Communication and Artificial Intelligence systems used for the CAESAR robot

Riaan Stopforth (ZS5RSA) and Glen Bright
Mechatronics and Robotics Research Group (MR²G), University of KwaZulu-Natal
South Africa

R. Harley
The school of Electrical and Computer Engineering
Georgia Institute of Technology
USA

1. Introduction

Robots are necessary for search and rescue purposes, to access concealed places and environments that fire fighters and rescue personnel cannot gain entry to. Three hundred and forty-three firefighters died at the World Trade Center during the September 11 attacks in 2001 (Wiens, 2006). Often these rescuers unnecessarily entered an environment that had unstable structures as there were no live victims to rescue. Sixty-five of these rescuers died due to searching confined spaces that had flooded (Kleiner, 2006). Rescue workers have about 48 hours to retrieve victims (Gloster, 2007). Several hours are lost when rescuers are unsure of buildings stability. After a disaster the structures are often unstable and rescuers need to evacuate until the rubble has stabilized. Frequently the rescuers have to evacuate even though a body part of a possible survivor is seen, due to unstable surroundings (Roos, 2005). 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 rescuers workers (Trivedi, 2001).

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 were involved in these rescue attempts. The robots that they used are shown in figure 1. The advantage of these robots above rescue members is that the disaster areas can be entered immediately after a disaster.

Problems identified at the World Trade Center as well as at the testing grounds of the National Institution of Standards and Technology (NIST) are that the robot's traction system malfunctioned. (Greer et al., 2002). More research is needed for the robots to withstand the harsh conditions of a fire (Wiens, 2006). Other problems observed were unstable control system, chassis designed for narrow range of environmental conditions and limited wireless communication range in urban environment as well as unreliable wireless video feedback

(Calson et al., 2004). Some robots were either too large or not easily maneuverable (Gloster, 2007).

Further problems experienced were that the setup time of the robots was too extensive and the human to robot ratio for transport and controlling were not ideally 1:1 (Greer et al., 2002). Problems were identified regarding the communication with the robots (Remley et al., 2007).

Fig. 1. The Inuktun MicroVGTV and I-Robot Packbot was used in the rescue attempts at the World Trade Center in September 2001

Communication is critical as the rescuers need to send instructions to the robots, but at the same time receive vital information about the environment. This could save lives as it could indicate poor structural areas, dangerous gases and extreme temperatures. Research has been performed to determine improvements and possible solutions to these problems experienced. These solutions include a combination of communication reliability in these environments, and a sensory system to allow the robots to maneuver across the terrain successfully.

The communication and sensory system is discussed as it was implemented on the CAESAR (Contractible Arms Elevating Search And Rescue) robot. These developments include communication protocols, hardware interface and artificial intelligence to indicate the safety and danger levels for both humans and the robot.

2. COMMUNICATION

The interferences that were experienced before are mainly due to the robots using Industrial, Scientific and Medical (ISM) bands. Many electronic communication units use the ISM bands which are unlicensed frequencies that have certain constraints. As USAR robots are used to save lives, it is suggested that licensed frequencies are utilized. This will significantly prevent interferences. The output power between the control unit and the robot can be constrained to prevent a signal from one unit overwhelming the signals from other units.

Another reason for failed robot communication is the loss of signals between the robot and its control unit. This is mainly caused by the frequency used. As wavelength is inversely proportional to the frequency and the antenna size is proportional to the wavelength therefore the higher the frequency, the smaller the antenna will be. Transmission efficiency decreases as higher frequencies are used. The signal penetration into buildings is also effected by the frequency used. Higher frequencies are capable of penetrating more dense materials that lower frequencies. The disadvantage of higher frequencies is that small items, such as dust particles, resonate at the high frequency therefore causing it to absorb the power of the signal. Therefore it is best to use a frequency in the center of the two extremes that will allow optimization for radio communication. The comparison of the different factors that are considered are shown in figure 2. Subsequently the decision is, to use UHF frequencies as these are able to penetrate with a relatively low power output and have a relatively good signal penetration property.

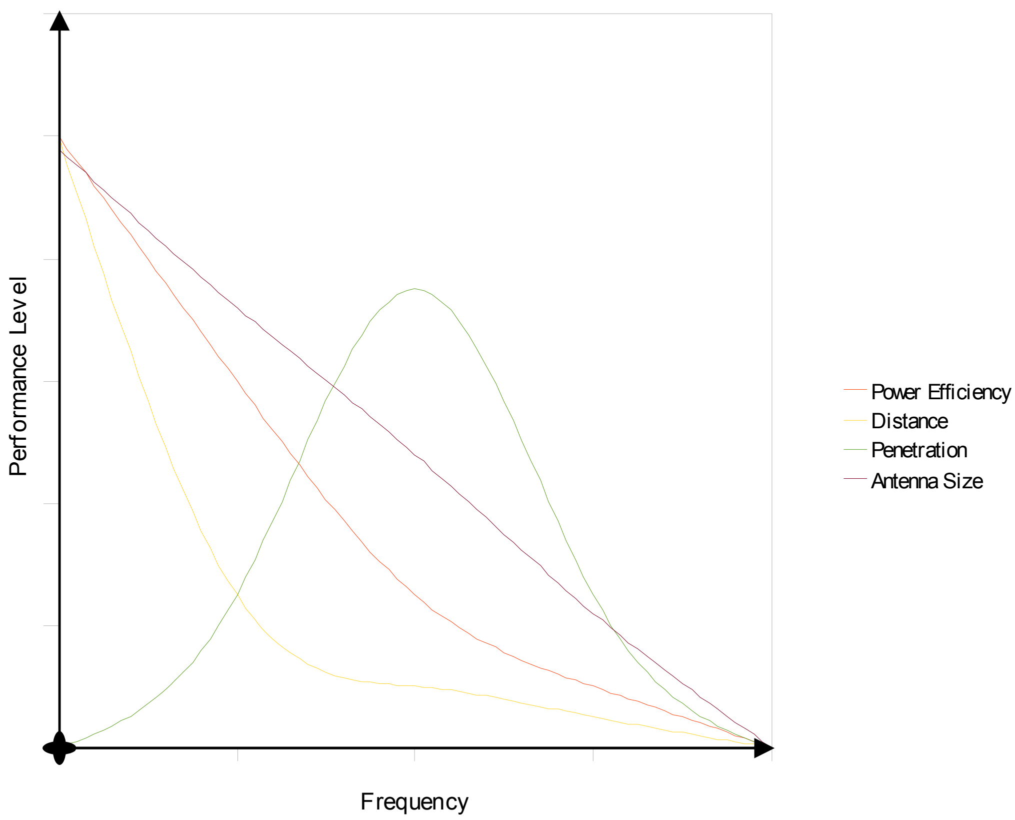

Fig. 2. Comparison of factors considered as frequency increases

2.1 Data Communication
Different modules and units are needed for the successful communication of video, audio and data. The modules that were used for the CAESAR robot, are discussed and explained.

2.1.1 Radio Modules
The Radiometrix narrow band FM multi-channel UHF TR2M-433-5 transceiver modules is used for the data communication. A photograph of one of these modules is shown in figure 3 (Radiometrix, 2004).

Fig. 3. Radiometrix TR2M radio module

The features of the TR2M modules are:

- Can be programmed to operate on any 5 MHz band from 420 MHz to 480 MHz.
- Fully screened
- 1200 baud dumb modem

Pertaining to the above features, these data modules will be valuable for the USAR robot. It enables the programming of the modules to operate on the frequencies supplied by the fire department. The power consumption is low which is vital for power saving. With this large range of operating temperatures the heat from the outside could be insulated and limited to the module.

The only problem that occurs regarding these modules is their inability to transmit more than 10 mW. An output power of 5 W is required for efficient communication with the restrictions of buildings and other power absorbers. A RF amplifier is needed to solve this problem.

RF amplifiers that amplify 10 mw to at least 5 W are either not readily available or they are expensive. In order to solve this problem, the final stages of Motorola MCX100 radios were used. The need arose for two of the three RF amplification stages as the amount of power that these final stages produce is sufficient, whereas the three final stages produce more than 5 W output power. Refer to figure 4 for the interconnection of these stages. The disassembly and reconstruction of these stages require the addition of discrete components. Not all the modules in the radio were used. These impedances of the missing modules are to be replaced. The circuit of the RF amplifier is traced with a probe to determine the amplification of each stage. There are two positive power supply points. Tracing the power point that was not powering the circuit of the first stage of the RF amplifier, it was found that there was a discontinuation for a closed loop circuit. This closed loop circuit was terminated to another module not used. By modifying the impedance on this point, a different output power was produced from the RF amplifier. It was discovered that a resistance of 300Ω made the RF amplifier produce 5W output.

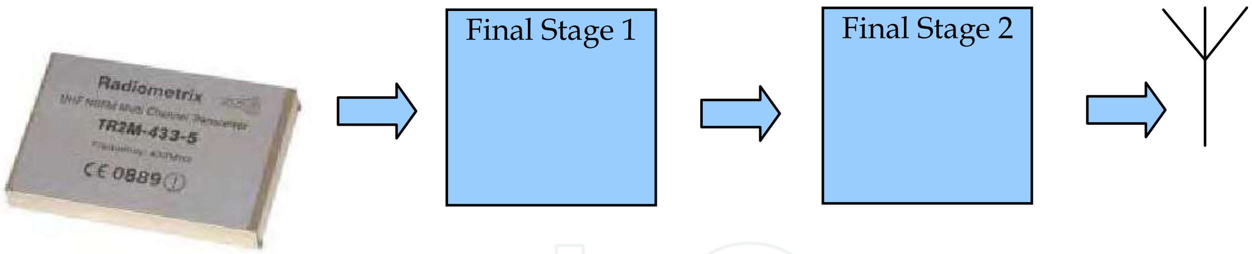

Fig. 4. Transmission process block diagram

A problem occurred in the reception, as the signal was not able to reach the TR2M module from the antenna due to the RF amplifier not being bi-directional. This could possibly be solved by connecting the antenna directly to the TR2M module and then reception would be possible, but the high output power from the RF amplifiers would terminate the operation of the TR2M module, as there is high power penetrating the sensitive module.

This problem was solved by the implementation of a switching circuit on the output to the antenna. Figure 5 illustrates the concept of this circuitry. While the two relays are in position 1, the TR2M module can receive data. Should the TR2M module need to transmit, then the relays are switched over to position 2, which will connect the TR2M module to the RF amplifier and in turn with the antenna. This prevents the need for two antennas and allows for only one radio module for data communication at each station.

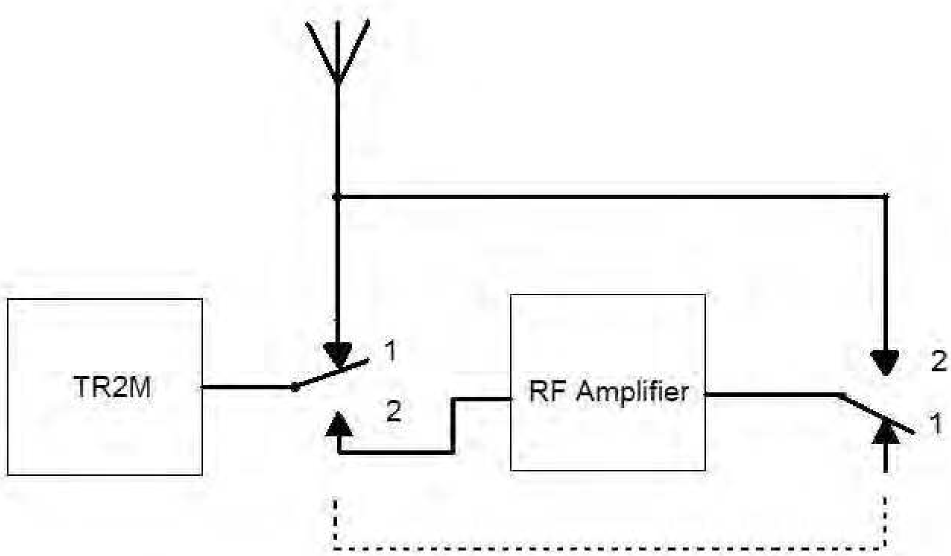

Fig. 5. TR2M and RF Amplifier with the appropriate switching

2.1.2 Protocols

The use of protocols is important for data to be successfully transmitted. Using available protocols is an option, but the performance and efficiency must be considered. Most existing protocols have been developed over many years and by various people. These protocols are optimized for best performance for a specific task.

The IEEE 802.11 protocol could be used for communication between the robots, but there is not always an Access Point available for the wireless communication. The communication between the robots will be an Ad-Hoc style. Since UHF frequencies are being used, the data rate will be less in comparison to that used by wireless communication, as they use frequencies in the 2.4 GHz band and the quality factor bandwidth decreases as frequency decreases. Due to the bandwidth being decreased, additional collisions might occur and therefore smaller packet sizes are needed. More data transmission from other stations is able to occur when the packet sizes are smaller.

2.1.3 Robot Communication Protocol

The Robot Communication Protocol (RCP) uses different aspects from the wired and wireless LAN protocols. The problem when using wireless communication technology is that it uses the 2.4 GHz band which causes the small particles of buildings to resonate at this frequency and to absorb energy which can prevent penetration through buildings. A further problem with the use of the IEEE 802.11 protocol is that its packets contain header details that will not be utilized for the USAR robots. This is therefore unnecessary data that will be transmitted and will occupy the use of the medium. In view of the fact that the baud rate of the data communication modules can be low, unnecessary data must be prevented as this can saturate the medium.

Another problem pertaining to the existing protocols is that they may possibly contain non-printable characters that cannot be processed by certain computers and microcontrollers. The printable characters are those that have an ASCII value between 31 and 127.

A new wireless communication protocol is required for USAR robots to utilize. A decision was made to use callsigns to identify the robots and control units to prevent communication interference. A six character callsign that consist of letters of the alphabet and numbers is assigned to each robot and control unit. This gives a combination of $36^6 = 2.17 \times 10^9$ different callsigns available.

There are two types of protocols that need to be transmitted namely: a "one way packet" that is sent from one station to the other and that needs no confirmation (referred to from now on as a Robotic One-way (RO) packet) and a packet which is sent from one station to the other and which replies with an acknowledgment of reception packet (referred to from now on as a Robotic Confirmation (RC) packet).

There are four packets for the robotic network namely, Request-To-Send (RTS), Clear-To-Send (CTS), Acknowledgment (ACK) and Data packet. The different packets with their fields are explained below.

RTS / CTS / ACK Packet

The packet format for the RTS, CTS and ACK packets are shown in figure 6.

Size	1 byte	1 byte	2 bytes	6 bytes	6 bytes	1 byte	1 byte
Field	Start	Type	Duration	RA	TA	Checksum	End

Fig. 6. RTS / CTS / ACK Packet

Start: The start character is for stations to identify the commencement of the packet. This is indicated with the hash (#) character. Should a station only start receiving in the middle of a transmission it will then recognize this and discard the packet. The purpose for the necessity of a start byte is that the transmission is asynchronous on a single channel.

Type: This field indicates the type of packet that is being sent. The indication for the RTS, CTS and ACK packets are the characters 0, 1 and 2 respectively.

Duration: The duration of the transmission is specified in this field. This provides the other stations with the time period to delay before attempting to transmit. The duration is specified by the number of characters. Time periods are calculated from the sum of the two bytes multiplied with x, where x is the time period for each character to transmit.

$$x = \frac{8bits}{baudrate} \tag{1}$$

Should these values be a "#" or "!", then the most significant byte must be incremented and the least significant byte must be decremented.

RA: This is the address of the receiving station. This field presents the opportunity for other stations to identify whether that the packet is for them or not. Should the packet not be intended for the station, the rest of the incoming packet can be disregarded and the station can start processing other incoming packets after the delay duration.

TA: This is the address of the transmitting station and is used by the receiving station to identify if the packet is from its approved station.

Checksum: This verifies the integrity of the packet. The field value consist of the sum of all ASCII values of all characters in packet modular 94 and the addition of 32. Should the receiving station receive a packet that is not approved then it is subsequently dropped. If the value of this field should be equal to "#" or "!" then the duration field is incremented and the checksum is recalculated. This field must be a printable character and not a control character (I.e. the character must have an ASCII value between 31 and 127)

End: This indicates the end of the packet with an exclamation mark (!) character.

Data Packet

The format of the Data packet is shown in figure 7.

Size	1 byte	1 byte	2 bytes	6 bytes	6 bytes	0–255 bytes	1 byte	1 byte
Field	Start	Type	Duration	RA	TA	Data	Checksum	End

Fig. 7. Data Packet

Start: The start character is for stations to identify the beginning of the packet. This is indicated with the hash (#) character. In the event that a station only starts receiving in the middle of a transmission, this will be identified and the packet will be discarded. The motivation for a start byte is that the transmission is asynchronous on a single channel.

Type: This field indicates the type of packet that is being sent. The identification of a RO Data packet is the character 3 while for a RC Data packet it is the character 4. The other possible values (except for the character values for # and !) for this field are reserved for future use.

Duration: The duration of the transmission is given here. This provides the other stations with the time period that they have to delay with before attempting to transmit. The duration is given by the number of characters. Time periods are calculated from the sum of the two bytes multiplied with x, where x is the time period for each character to transmit.

$$x = \frac{8\,bits}{baud\,rate} \tag{2}$$

Should these values exist of a "#" or "!", then the most significant byte must be incremented and the least significant byte must be decremented.

RA: This is the address of the receiving station. This gives the opportunity for other stations to identify whether the packet is meant for it or not. In the event that it is not, the station can ignore the rest of the incoming packet and start processing other incoming packets after the delay duration.

TA: This is the address of the transmitting station. This is used by the receiving station to identify that the packet is from its relative approved station.

Data: The data for specific instruction or information between the stations is stored in this field. The only characters that are not allowed in this field are the hash (#) and the exclamation mark (!) seeing that these are the start and end characters respectively. Control characters are also not allowed in this field.

Checksum: This verifies the integrity of the packet. The field value consist of the sum of all ASCII values of all characters in packet modular 94 and the addition of 32. Should the receiving station receive a packet that is not approved it is subsequently dropped. If the value of this field is equal to "#" or "!", the duration field is then incremented and the checksum is recalculated. Furthermore this field must be a printable character and not a control character (I.e. the character must have an ASCII value between 31 and 127)

End: This indicates the end of the packet with an exclamation mark (!) character.

2.1.3.1 Communication Procedure

The description of the communication procedure is described by means of two stations; station A and station B. Should station A want to transmit, it would observe whether no transmissions are occurring. If none are detected, then station A starts transmitting a RTS packet. All the stations in the vicinity of station A will delay transmission for the period of the duration field in the RTS packet. The delay duration period consists of the sum of the following:

- the time period needed to transmit the RTS packet
- the time period needed to transmit a CTS packet
- the time period for the Data packet

- the time period to transmit an ACK packet (if this is needed)
- the sum of the processing time at each station

Station B receives the RTS packet and replies with a CTS packet which contains a delay duration period which is:

- the sum of the time period for the CTS packet
- the time period to transmit the Data packet
- the time period to transmit an ACK packet (if this is needed)
- the sum of the processing time at each station.

Station A responds with the Data packet that contains a delay duration period which is the sum of the time period for:

- the time period to transmit the Data packet,
- the time period to transmit an ACK packet if this is needed
- the sum of the processing time at each station.

Station B will reply with an ACK packet should the last received packet have a type value of 100. This packet will contain a delay duration period which is the sum of the time period to transmit the ACK packet as well as the processing time at each station.

Given that there is no Access point that is stationary, there is no station that controls communication within the network. In figure 8 four stations are shown with their respective radio coverage. C1 and R1 are control unit 1 and robot 1 respectively and C2 and R2 are control unit 2 and robot 2 respectively.

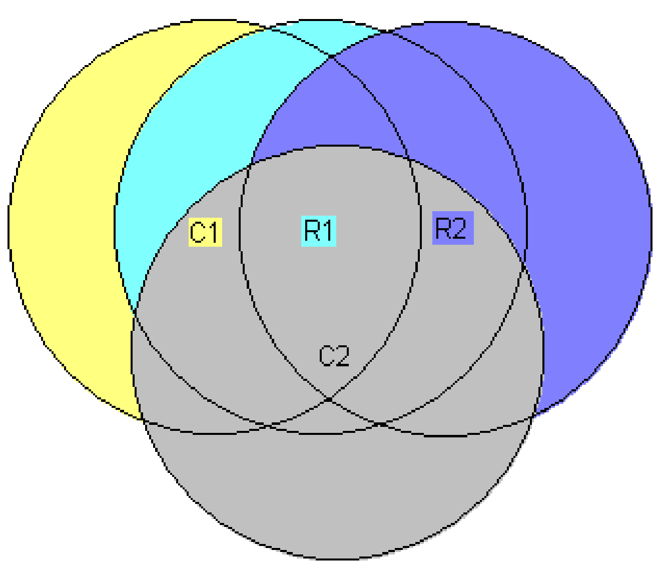

Fig. 8. Radio Coverage of two control units and two robots

As noted in figure 8, C1 is in radio coverage with R1 and C2; R1 is in radio coverage with R2 and C2; R2 is in radio coverage with C2. Since C1 and R2 are not in radio coverage packets to request transmission will not be received between these two stations. This is not a great disadvantage as the different stations operate in an ad hoc system. Of importance is the aspect that each robot is able to communicate with its own control unit.

Should a RTS packet be transmitted by C1 then R1 will subsequently receive the request and reply with a CTS packet. This CTS packet, which will contain a duration field, will be received by R2 as well. In view of the fact that R2 has received this packet, it will delay with any transmission for this time period before trying to transmit again.

In the instance that both C1 and C2 transmit a RTS at the same time, R1 will then receive data that will be a combination of data from the two control units. R1 will reject this data, as it will not recognize it or because it will not exist of an acceptable packet. After a time-out period C1 will realize that R1 has not responded and will transmit the RTS again if required.

As the RTS packets are relatively small, the overhead of retransmission would be small if two stations should transmit the same time. The sum of data being sent in the Data packet is limited to 128 characters and it need not be necessarily sent in a specific format, providing the format is understandable between the respective control units and the robots.

The advantage of the RCP is that a computer system could be connected to a modem that uses the same protocol and this modem could then transmit and receive instructions and data to a large network of robots. In this situation the computer will be the control unit and will not be dedicated to only a single robot. This network of robots could then be controlled to perform a task that could have a greater efficiency than a single robot.

The RCP packets that are used to control a robot have smaller packets sizes of at least 38 % compared to those used by hard-wired computer network protocols and 33 % compared to that used by IEEE 802.11 protocol. Communication between the robots and their control units are more reliable when used in a network scenario. The use of a computer network protocol could be valuable when the robots have to transmit data and information that involves more than just the basic instructions.

2.1.4 Modular Approach for Layered Model

A layered model similar to the OSI model is needed for data communication. Each layer has its unique task to optimize the communication. The advantage of having a layered model is that each layer can be modified and optimized without affecting the other layers. The layered model can be represented as indicated in figure 9.

Application
Data link / Transport / Session / Presentation
Physical

Fig. 9. A three layered model

This model has been divided into three layers as each layer will be controlled by a separate module or microcontroller. The Physical layer consists of the hardware that will be used. In the case of the USAR robot, this will be the radio modules that will act as the transceivers.

The layer that is a combination of the Data link, Transport, Session and Presentation will be controlled by a single microcontroller. The Data link layer is in control of the packets that are being sent, while the Transport and Session layer is responsible for the packet's control and transmission permission respectively. All the received data must be presented in a format for the computer to understand. This is achieved by the Presentation layer.

The Application Layer is involved in the displaying of the information and with the interaction with the user. This layer is also involved in the output, being the movement of the motors and any other attachments of the robot. This layer will be controlled by a microcontroller which could be attached to other microcontrollers or modules, depending on the complex of the attached module.

2.2 Voice Communication

Voice communication between the robot and the rescuers is essential for the rescuers to get information from survivors. Rescuers can also calm the victims when the robot approaches and notify victims that help is on the way and of possible ways to save themselves. The voice communication between the robot and the rescuers will be achieved through the video communication but communication between the rescuers and the robot is still required.

Two radios are needed for this communication to occur. Since one of the assigned frequencies is used for the data communication, the other assigned frequency is to be used for the voice communication. It was thus decided to use Amateur radios for this communication as it was possible to purchase them due to a license obtained.

The decision was to use the Yaesu VX-7R and VX-3E transceivers. These radios can be modified to operate on these emergency bands and have different useful features. Diagrams of the Yaesu VX-7R (Vertex, 2002) and VX-3E (Vertex, 2007) are shown in figure 10.

Fig. 10. Diagram of the Yaesu VX-7R and VX-3E radios

The Yaesu VX-7R have the feature to operate on UHF bands. The Yaesu VX-7R is used in the control unit. It has the useful characteristic of a keypad, allowing the rescuers to tune into frequencies other than those used for the robot, if so required. With this radio it is possible for the rescuers to tune into the audio frequency of the video transmission from the robot, should the sound from the television be unclear.

The Yaesu VX-3E has feature that it can receive between 420 and 470 MHz. The Yaesu VX-3E is used mainly for reception of audio in the robot. The useful characteristics of the Yaesu VX-3E is that it is small in size, light weighted and can operate at temperatures that could possibly occur in the robot.

2.2.1 Microphone and Speaker adapter

The audio input to the video transmitter, (discussed in Chapter 2.3 – Video Communication) needs to have an impedance of 600 Ω and a maximum voltage of $1V_{P-P}$ or 0.775 V_{RMS}. A 600 Ω dynamic microphone was initially connected to the input of the audio as there was no verification as to whether the transmitter had a build in preamplifier. This did not seem to work, so a mono microphone preamplifier is used to amplify the signal from the dynamic microphone. While the preamplifier is connected to the transmitter, the preamplifier output is tested on an oscilloscope and the gain is altered to get a maximum output of $1V_{P-P}$. The schematic of the microphone preamplifier is shown in figure 11 (Excellence, 1998).

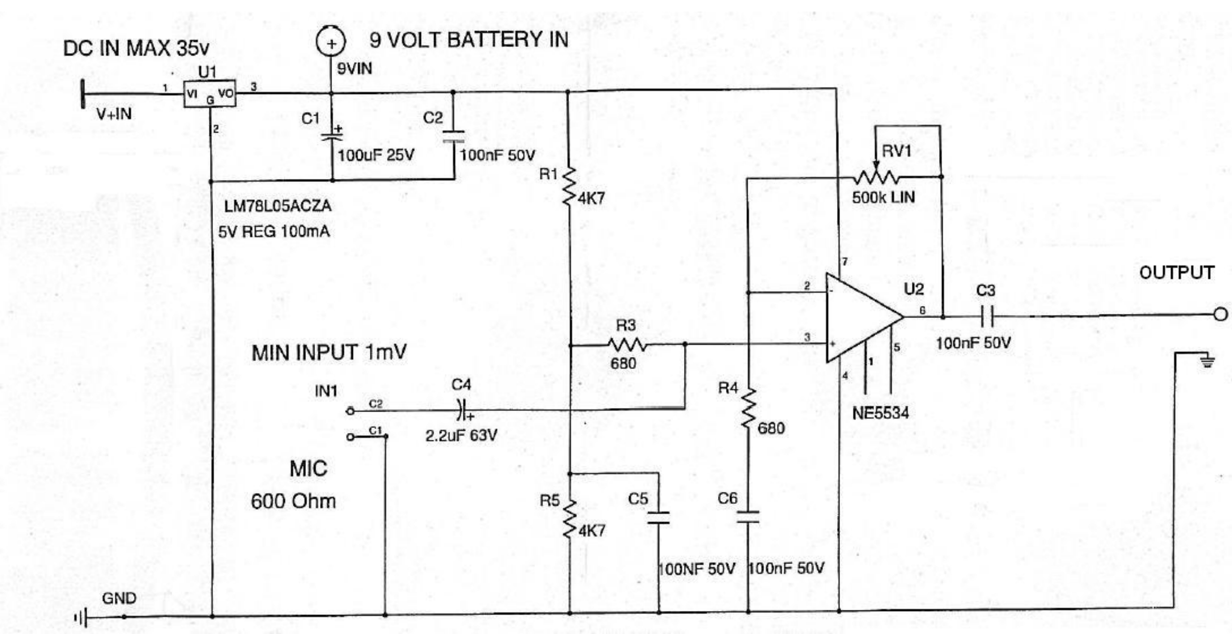

Fig. 11. Schematic of the microphone pre-amplifier

The dynamic microphone used is manufactured from plastic which will result in a problem at high temperatures. Research has been performed to determine the availability of high temperature microphones but the research proved unsuccessful. It is therefore decided to continue using the plastic microphone to enable the testing of the principles being discussed.

An ear piece with microphone is used in the Yaesu VX-7R radio, to allow the controller to communicate with any victims. The VOX-activation function could be set to allow transmission of spoken voice.

A 1.5mm earphone plug is used for the Yaesu VX-3E radio and connected to an 8Ω speaker. Research was performed to determine whether speakers were available that would be able to resist the high temperatures, but none were found. An ordinary speaker is used to prove the principle.

2.3 Video Communication

The video is from the FLIR PathFindIR thermal camera shown in figure 12 (FLIR, 2006). It has the following specifications:

- Size: (58mm x 57mm x 72mm)
- Input Voltage range: 6V – 16V
- Power dissipation: Less than 2W
- Weight: less than 0.4 kg

The PathFindIR is ideal for this project, as it is small, does not weigh much, and is affordable compared to other available thermal cameras. It has a low power dissipation and can operate from -40 °C to 80 °C. Should the temperature decrease below -40 °C, the heating element is switched on, therefore allowing images to be transmitted in cold environments.

The video from the PathFindIR needs to be transmitted. ICASA (Independent Communication Association of South Africa) and Sentech have given permission to use channel 54 (735 MHz) for video transmission, on the condition that the output power is less than 1W, and the transmitter is calibrated by one of their approved dealers.

Fig. 12. FLIR PathFindIR thermal camera

The modulator and IF converter is used to generate the video on the required frequency. This signal is then amplified to 1W. This amplifier is shown in figure 13 (Jackel, 2008).

Fig. 13. 1W UHF amplifier

These modules can operate between 470 – 862 MHz. It has been confirmed that all output power for communication must be at least 5W(Reynolds, 2008) for search and rescue reasons. As there is a restriction for the video output power, 1W is used to prove the concept for this robot. It is suggested that a video frequency is assigned for search and rescue purposes so that the output power can be increased to 5W.

A block diagram of the interconnection between the PathFindIR, converter/modulator, microphone, audio preamplifier, video amplifier and antenna is shown in figure 14.

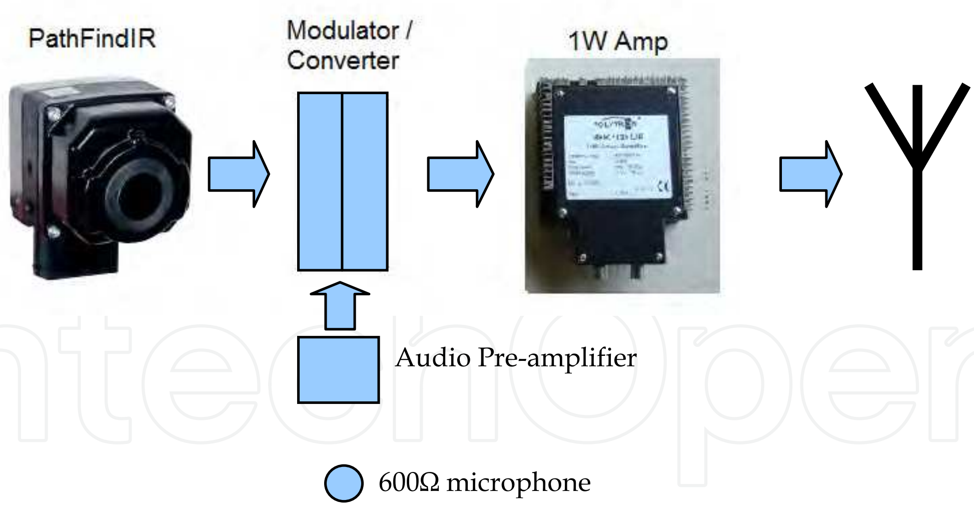

Fig. 14. PathFindIR connected to the modulator/converter, 1W UHF amplifier, audio preamplifier and antenna

2.4 Antennas

Antennas are the source of transmission into the medium of air and the absorber of signals from the medium of air. Different antennas have different properties of radiation patterns and polarization. This is a topic in communication that is often neglected, but the antenna used has an effect on the performance of transmission and reception of signals. The antenna of a radio can influence many factors that can be the cause of many problems. Calibrating and selecting an antenna influences the efficiency of output power and signal strength that will be radiated from a radio.

The antennas used were investigated. The orientation of the antenna effects the polarization of the transmitted waves. It would be ideal to have vertical and horizontal polarization. The best antenna for this purpose is the egg-beater type. It gives vertical and horizontal polarization, but it has the disadvantage of being relatively large, which is not ideal, as one of the objectives of a USAR robot is to design it as small as possible.

Vertical antennas were investigated and a problem encountered is that the base plane shields the signals from being transmitted through it. Different fractions of the wavelength antennas have got different properties. A ½ wavelength antenna has radiation lobes that are perpendicular to the antenna, while the ¼ wavelength antenna has radiation lobes that are at an angle of about 45 degrees. The use of the property of the ¼ wavelength antenna will work well as it was found that it has a degree of output power directed towards the end point of the antenna. The only disadvantage of this type of antenna is that there is no radiation past the base plane.

This problem is solved by removing the base plane and replacing it with a piece of coaxial cable that is longer than the ¼ wavelength. The reason for the need of the base plane or coaxial cable is that it produces the negative part of the modulated sine wave. With the removal of the base plane, the radiation from the antenna is relatively isotropic, with low radiation towards the end points of the antenna. The antenna then is seen as a ½ wavelength dipole antenna. This isotropic radiation pattern is caused by the minor lobes that are allowed to be radiated next to the main lobe. When the robot is a number of wavelengths above the ground, the radiation pattern will become more isotropic because of more lobes, and will lower the elevation angle of the lowest angle lobe (Roos, 2005). This antenna has the disadvantage in that it is not being vertically and horizontally polarized. This is solved by using an egg-beater type antenna that is scaled in size at the receiving unit. It will then be able to receive any polarized signal (discussed in section *2.4.2 Eggbeater Antenna Design*).

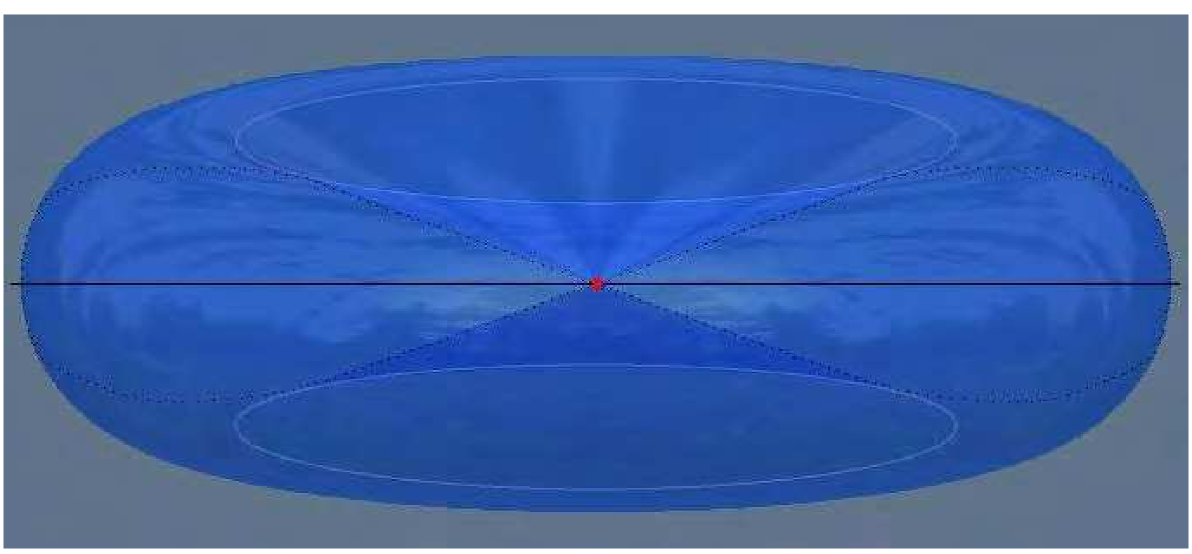

Fig. 15. ½ wavelength radiation pattern

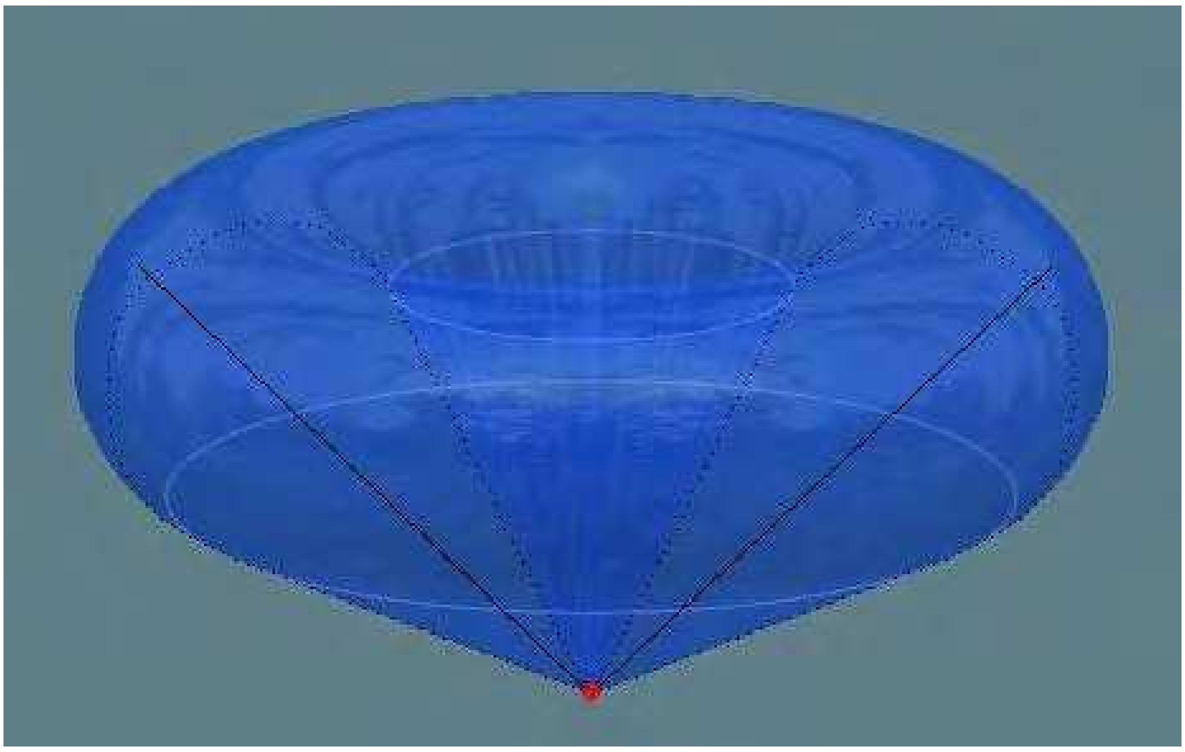

Fig. 16. ¼ wave radiation pattern

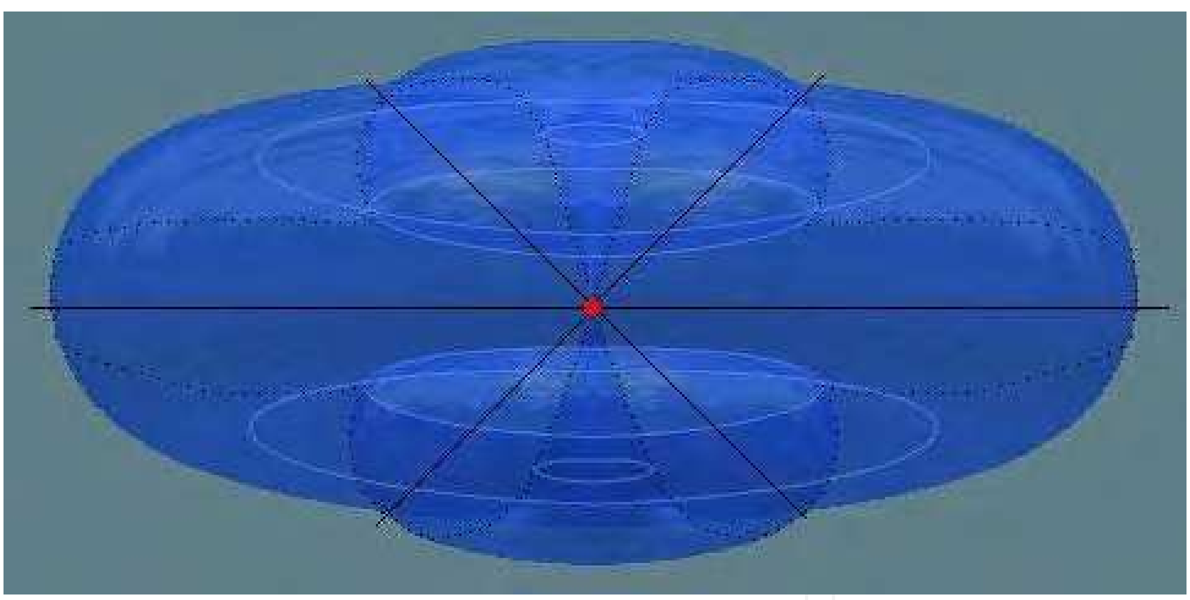

Fig. 17. Radiation pattern of antenna that is used.

Communication is improved with the use of UHF frequencies because, the penetration of the signal is increased, the antenna is relatively small and the transmission efficiency is still acceptable. With the use of a dipole antenna that has coaxial cable for the ground plane, the radiation pattern is increase by 100 % in terms of direction compared to an antenna that has a base plane. The radiation distance decreases as the output energy remains the same and is spread over a larger angle. The polarization of the radiated waves are in the same orientation as the antenna's orientation and can be received with an egg-beater antenna that is capable of receiving any polarized signal.

2.4.1 Quarter-wave Antenna Design

The length of the full wave antenna in free space is calculated from equation 3. This equation is valid for transmission in free space.

$$\lambda = \frac{300}{f} \tag{3}$$

where: λ = wavelength in meters

f = frequency in MHz

The surrounding air has an effect on the antenna, so a factor η has to be multiplied with equation 4. The value of η is variable and depend on the antenna's surroundings. As the robot will be operated in conditions of smoke, heat and with various objects surrounding it, the value of η would vary.

Equation 4 is used to calculate the wavelength of the antenna. This length of antenna wire is then cut and connected to the radio with a Standing Wave Ratio (SWR) meter, which is connected in series with the feed line. Millimeters of the antenna is trimmed away until the SWR value is very close to a SWR ratio of 1:1.

SWR is the ratio of the forward and reflective power. Power is reflected back into the transmitter when the load does not have a matching impedance to that of the characteristic impedance. The SWR of a specific load can be calculated with equation 4 (Frenzel, 2001).

$$SWR = \frac{1 + \sqrt{P_R / P_F}}{1 - \sqrt{P_R / P_F}} \tag{4}$$

From equation 4, it is seen that as P_R decreases, the SWR will tend to 1. To determine the SWR of a specific antenna, the meter is calibrated so that there is maximum deflection for the forward transmission of a signal, and then the reflective signal back into the system is read. This reading is performed every time an alteration of the antenna is made, until the SWR is close to 1:1. The ideal situation is to have a SWR of 1:1, but there are many factors that can influence this reading, such as surrounding objects.

An antenna tuned for a frequency in the UHF band is compatible for most frequencies in the UHF band. This characteristic is used to tune the antenna for a frequency of 450 MHz. With the use of equation 3, the antenna wavelength is calculated as:

$$\lambda = \frac{300}{450} = 667mm \tag{5}$$

The full wavelength is 667 mm, but since a quarter wavelength antenna is to be used, the antenna length required will be 166.75 mm. From this length, the antenna is lengthened or trimmed until a SWR of 1:1 is obtained. This is needed as the antenna is operated in an environment that is not free space. The final antenna length is 170 mm.

2.4.2 Eggbeater Antenna Design

Different forms of the eggbeater antenna design were considered. The testing of the antennas were performed with the use of a RF generator and a SWR meter. A receiver with a horizontal antenna was set up. The strength of the signal received by the receiver is displayed on a signal analyzer.

A folded dipole antenna was initially considered. This is a dipole antenna that is bent into a loop, bringing the ground and live point to each other, but not touching each other. The same configuration is used for another folded dipole antenna that is placed 90 degrees to the first one. The two loop antennas are separated with a quarter wave stub, so that the transmission between the two loops are 90 degrees out of phase and therefore prevent cancellation. The quarter wavelength coaxial cable stub must be shortened depending on the velocity factor of the transmission line. This value typically varies between 0.6 and 0.7. The velocity factor of a RG-174 coaxial cable is 0.66. This quarter wave coaxial cable length can be calculated by equation 6 (Frenzel, 2001).

$$\frac{1}{4}\lambda = F\frac{75}{f} \tag{6}$$

where F is the velocity factor of the coaxial cable.

It is very difficult to determine the exact length of the coaxial cable stub, as the theoretical value does not correlate to that of the practical assessment. Therefore a Dip Meter is used to cut the exact length of the coaxial stub. The Kenwood DM-81 Dip Meter was used for this. A photo of this Dip Meter is illustrated in figure 18.

The Dip Meter has a connection for a coil for the required frequency. A coil for a harmonic of 450 MHz was used. As the dial of the Dip Meter is not very accurate, the frequency counter that is on the Yaesu VX-7R was used to get the resonating frequency close to 450 MHz.

The Dip Meter is calibrated on the resonated frequency and a portion of coaxial cable is then placed next to the coil. A single loop then is made from a piece of wire and is soldered between the center conductor and the outside braid. Initially this loop is placed around the coil to get a broader band reading. The dial is cautiously turned until the Dip Meter is at full deflection. With this configuration, 2 mm pieces are cut from the coaxial cable, until it is detected that the Dip Meter is deflected towards zero. This is an indication that the coaxial cable being tested is absorbing most of the power at that frequency and that the coaxial cable is exactly a quarter wavelength which also incorporates the velocity factor.

The tests proved that the antenna is relatively omni-directional, but there is a couple of cancellations of signals where two parallel or perpendicular antennas cancel each other.

The eggbeater antenna was then considered. The eggbeater antenna consists of two loops that are perpendicular to each other. A quarter wavelength stub is placed between the two loops to cause the transmission between the two antennas to be 90 degrees out of phase. The tests confirmed that this type of antenna is more omni-directional and has relatively rare cases of signal cancellation. There is more dips in the signal strength than complete cancellation.

The problem with this type of antenna is that the loops must have a full wavelength circumference, making the diameter of the loop relatively large. This causes a space problem in the robot casing for this type of antenna (at 450 Mhz). The loop can be made smaller, but then higher frequencies must be used. As we want to use UHF frequencies, it would not be ideal to use smaller loops.

Resulting from this, the decision is to use the eggbeater antennas in the control unit where there is not as much constraints in size. Should the robot contain an antenna that is polarized in a single direction, then the eggbeater antenna (that has horizontal and vertical polarization) will be able to receive the transmitted signal. The tested eggbeater antenna is resonating between 440 MHz and 490 MHz, which is ideal for the available frequencies.

Fig. 18. Kenwood DM-81 Dip Meter

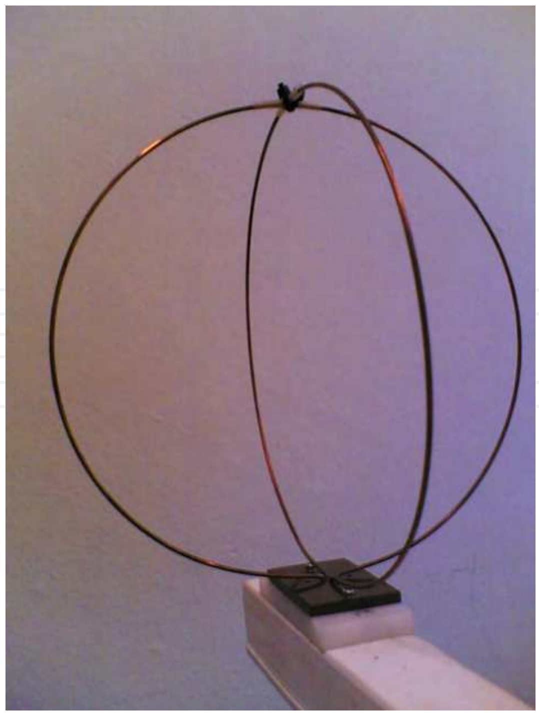

Fig. 19. Eggbeater Antenna

3. Gas Concentration Decisions

The gases that are of main importance in a search and rescue event is carbon dioxide, carbon monoxide, hydrogen sulphide, methane and oxygen (Gloster, 2007). Most sensors give an output of gas concentration, which is measured in parts per million (ppm). This data may be meaningless to the controller as it might hold no threat. An example will be the detection of methane gas. Should the robot detect 1ppm of methane, this could possibility not be dangerous, as it could be either a natural gas in the environment or of such a small quantity that it won't cause an explosion.

3.1 Gas Analysis

Further analysis of the gases and their respective properties need to be investigated. Different aspects of the gases were analyzed, to determine the concentrations that would be considered dangerous.

The Immediately Dangerous to Life or Health (IDLH) levels are used for non-emergency and emergency scenarios (Aerotech, 2009). These IDLH concentrations are determined with the following considerations (NIOSH, 2004):

- People must be able to escape the danger without the loss of life or irreversible health effects that could happen after exposure to that environment for a time period of 30 minutes.
- Prevention of severe eye or respiratory irritation, which will prevent a person from escaping the dangerous environment.

The compiled properties of the gases are represented in table 1.

Substance	IDLH (ppm)	TLV* (ppm)	Smell	Flammability percentage	NFPA – Health / Flammability / Reactivity
CO_2	40 000	5 000	Odorless	Non flammability	3 / 0 / 0
CO	1 000	25	Odorless	12% - 75%	3 / 4 / 0
H_2S	100	10	Rotten Egg	4.3% - 46%	4 / 4 / 0
Methane	5 000 ***	1 000	Odorless	5% - 15%	1 /4 / 0
Oxygen	**	**	Odorless	Non flammability **	N/A **

* Threshold Limit Value
** Oxygen is not flammable, but assist with combustion Oxygen level that are required to function mentally is 19.5% (NIOSH, 2004). Higher concentrations of Oxygen does not have serious effect on a person, but could cause sever explosions.
*** As methane is an asphyxiant, there is no IDLH data available (Stanford, 2008). A value for IDLH of five times that of the TLV is used.
Table 1. Properties of gases of interest.

Oxygen reacts with carbon to form carbon dioxide, therefore, as the carbon dioxide levels increase by x%, the oxygen levels will decrease by x% (U.S. OSHA et al., 2001). In the event that the oxygen levels decreases by x%, and the normal levels of oxygen in our atmosphere is considered to be 20.9%, then the oxygen level will decrease by (x / 20.9)%.

Concentrations of the gases up to the level of the Threshold Level Value (TLV) are considered to be safe. Any gas concentrations between the TLV and the IDLH are considered unsafe, while any concentration above the IDLH are dangerous. Table 2 shows a combination of all these properties in percentages.

Substance	$Unsafe_{human}$(%)	$Dangerous_{human}$(%)	Flammable (%)
CO_2	0.5	4	Non-flammable
CO	0.0025	0.1	12% - 75%
H_2S	0.001	0.01	4.3% - 46%
CH_4	0.1	0.5	5% - 15%
O_2	< 19.5	< 16.9	Non-flammable

Table 2. Gas properties in percentages

Using the above data, it is possible to alert the rescuers in time of different possible conditions that could occur in the environment. These conditions could be either considered dangerous for humans or for the robot. With the information the rescuers could determine whether to risk their lives or the robot to enter a room with this environmental conditions.

3.1.1 CAESAR PC AI for Gases

Fuzzy logic is the way to determine logical expressions that are neither true or false. This type of reasoning is used to determine the unsafe, danger and flammable possibilities. The standard rules for fuzzy truth (T) are the following (Russell & Norvig, 2003):

$$T(A \wedge B) = \min(T(A), T(B)) \tag{7}$$

$$T(A \vee B) = \max(T(A), T(B)) \tag{8}$$

$$T(\neg A) = 1 - T(A) \tag{9}$$

For the above rules to be applied to the gas concentrations, it needs to be associated with a relationship referenced to the percentages in table 2, which are the boundaries. The value g_n which is the specific gas concentration read from the sensors, is a value per million. This value has to be normalized with respect to 1 million to get a ratio. The unsafe value for humans (u_h), dangerous value for humans (d_h) and flammable value (f) are also normalized with respect to 1 million to get a ratio for the boundary values. Equations (10), (11) and (12) are used to determine A, B and C respectively.

$$A = g_n - u_h \tag{10}$$

$$B = g_n - d_h \tag{11}$$

$$C = g_n - f_{min} \tag{12}$$

In the event that the values of A,B and C are negative, the environment is safe for humans. Should any of the values become positive, it indicates that the gas concentration is either unsafe, dangerous or flammable.

Using equation (8) and equation (9), and only the positive numbers of A, B and C, (denoted by pos()), then

$$T(pos(\neg A) \vee pos(\neg B) \vee pos(\neg C) = \max(T(pos(\neg A)), T(pos(\neg B)), T(pos(\neg C))) \tag{13}$$

Combining equations (10), (11) and (12) with equation (13), results,

$$\begin{aligned} &T(pos(\neg(g_n - u_h)) \vee pos(\neg(g_n - d_h)) \vee pos(\neg(g_n - f_{min})) \\ &= \max(T(pos(\neg(g_n - u_h))), T(pos(\neg(g_n - d_h))), T(pos(\neg(g_n - f_{min})))) \end{aligned} \tag{14}$$

Let equation {14} relate to a function (K) that returns a solution to the logical expression. The relationship to determine if the gas concentration are unsafe, dangerous or flammable, the boundaries u_h, d_h and f_{min} are compared to ¬K, which concludes the possible decision (D). With this model, it specifies P(Safety of the environment | specific gas concentration).

Different solutions are expected from each gas analysis. All the solutions from the different gases are required to determine the safety of the environment. As the order of safety (being unsafe, dangerous and flammable) decreases and the gas concentration increases, the final decision is considered in respect to the worst solution from the different gases. This is expressed as the worst safety which is max (D_n). Should one gas concentration be flammable but another only unsafe for humans, then the flammability of the gas takes priority.

For the above equations to be valid, the gas concentration in table 2 needs to be converted to a ratio with respect to 1 million. As it becomes more dangerous for humans when the oxygen decreases, the values required are subtracted from 1 million. This allows for monitoring values that will be increasing throughout the table. The measurements for the oxygen concentration will also need to be deducted from 1 million to get an accurate decision. This is shown in table 3.

Substance	Unsafe_{human}(ppm)	Dangerous_{human}(ppm)	Flammable_{min} (ppm)
CO_2	500	4000	Non-flammable
CO	25	1000	120 000
H_2S	10	100	43 000
CH_4	1000	5000	50 000
O_2	805 000	831 000	Non-flammable

Table 3. Gas properties in ratio with respect to 1 million

With the above information certain decisions can be made. Should the gas concentration be between Unsafe_{human} and Dangerous_{human} then the robot could continue to search for victims. In the event that the gas concentrations is higher than the Dangerous_{human} level, the possibility for humans to survive in these conditions are decreasing and the rescuers must decide about entering the environment depending on other safety issues. These safety issues could be falling debris or unstable surfaces. As the gas concentration for the flammable_{min} condition is much higher than that of the Dangerous_{human} levels, it could imply that humans would not survive in these environments. The robot could make the decision to evacuate the environment and possibly save itself from an explosion, or searching for survivors in other areas of the disaster. These logical decisions will be determined from a weighting table shown in table 4.

There are two types of warnings that have to be considered. The unsafe / danger factor for humans and the danger factor for the robot. A model is required to determine the danger for humans. This is achieved with equation (15).

Substance	Unsafe_{human}	Dangerous_{human}	Dangerous_{robot}
CO_2	1	2	0
CO	1	2	1
H_2S	1	2	1
CH_4	1	2	1
O_2	1	2	0

Table 4. Gas weighting factors

$$Danger = (100/2\text{n})(w_u p + w_d q) \tag{15}$$

where n = number of gases being considered

p = number of gases that give an unsafe warning

q = number of gases that give a danger warning

w_u = unsafe human weighting factor

w_d = Dangerous human weighting factor

The above model will give a percentage of danger for humans. As the number of unsafe and dangerous factors for humans increases, the model increases the percentage value.

A model is also required for the danger of the robot. As seen in table 4, carbon dioxide and oxygen does not have a weighting factor, as these gases are not flammable. This danger for the robot is expressed by the model shown in equation (16).

$$Danger_{robot} = Gas_{HighestConcentrationPercentage} + \left(\left(\frac{100}{\text{m}}\sum_{n=1}^{\text{n=m}}\frac{\text{x}_\text{n}}{\text{D}_\text{n}}\right)\left(\frac{100-\text{Gas}_{\text{HighestConcentrationPercentage}}}{100}\right)\right) \tag{16}$$

where m = number of gases not giving Danger warnings and that $w_n \neq 0$

D_n = danger that gas n has on robot ($\text{flammable}_{\text{min}}$)

Should any one gas have a concentration that is higher than $\text{flammable}_{\text{min}}$, the environment is considered to be 100% dangerous for the robot. The danger for the robot could increase as other gas concentrations increase, but it will never decrease below the highest danger percentage.

Equation {28} could be used to determine the danger or unsafe value for humans, but D_n will be the danger or unsafe value that gas n has on humans. This is a more accurate result compared to equation {27}, which only monitors the limits of the gas concentrations.

The models shown give a probability that humans would be able to survive in the surrounding environments and the probability that the robot is in a dangerous environment. All the decisions described above are performed by the control station, as it randomly requests for environmental status. The CAESAR robot responds to the request and awaits for it's next instruction. The control station considers the procedures that the rescuers and the robot must follow from the information received.

4. Conclusion

The Radiometrix TR2M modules with its related features, as well as the programming of the modules are discussed. Protocols and the basic procedure of the IEEE 802.11 protocol are explained, and a new robotic communication protocol, with its procedures of operation, are explained. The Robotics Communication Protocol (RCP) has a decreased size of 33 % to 38 % compared to IEEE 802.11 and hard-wired computer protocols respectively.

Specific features of voice communication with the Yaesu VX-7R and VX-3E radios are explained. The modification of the Yaesu VX-7R are also discussed, enabling communication over the allocated frequencies.

Further research should be performed in the development of microphones and speakers that are able to withstand high temperatures. An explanation is given for the video communication between the thermal camera and a television receiver for a successful observation of the robot's surrounding environment.

Radiation properties of feasible antennas are discussed, and the advantages and disadvantages of the vertical and eggbeater antenna are clarified. The testing procedures and verification of the different antennas and the radiation performance of the chosen antennas are also discussed.

Decisions are made from the analysis of gases and their concentrations in the environment. Models are developed that enable this analysis, determining if the environment is dangerous to humans or for the robot. This will assist rescuers to determine whether it is safe or worthwhile to risk their lives to enter the disaster.

With the improvements made on the communication and AI for gas detection it thereby allows a reliable control and communication interaction between the control station and the USAR robot. This also supplies the rescuers with critical information about the environment, before they enter and risk their lives in the unstable conditions.

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Mobile robots navigation includes different interrelated activities: (i) perception, as obtaining and interpreting sensory information; (ii) exploration, as the strategy that guides the robot to select the next direction to go; (iii) mapping, involving the construction of a spatial representation by using the sensory information perceived; (iv) localization, as the strategy to estimate the robot position within the spatial map; (v) path planning, as the strategy to find a path towards a goal location being optimal or not; and (vi) path execution, where motor actions are determined and adapted to environmental changes. The book addresses those activities by integrating results from the research work of several authors all over the world. Research cases are documented in 32 chapters organized within 7 categories next described.