Experiments with Sensors for Urban Search and Rescue Robots

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***Abstract*— The social impact of urban devastations has given rise to the field of Urban Search and Rescue Robotics[1]. The interest in this field has increased during the last few years due to several devastations occurring all over the world with thousands of victims. We hereby present the results of our experiments with sensors designed and developed for a homogenous team of USAR robots that was developed for the RoboCup Rescue 2001 contest. Rather than relying on the special features of the contest environment we designed the robots to be capable of operating in real world. The aim of this article is to present our experience and experimental results with various sensors designed and developed.**

***Index Terms*— Urban Search and Rescue, Robotics, RoboCup Rescue, Behavior Based, Sensor, Mobile Robot**

I. Introduction

We hereby present our experience and experimental results with sensors designed and developed for a team of USAR robots. The robots were developed for and competed in the RoboCup Rescue 2001 physical league. During the contest the National Institute of Standards and Technology (NIST) test course was used. The test course is specially designed in order to incorporate various realistic situations that a search and rescue robot has to deal with [1]. The robots we developed are designed for the yellow zone's environment, that provides an environment where initial tests can be performed without the requirement for expensive specialised robots capable of navigating over and into debris. Applications in the real world can be cases of chemical threats, nuclear accidents, or generally places where it is dangerous for people and animals.

The Robocup Rescue contest provided a complex semi-realistic test environment for our robots, and we report here the experimental results of the sensors performance. In what follows we will present the development, experiments, and results, suggesting directions for future research.

A. Related Work

A biomimetic approach in search and rescue robots is used in [2] that was inspired by the foraging behaviour of insects.

In [3] a heterogeneous team of USAR robots based on an mixed-initiative control approach is presented. This is a teleoperation approach. Human operators guide the robots using sensory feedback, and only the sensing and detection of the victims is done autonomously.

Competitive approaches include conditioned animals like rats [4] approach that comes with social implications of manipulating animals. We have to admit that using animals seems to be able to provide better capabilities of locomotion in cluttered environments but there are situations where animals cannot go because of chemical or nuclear contamination.

In [5] ultrasonic sonars were placed in a way that offers better coverage and features detection in office environments.

B. Motivation

Most of the USAR robotics development work uses adapted off-the-shelf mobile robot platforms rather than specifically targeted designs. Our robots were experimental prototypes with specialised custom built electronics designed specifically to investigate minimal requirements for satisfactory performance in the NIST test environment.

II. Design

The robot is three wheeled with two driven wheels on the front and one undriven rear wheel. This configuration provided a cost effective platform for experimentation (figure 1).

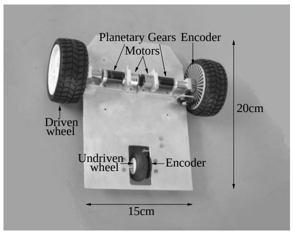

Fig. 1. The robot base with the wheels and the dimensions.

The driving system contains two independent DC motors. For reduction of the rotation speed and increase of the output torque we used decreasing planetary gearbox of $1:80$ gear ratio. We drive the motors in voltage mode in order to have the ability to determine the speed by controlling the voltage. This is accomplished by suppling a PWM waveform to the motors. The robot has a maximum speed of $20cm/s$.

The power supply is provided by 8 cells of NiMH (capacity 1200mAh), connected in a series (giving a battery of

[1] Urban search and rescue (USAR) refers to the case where people are trapped in man-made structures, like buildings.

$8x1.2V = 9.6V$). This type of cell was selected because it keeps its voltage almost constant until its death and it was appropriate because we need the robots running for as much as possible. During our experiments we measured operational durance of $40 - 45min$.

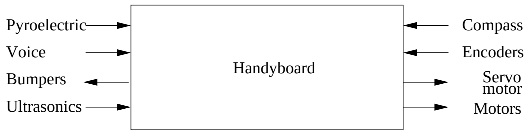

Fig. 2. Block diagram of the Electronic connections.

The on board controller is based on a Handyboard V1.2, with $32KB$ RAM that is battery backed. We designed and tried six sensors that we describe in the next section.

III. Sensors Design

The sensors we use can be discriminated to:

- obstacle avoidance sensors
- location estimation sensors
- victim detection sensors

For obstacle avoidance we use ultrasonic sonars and bumpers; for location estimation we use path integration by dead reckoning and a magnetic compass; and for victim detection we use a pyroelectric sensor for body heat detection and a voice detector.

A. Ultrasonic Range Sensors

Four ultrasonic sonars are used as range sensors (model SRF04 from Devantech). They exploit the physics of sound waves to estimate distance by measuring travel time of a reflected ultrasonic waveform.

Each robot employs 4 ultrasonic sonars (figure 3) two on the front used for obstacle avoidance, and two on the sides to be used for mapping purposes in future work.

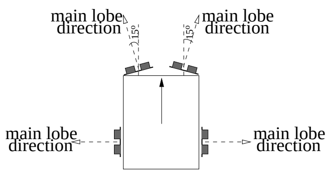

Fig. 3. Top view of the placement of the ultrasonic sonars.

The maximum range of the ultrasonic sonars is $1.5m$. The two ultrasonic sonars, on the front, are $15°$ each turned as the arrows show (figure 3) in order to increase the coverage angle on the front and to avoid unnecessary double coverage. Also they are some degrees inclined looking up in order to minimise reflections from the floor.

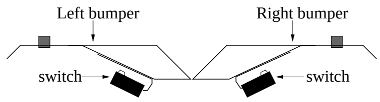

Fig. 4. Top view of the bumpers.

B. Bumpers

Two bumpers (figure 4) placed on the front of the vehicle are used for obstacle detection and avoidance.

They are used as “back-up” collision avoidance sensors. They proved to be very useful in cases where the ultrasonic sonars were no operating due to malfunction or the surface faced as obstacle was not giving enough reflection (see section V-E)

C. Wheel Shaft Encoders

For dead reckoning we use two incremental optical encoders. We decided to use one optical wheel encoder on the left driven wheel (144 pulses per revolution) and one on the undriven rear wheel (72 pulses per revolution). The ratio of the wheel circumferences is $\frac{Driven\ Wheel\ Circumference}{Rear\ Wheel\ Circumference} = 2.05$ thus both the encoders give almost the same amount of pulses per distance unit.

D. Compass

We used a magnetoresistive compass (model CMPS03 from Devantech) with set-reset offset elimination (see [6] and [7]). It offers accuracy of $4°$ and resolution $1.4°$ (with 8bits data word) that is good enough for our application. We use the I^2C bus for communication with the Handyboard.

A calibration must be performed each time the compass is used in a different place in order to cancel the effect of differences in inclination. The output values of the compass are not spread evenly in the range $0° - 359°$ but there are ranges that are more sparse populated or more crowded. The processing algorithm converts compass readings ($0 - 255$ range) to degrees ($0° - 359°$ range) performing concurrently corrections and linealisation.

E. Voice Detector

A voice detector is used to detect a sound in the human voice spectrum and with short durance (like words with pauses among them). The block diagram of this sensor is depicted in figure 5.

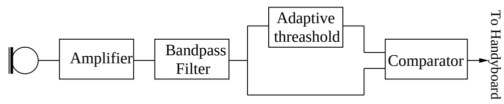

Fig. 5. Operation block diagram of the voice detector.

The directionality of the sensitivity diagram of the microphone was increased by using a primitive ear. That is a cylinder attached on the microphone giving a polar sensitivity diagram with 25° wideness.

The voice sensor has an adaptive activation threshold. Therefore sounds that are in the human voice spectrum but produced constantly are ignored (ambient noise).

F. Pyroelectric Senor

The pyroelectric sensor we use is like those used in burglar alarms for detection of human body heat [8]. This sensor requires motion of the source in order to detect it, therefore we decided to create artificial motion by moving the sensor itself. For this purpose the pyroelectric sensor was mounted on a servo motor that continuously scanned back and forth over 170° (figure 6).

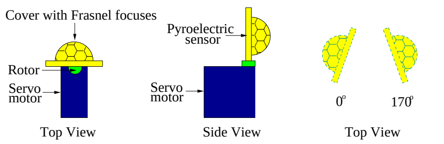

Fig. 6. Top and side views of pyroelectric sensor mounted on a servo motor.

A π shaped cover restricted the view angle of the sensor to 30° in the horizontal plane and to a maximum coverage distance of 6m. These improved the directionality and the reliability of the detection.

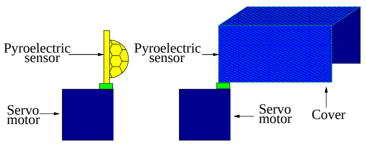

Fig. 7. Side view of a pyroelectric sensor mounted on a servo motor without and with the cover placed.

As a result of the behaviours, corresponding to heat detection, when a heat source is detected the robot turns towards the victim by turning an angle equal to that of the servo motor rotor at the moment of detection (figure 8).

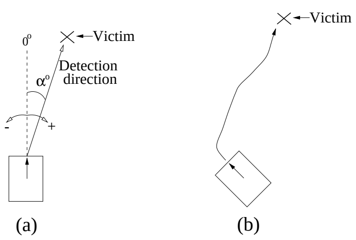

Fig. 8. (a) Definition of the detection angle. (b) Path followed in a run with one victim and without obstacles.

IV. Small Scale Experiments with Sensors in Lab

Experiments of the efficiency of the obstacle avoidance and heat detection sensors combined with the behaviours were performed in a small scale environment inside the Edinburgh robotics lab. In an area of 2m x 2m we used two different configurations of 5 small obstacles in order to examine the ability of the robots to reach to one or more victims[2]. The heigh of the obstacles used is such that allows the robot to detect the victim from everywhere in the test area. The robot was starting from various positions and orientations as indicated in figure 9 by the dotted robots.

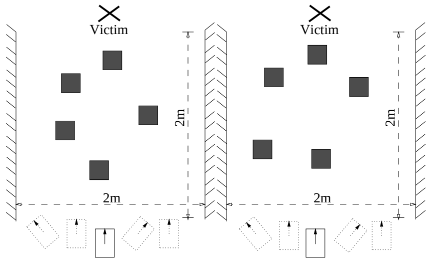

Fig. 9. Top view of the small scale experimental environment. Two different configurations of the experimental scenario are depicted.

We executed 15 experiments with one victim in one side of the area and the robot starting on the opposite side as indicated in figure 9. From the 15 cases tried 14 were successful and regardless of the presence of obstacles, the robot arrived at the victim in a mean time of 40s. In the one unsuccessful trial the robot lost the victim because of the obstacles that caused it to change its heading too much. This was a consequence of the limited scan angle of the servo motor. In default of a much wider scan angle servo motor this problem could be avoided by adding a generalised full circle search scan by rotating the robot in cases where a heat source had been lost. This could also be developed to help to solve the multiple victim problem that we mention in the next paragraph.

Trials with more than one victim in different locations show that the robot was aiming for one victim and losing the others. Even if it proceeded to detect the other victims, it often re-detected the previous victim and returned. This happened in our own lab tests, using standing people in place of the prone victims of the contest scenario.

While it did not happen in the NIST test environment (as discussed in [9]) it would still be useful to avoid this multiple victim aliasing problem, since specific body counts are often very important in these operations. This could be done by using the compass and a general full circle scan on each novel detection to identify the total count and relative bearings between them. These heat-source "landmark" bearing snapshots could be used as a basis for the simple ant-bee navigation schemes discussed in [10]. This would provide a basis for mapping, enumerating, and if necessary, investigating, multiple heat sources in a single "room".

In the NIST test course the combination of ultrasonic rangers, bumpers, and pyroelectric sensors and behaviours proved adequate for manoeuvring and locating victims in the small scale

[2]The term victim, in this experimental scenario, means a human who was standing in a place.

test field. However, we feel it would be useful to add the capability for disambiguating multiple victim aliasing as discussed above.

V. Sensors Testing

The RoboCup Rescue contest was a good opportunity to test the individual sensors in many different and realistic situations. In what follows we present the results of our experiments in the NIST test course and other real world environments.

A. Body Heat Detection

The dolls used as the victims during the contest had heat pads covering most of their body to make them emit heat. Experiments conducted with available samples showed that the pyroelectric sensors were not as sensitive as when a human was in front of them. Therefore, we concluded that they were not imitating accurately the transmission spectrum of human body. Thus the sensor being designed and tuned for the wavelength (peek at $700nm$) emitted by human body was not so sensitive when facing the dolls.

The experiments conducted convinced us that the use of rotation of the pyroelectric sensor gives enough information of the direction in which a victim lies. As one can see in figure 8.b, the robot eventually after several direction corrections reaches the victim.

One problem with body heat detectors is that they detect other heat sources, such as home heaters, which mislead the robots, figure 10. However, in a disaster heating does not normally operate, either due to damage or temporally deactivation for security reasons, but this is not always the case.

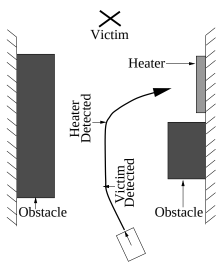

Fig. 10. The robot looses a victim because it detected a home heater.

We also discovered that heat from the electrics of other robots was detectable. Thus, special care should be given to avoiding interference by other members of a team of robots. Suggested strategy can be the use of intercommunication in a form as simple as transmitting a warning sound wave that other members of the team can detect when they are too close, to more elegant approaches like radio communication that can provide information of estimated location of the individuals in order that others can avoid the region. Exploitation of the same effect can give information for the location of other robots.

Use of vision could aid in the clarification of the incertitude between human produced heat and other sources. We avoided vision to keep cost and complexity in a completely autonomous system low.

Additionally pyroelectic sensors by detecting hot bodies give information about whether the victim is alive or not.

The pyroelectric sensor could detect a victim behind a plastic curtain or window, but not glass. This is to be expected because of their transparency (or lack of it) to the infrared frequencies in question. Thus we should not assume that whatever is visible with naked eye it will be visible in infrared.

B. Voice Detection

In the RoboCup Rescue contest we were able to test the performance of the voice detector with the tape recordings of the "voices" used in the contest. The detector was able to detect the victims' voices at a maximum distance of 60cm in the acoustic axis of the microphone, if there were no obstacles in the middle. But if there is debris over a victim the robots will not be able to detect this loudness of voice.

During the contest the voice detector was also being activated because of the noise level produced by the audience. Thus we decided that the voice detector was basically reducing the performance of the robot under these conditions and more elaborated techniques are needed. Of course it could be the case that this is an artificial problem which wouldn't apply in a real USAR situation. However, if more sophistication in voice detection is required, it would be a simple addition to use a microphone and send the audio signal back to a human operator who could listen and decide. It could also be useful to add a transmit voice channel with a loudspeaker so that a human operator could speak to the victim via the robot.

Furthermore, in rescue operations special designed supersensitive microphones are used to detect voices or knocks or even heartbeat produced meters away under debris. Special designed robots could employ such technology of sound detection.

C. Wheel Encoders

For dead reckoning we use the incremental encoder in the undriven rear wheel and for measuring steering angle the encoder on the driven wheel. The rear undriven wheel rotates only when the robot actually moves. On the other hand the driven wheels can be rotating even when the robot is snagged on an obstacle, giving encoder pulses that don't correspond to motion.

We performed dead reckoning experiments on the even floor used in the NIST test course and 20cm/s speed. During this experiment we were using both the encoder on the undriven wheel and one encoder on a driven wheel. In order to measure the error we measured the distance covered by the robot in straight line assuming that the floor is perfectly level. Then we compared this measurement with the result of the odometry. It is clear that there is a factor of error in measurements because the floor is not perfectly level. But this error is inherent in the environment in which the robot should operate.

Running in a straight line of 6m length we were measuring distance with both the encoders and independently for each one.

We measured average dead reckoning error of 3% for both the encoders (differences in error measured for the two encoders are statistically insignificant). This is an expected result because in such even floor all the wheels are in constant contact with the ground and there is a lot of friction between the floor and the wheels not allowing them to rotate freely without actual robot motion.

The results were different while repeating the same experiment on sand surface. The average error for the undriven wheel encoder is considerably lower than that for the encoder on the driven wheel. Whenever the robot was snagged the driven wheels were rotating freely measuring translation while the robot was just at the same place. The position of the centre of mass is very important here for obtaining constant contact with the floor, and thus small error in dead reckoning.

While steering on the spot the rear wheel doesn't rotate, because it skids sideways, but the two driven wheels delineate the circumference of a circle around the centre of which the robot rotates. Therefore, by using the shaft encoder on a driven wheel we can have accurate measurement of steering angle. The accuracy depends on the resolution of the encoders and the floor surface. With experiments for various relative steering angles we measured average accuracy of steering $\pm 3°$. By using the encoders for performing roughly 80% of the steering angle and then the magnetic compass for adjusting the steering angle we obtained accuracy $\pm 1.5°$ as discussed in [9].

D. Magnetic Compass

A compass is very useful sensor for location estimation. One of the first experiments was to test the influence of the chassis magnetic field to the compass indications. Due to the choice to use aluminium chassis the only significant magnetic field source on the vehicle was the motors. Their influence was a change to the indication in the range $\pm 2°$ depending on the position of the compass. Measurable change in indication there was only when the compass was closer than $8cm$ to the motors. In the end we placed the compass on the back of the vehicle, well away from motors and other electronics. It performed well here.

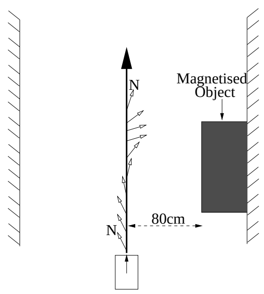

Fig. 11. Change on the North direction measurement while moving besides a metallic cabinet.

By trying the compass in both Edinburgh and Seattle we realised that after calibration in different places of the globe the behaviour of the compass is very different. Even if in the same place two compasses, of the same type, have different behaviour. This is probably because of differences in the components and in the placement of the magnetoresistive sensors and the set-reset coils during manufacturing.

These considerations lead to the decision of finding a way of measuring heading without requiring changing the function that converts compass readings to degrees in the code for each place we are going to use the robots. Thus we developed an autonomous calibration behaviour as described in [9]. In this method the robot combines information from the encoders and the compass to calculate a lookup table for the compass.

Experiments show that disturbances to the earth's magnetic field inside buildings are very common, whether due to passive magnetic materials such as steel, or magnets, such as in loudspeakers (figure 11). Therefore, we decided to use the compass only for relative angle measurements, such as in steering on the spot. Because of the use of relative angle measurements the error doesn't depend on the steering angle. This is very useful in obstacle avoidance because the robot can recover its initial orientation after avoiding an obstacle.

E. Ultrasonic Range Sensors

The ultrasonic range sensors were tested both in the NIST test course and other situations. The results of our test runs in the NIST test course are consistent with those from the small scale environment tests of section IV. The ultrasonic range sensors are very efficient for obstacle avoidance. They provide detection of obstacles before contact. This is very advantageous in cluttered environments for avoiding collisions and mechanical straining.

We experimented with a number of different surfaces: walls, wood, curtain cloth, glass, and reticular fence. Generally the detection depends on the angle with which the sensor faces the obstacle.

The maximum angle for which a obstacle is detectable depends on the surface material. The ultrasonic range sensors are reliable when they are in front of the walls, wood, and windows, as far as the facing angle is not too big. With cloth the sensitivity is not so good because the cloth absorbs a lot of energy from the ultrasonic wave.

Experiments on front of a $45°$ inclined glass surface (figure 12) show that the ultrasonics were detecting it only if the distance was smaller than approximately 40cm, for bigger distance it was "invisible".

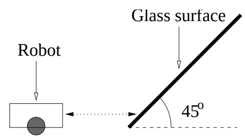

Fig. 12. Side view: Experiment on front of a $45°$ inclined glass surface.

Experiments in front of a plastic reticular fence show that the mesh was detectable. This is because even the reticular surface gives enough reflection due to the wideness of the ultrasonic sensitivity diagram of the sensor. Emitting and receiving reflections from a large surface produces enough returned power to be detected.

The ultrasonic range sensors have the disadvantage that are power consuming sensors and this is the reason we tried to use a minimum number of them. Also they are prone to noisy measurements. Therefore, taking several measurements and using statistical manipulations to reduce errors it is advisable. A strategy that gives reliable results is receiving several measurements, eliminating the maximum and minimum value, and then averaging the remnant measurements.

It proved to be a good sensor modality for obstacle avoidance in the yellow zone, the robot managed to cover an average of 40% of the field without being snagged on any place. But ultrasonic sensors, in many cases, are not adequate for detecting thin bars like the metallic legs of a chair. We finally concluded that it is reasonable to use a back up sensor for obstacle avoidance such as the bumpers described in the next paragraph.

F. Bumpers

In cases where the ultrasonic range sensors fail to give accurate information about the existence of an obstacle bumpers proved very useful. Bumpers are purely mechanical and structurally simple and therefore reliable as sensors. To avoid the shock of collision damaging the electrical switch the bumper should release a switch on collision rather than force a switch closed. To avoid collision shock damaging the robot care should be paid to keeping the mechanical shock within acceptable limits by taking account of the robot's speed and if necessary providing shock absorption such as by elastic pads or springs.

G. Localisation

Knowing the robot's position is very important because the robot should be able to inform the human operators where the victim has been found. However position estimation is a difficult task involving uncertainties and depending on the environment. The accuracy of location estimation it should be such that gives enough information of where the human rescuers should go to find a victim. For location estimation we use path integration employing the dead reckoning encoder to measure translation and the magnetic compass to measure steering angles [9].

In the runs in the NIST test course became apparent that the main problem with this approach is that when the robot collides with obstacles, it skids accumulating position error. After a few collisions the location indication it is completely wrong. This is because we use the compass to measure only relative rotation and therefore if the robot rotates as a result of a collision a non detectable error is added. Measurement of absolute direction would be advantageous.

The accuracy of the location estimation also depends on the characteristics of the environment (e.g. floor surface etc). A method that can help is the use of artificial beacons outside the building to aid as reference points. Furthermore, it could be possible instead of informing for its actual position the robot to stay besides the victim "asking for help". That could be the transmission of a sound wave (or something similar) that human rescuers can locate and reach to the victim besides the robot.

It seems that path integration it is not a good enough approach for USAR applications. The robots should be able to operate in different environments reasonably well and for this reason environment independent location estimation techniques should be used.

VI. CONCLUSIONS

In this paper we presented our experience and experimental results of using sensors designed and developed for a team of USAR robots that competed in the RoboCup Rescue 2001. The NIST test course offered a semi-realistic environment for experimentation with the sensors. We hereby tried to investigate minimal requirements for satisfactory performance in the NIST test environment and other real world environments.

In future work will be intresting to experiment with chemical sensors capable of detecting pheromones that is a characteristic of human presence.

Another extention could be to experiment with is the combination of pyroelectric sensor with cameras in order to discriminate between alive humans and other heat sources.

We do believe that this is a research field that can contribute to the improvement of the efficiency of search and rescue operations.

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