims in areas of the building other than where the rescuers are, would be useful.
Understanding has been gained in the following areas; how radio waves operate in different environments, antenna designs, composite materials properties and development, mechanical constructions and development, emergency response training and scenarios.

10. Conclusion

Previous USAR robots and their associated problems have been discussed. The design and concepts used for the development of this research has been briefly explained. Each system was individually tested and experiments were performed to determine the specification of the robot. After additional tests were performed, explanation of the results in a controlled environment that simulated a burning building were presented. The contributions that received focus in the research are the improvements of the mechanical system, communication system and sensory system to provide a platform for further development in USAR robot research.
Communication improvements have been developed, resulting in consistency with the use of UHF dedicated frequencies and 5W transmission power. These improvements allow for Line Of Site and Beyond Line Of Site communication. The developed Robotic Communication Protocol allowed data reliability with the usage of both a single frequency and multiple stations needing to transmit and receive. Corruption of data due to interference is also prevented. Eggbeater antennas made it possible for omni-directional communication irrespective of the position of the robot within a building. Two way audio communication is established, allowing rescue workers to supply victims with critical information to survive and to receive audible information from the surrounding area. Thermal video transmission from the CAESAR robot allowed visibility of the surrounding area. Dangerous areas and victims could also be observed, which was not possible with a normal camera.
CAESAR's tracks prevented slippage on smooth surfaces. Slippage was experienced on rougher surfaces, but CAESAR was able to proceed forward as the flipper arms assisted with climbing over obstacles. Transformation of the flipper arms does not only allow for gradual lift of the body, but for lifting either the front or back up for better manoeuvrability. The integration of the motor and drive systems made it possible for the flipper arms to rotate while the tracks are turning. The Kevlar and phenolic resin composite body ensured a strong body, protecting the delicate components and modules inside. Heat is also reflected from the outside with the aluminized Kevlar, preventing the electronic components from increasing temperature due to the outside environment.
The control unit consisting of a GUI, made it possible to control different robots with a single interface. Though only one robot can be controlled at a time, it is uncomplicated for one person to switch between robot controls. This relieves other rescue workers to assist with the disaster scenario. The GUI supplies controls to move the robot, visuals to view the receiving video and information determined from the AI models. Gas concentration levels for unsafe and dangerous conditions have been used as guidelines to determine the safety of victims and rescue workers. By using these concentration levels, it was possible to develop fuzzy logic models and therefore determine what percentage of the danger existed in the surrounding environments.
With the use of the encoders it is possible for CAESAR to determine the orientation of itself and the flipper arms, and with the use of the ultrasonic sensors it is possible to detect obstacles. With this information, the internal AI of CAESAR can determine the orientation of the flipper arms to allow for the best way to manoeuvre over the obstacles.
Field testing verified many of the expected results. The setup time was 153 seconds, which consisted of connecting the different power points from the car to the modules in the trailer. The PC bootup also consumed a large portion of the time. This time period could be minimized if a mini-bus is used for the transportation method as the setup could be completed in advance. All the modules and control systems will be pre-installed, allowing the PCs to be booted while approaching the scene. The CAESAR robot is switched on by a remote control, and is ready for instructions within a second. With the minibus it would be possible to have a ramp that the robots could deploy from and therefore eliminate the need to unload it by more than a single person.
The manoeuvrability of CAESAR was tested in the built scenario structures and at the fire department's training facilities. Gas concentration and danger levels were shown with the GUI. Audio, data and video communication were tested in the built-up environment. With the use of Lithium-ion batteries the overall length of the use of the robot will be increased dramatically.
The minimum specifications required from the fire department were thermal imaging, gas sensing, manoeuvrability, audio feed, telemetry, thermal shielding and keeping the weight and size as low as possible. All of these specifications were integrated within CAESAR.
The incorporation of the above improvements made it possible to have a robot that will assist the rescue workers and firefighters in rescue attempts. Victims can be located, and dangerous environments can be observed. Confined spaces can be entered and searched, without risking the lives of rescue worker unnecessary when there are no living victims in these dangerous environments.

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