An Automated Cleaning System for Hospitals

M.Eng in Mechanical and Manufacturing Engineering

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Masters is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Date: _______________

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I would like to thank my parents and family for their continued support throughout the course of my research, for listening to my moments of triumph and defeat and more recently for helping me get my thesis written.

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Abstract

Insufficient hygienic practices in Irish hospitals coupled with one of the highest number of reported cases of MRSA in Europe have highlighted the need for solutions to aid in the task of cleaning.

This automated cleaning system consisted of two robots: a core robot developed separately with navigational and task scheduling capabilities integrated. The cleaning task was carried out by making use of a commercially available Roomba vacuum cleaner which had been adapted to operate in conjunction with the core robot. A uni-directional communications was established; commands were sent from the core robot to the Roomba.

A visual analysis software, by the name of RoboRealm, was integrated into the system as the primary component. The initial role of the software was to allow the vacuum robot to orientate itself in order to enable transport from location to destination by means of visually tracking an object of interest. The object was to be located on the rear of the core robot.

Subsequently the visual recognition aspect took on a greater role and encompassed a system by which commands were issued by the main robot and visually interpreted by the Roomba. This enabled the cleaning system to issue uni-directional commands and therefore carry out regular cleaning of any room, spot cleaning on a small spillage, following from one location to a destination or pause at any point during transport for emergency reasons.

All tasks were deemed to be completed, however the prototype has not been completed and future work is still required in order to further the work carried out thus far. The robot successfully received the commands and activates the relevant programming as instructed. A critical analysis and recommendations for future work finish the report.

Publications

- Griffin, C. and Szecsi ,T. (2008): Development of an automated cleaning system for hospitals. In: D.T. Pham et al., eds., Proceedings of the 4-th Virtual International Conference on Intelligent Production Machines and Systems (IPROMS), Cardiff, UK, 1-14 July 2008, Elsevier Ltd., Oxford.

- Szecsi, T., Mamun, K., Hasan, K., Islam, A., Griffin, C., Hoque, M. (2008): Hospital Robot Module Development in the IWARD Project. In: Proceedings of the 6th CIRP International Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '08, 23-25 July 2008, Naples, Italy.

- Griffin, C. and Szecsi ,T. (2009): A vision system for an automated cleaning robot. In: D.T. Pham et al., eds., Proceedings of the 5-th Virtual International Conference on Intelligent Production Machines and Systems (IPROMS), Cardiff 6-17 July 2009, Elsevier Ltd., Oxford

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1.1 Introduction & Background

The IWARD project; Intelligent Robot Swarm for Attendance, Recognition, Cleaning & Delivery [1] is comprised of a number of mobile robotic platforms constructed with the ability to autonomously navigate throughout a hospital facility in which they were intended to operate. As is suggested in the name, the robots were designed for multiple tasks. This was achieved by developing modular robots where necessary components were interchangeable in a quick and easy manner.

The IWARD base robot consisted of an aluminum chassis that held all essential drive components. In order to navigate, the robots utilized a semi-circular array of sonar sensors on the front, which was located above a laser scanner capable of measuring numerous distances along a single horizontal axis. An impact sensor was attached along the leading edge of the robot in the event of a malfunction of the wireless sensors occurring or in the rare instance where an obstacle was, for any reason, not detected in advance. For reasons of prototyping two robot platforms were developed which differed slightly in design, but both robots contained identical sensors and functionality. Figure 1 below shows two of the IWARD robots side by side

The IWARD project group consisted of a number of universities and companies throughout Europe working in conjunction with each other, each assigned an area of to concentrate on. The role of Dublin City University in the IWARD consortium was to develop the interchangeable modules necessary to complete the individual tasks. Other modules developed concurrently with the cleaning system were a secured storage compartment with electronic lock and restricted access for authorized personnel only for the purposes of delivery, a set of sensors for continued monitoring of the immediate environment and a system capable of leading a patient from one location to the other within the confines of the hospital.

Figure 1: IWARD robots [2]

Dublin City University is a partner of the EU-funded FP6 project called Intelligent Robot Swarm for Attendance, Recognition, Cleaning and Delivery (iWARD) (www.iward.eu). DCU is also a partner of the EU-funded FP6 Innovative production Machines and Systems (I*PROMS) Network of Excellence (www.iproms.org).

1.2 Project Objectives

The purpose of this research was to develop an automated cleaning system using a Roomba robot vacuum cleaner as the platform upon which all other components would be mounted. The software developed for use in the main IWARD robot contained a scheduler to maintain a record of what tasks had been carried out and what the upcoming jobs were and as previously stated, the robots were able to safely navigate from room to room as necessary. Therefore the Roomba cleaning robot was not required to contain navigational or scheduling capabilities since it was intended to act in conjunction with the IWARD robot and was a modular component rather than as an independent system.

The main objectives of the robot were to:

- Ensure successful communication with the vacuum robot.
- Discover a successful method for the vacuum robot to be transported from the current location to a destination within the confines of the hospital facility.
- Issue a variety of commands to the cleaning robot and ensure task is completed.
- Isolate a reliable method for cleaning robot to focus on a particular spillage.

The general objectives were stated without including methods by which each task was to be accomplished as long as the cleaning system remained in line with the entire project. Restrictions imposed on the project were that the Roomba should maintain a vertical height as low as possible to enable cleaning under beds in a hospital ward. The researcher should also endeavor to keep the cost of the system as low as possible to ensure a prototype that would, in future, be capable of being easily reproduced so a number of cleaning units could be present in any single hospital environment.

1.3 Problems in Irish hospitals

In early 2008 results were published [3 & 4] of a hygiene audit that had been carried out in all publically run hospitals throughout Ireland. This was the 2nd such audit that was conducted by HIQA (Health Information and Quality Authority) in as many years, and the 4th survey of this kind that took place since 2005. That first survey, run by the Health Service Executive (HSE), declared that 91% of hospitals examined were found to have inadequate hygiene standards. 2007 saw the first independent study carried out by the HIQA where no public hospital in the country was found to have a rating of ‘very good’ or better, once the results were published. Out of the 51 hospitals included in the survey, nine were rated as ‘poor’ while thirty-five hospitals achieved a rating of ‘fair’. A mere seven hospitals in 2007 achieved the status of ‘good’ while none received any higher rating. Those audit results illustrated factual data why hygienic practices in hospital environments required improvement. The goal of the IWARD project was not to replace current practices, but to aid with those tasks. The results of the 2008 survey were an improvement, however they were still deemed to be below an acceptable level of hygiene for the hospital service in general. One hospital in later this survey achieved the rating of ‘very good’, while eleven were deemed to be in ‘good’ hygienic condition. As with the previous year there were still nine hospitals listed as having ‘poor’ hygienic standards in accordance with the criteria laid out by the HIQA.

As recessionary times hit globally, staff shortages become an ever-increasing problem. With management in hospitals being forced to provide cutbacks in expenditure, the issue regarding cleanliness remains ever present. A smaller number of employees must consistently and reliably provide an equivalent level of service which is increasingly difficult, seeing as the focus would be placed on care of patients rather than a task seen as secondary; cleaning. In this instance a system of automated robotic platforms with the ability to perform a number of rudimentary tasks has the potential to save valuable time that could be utilised by a nurse in the care of patients.

1.4 Emergency Hygiene Requirements

Recent years have shown that there are periods when special controls must be implemented in times of crisis or great concern. 2001 saw such a period with the outbreak of the foot and mouth disease in Ireland. Although somewhat confined, it proved that measures must be in place to combat any such potential risk or widespread disease or infection. In an effort to protect patients who could potentially be suffering from a weakened immune system, safety precautions would be vitally important should a similar outbreak occur again. Any easily transferable infection, especially by shoes, is an opportunity where an automated cleaning system could be of tremendous use in areas of high traffic. In a scenario where a prototype had previously been shown to be successful and reliable, and was subsequently re-designed to be utilised in a real-world environment, it could be this cleaning system that would prove highly important in protecting patients and staff alike. Such a system would necessitate an additional sterilised wet clean function in order to effectively combat the spread of any harmful bacteria or virus.

It is important that management within a hospital have planning carried out in advance with detailed plans available in the event of such an outbreak occurring at any time. Once any sign of problematic infections have been detected, regardless of whether it is has been shown to be present within the direct vicinity of the hospital, the automated cleaning system could be employed to pay additional attention to high traffic areas in a preventative measure to protect all peoples potentially at risk.

In what would be considered a huge problem, but not classed as an outbreak is the issue of MRSA in hospitals. Methicillin Resistant Staphlococcus Aureus is a potentially dangerous bacterium, which has developed a resistance to antibiotics. In patients where a weakened immune system has already developed due to a prior illness, this bacterium can further deteriorate the health of the patient, or in some extreme cases cause death. The spread of this infection has become a topic receiving ongoing attention in the media due to the widespread problems caused within Irish hospitals. Regular stories emerge to the public of deaths relating to the MRSA bug, resulting in a continued awareness of the extent of the infection. Figures available indicate that in 2003, Ireland recorded the highest numbers of reported cases of the MRSA strain in Europe [5]. These figures, in that year, were as high as 119 cases per million. This was over twice the number of cases reported in the next worst country which was Portugal, with 46 cases per million. Reports state [6]“MRSA is commonly transmitted between people by touch. People can also pick up MRSA from dust containing contaminated skin particles and from objects in the environment or surfaces that may have the bacteria on them.”

The fact that infection can be transmitted by dust particles merely reinforces the need for the inclusion of an automated cleaning device within any hospital environment. Such a system would not eliminate the bacteria or the infection from a hospital, but by removing some of the dust the risk of further contamination would be reduced. Each additional hygienic device within any hospital environment is utilised as a small part of the over-all solution.

1.5 Justification of Project Execution

As has been briefly illustrated, the Irish health sector contains areas in which improvements are necessary. Not only must a hospital appear aesthetically pleasing, but it must also maintain a satisfactory level of cleanliness based on the standards as laid out by the HSE for reasons of patient safety. An automated system to aid in the daily routine of cleaning would prove an effective addition in the preventative measures against such infectious agents such as the MRSA bug. In times where such a system was not implemented daily, it still retains the potential to be an action put in place during extreme times of need where a transmittable disease threatens patients and staff.

2.1 Literature Review

Research was conducted in order to find existing technologies that may have proven useful for areas within the cleaning system. Investigations were made into areas of visual analysis, distance measurement and existing cleaning solutions for purposes of comparison.

2.1.1 Imaging analysis for distance measurement

“Design of Distance Monitoring Algorithm for Robotic Applications” was the name of a project carried out in the University of Iowa in spring of 2009 [7]. The aim of the research was, as the name suggests, to develop an algorithm for distance measurement making use of a generic web-camera as well as a visual analysis software known as RoboRealm. According to the background theory the initial concept for the system was to release a set of three robots into an unknown environment where they would subsequently roam throughout the area and “produce a map of the surroundings, based on the information obtained from various sensors in the system”

As stated by the authors, Chen & Schelin, the intention of this publication was to develop a visual system that could be incorporated into the existing hardware, previously made available to the authors, without the addition of many new hardware components. The basic operating principle was to use the camera in conjunction with a laser diode and then to process the visual information by means of a software program to locate the laser dot. Based on the location of that laser dot, information regarding linear distance to a surface in front of the camera could be calculated. Figure 2 below illustrates the principle upon which the linear distance was determined. By initially measuring the vertical height from the camera lens to the laser diode (h) one can use simple trigonometry to calculate D, the distance from the camera to the object by utilising the equation $D=h/\tan\theta$, where θ is the angle between the projected dot and the middle of the image.

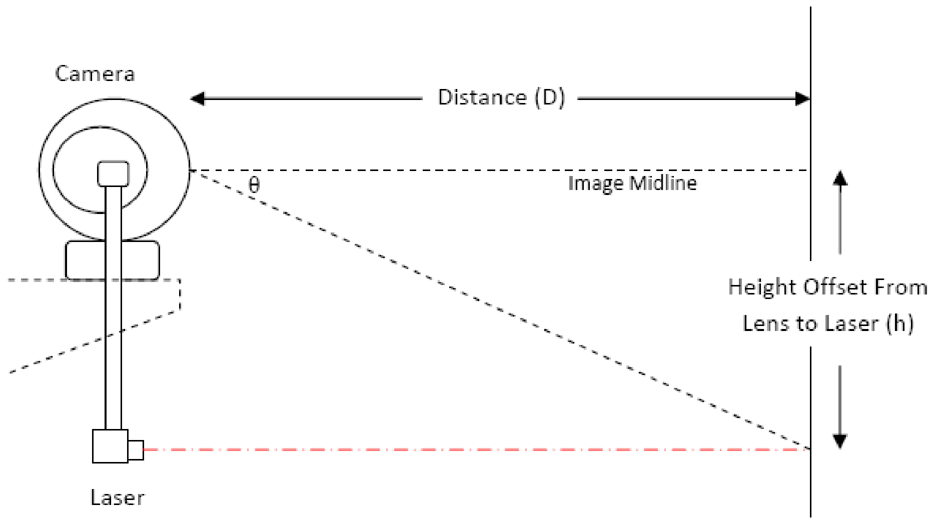


Figure 2: Distance vs. Height [7]

RoboRealm was used to determine the value for D in the above figure after the red dot was correctly identified. The location of the laser dot was obtained by assuming that all associated pixels would be of a bright red colour. The laser point was, as shown below in Figure 3, assumed to be within a centre margin below the centerline of the image. The distance between the laser dot and centerline was then measured by RoboRealm and returned as a corresponding height (h). That value was then inserted into the mathematical formula previously mentioned to determine D, the distance from the camera to the object.

*"*pfc*" in Figure 3 is "pixels from centre"

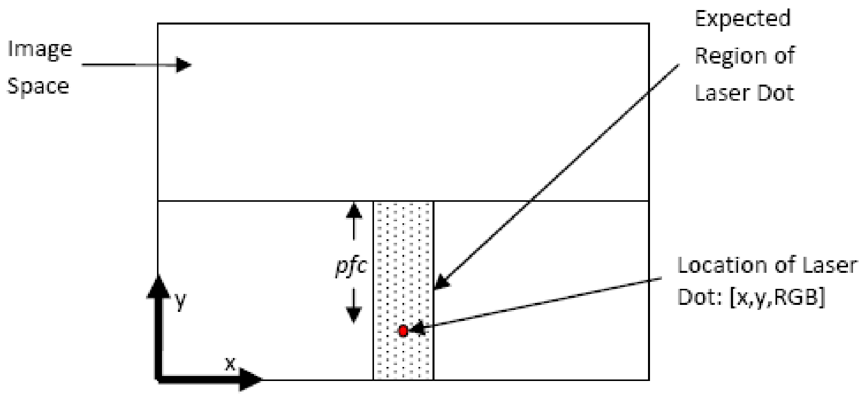


Figure 3: Location of red dot [7]

The result was a calibrated system where the visual distance measurement system was integrated into a mobile robot platform where successful testing was carried out by means of programming the robot to stop once it came within certain proximity of an obstacle. The error in the system was approximately ±6” deviation in 100”, which fell within the parameters laid out at the beginning of the research. This result surpassed the objectives as laid out in the introductory section which required an operational distance to merely exceed 30 inches.

This research carried out by Chen & Schelin illustrated the practicality of using an image analysis component on a mobile robotic platform. As shown in the published document, an iRobot Create was used as the chassis upon which the robot was built; this model is in many ways very similar to the Roomba, which is sold by the same company. The use of the RoboRealm visual analysis software proved that the two components could successfully & reliably be used in conjunction with each other.

Later in this document it will be illustrated why a vision system was required to be used in the development of an automated cleaning system, and it was based on the success of the above project that the same visual analysis software was chosen for investigation for use with the Roomba vacuum cleaner. Although used in a somewhat different capacity it had been illustrated that the hardware and software integration was successful and the system resulted in a working prototype and as such it was hoped that the integration for the cleaning system would not prove difficult, thus eliminating wasted time on other potential solutions.

It is the opinion of this author that some external light sources could have the potential to largely interfere with the results published by Chen & Schelin. The reason for this is that over a distance close to the maximum working distance of the system the intensity of the red diode would severely drop. Perhaps this was a property that was noted during the research and testing, however, since it is not mentioned in the results section it cannot be assumed whether the researchers experienced this problem or not. In a theoretical situation where the red diode was pointed at a surface which was brightly coloured and well lit by ambient light the laser point may have proved difficult to detect as this can, at times, be the case when viewed with the naked eye. Secondly the chapter dealing with optimization mentioned a glare present when the diode was pointed at a polished cement floor; one of the two solutions to this problem appeared to be a pulsation scheme where the difference between two successive frames (namely the red dot) was isolated. Although the first solution; an intensity threshold, could have solved the problem, there appears to be no benefit in the pulsation scheme to remove glare; as soon as the diode activates the glare would immediately be present. Despite these opinions the section announces that the algorithm was improved, however as expected “not all errors could be avoided”.

2.1.2 Cricket based navigation

A project was carried out in Hallym University, Korea, titled “Design and Implementation of Cricket-based Location Tracking System” [8] which endeavoured to present a novel approach to indoor location tracking for the purpose of asset tracking and monitoring. The group who conducted the research decided upon the use of a Cricket Indoor Location System in order to be able to determine in real-time where the mobile robotic platform was within the mapped environment. Although carried out on a minimised scale, the principle of operation would in theory operate almost identically on a larger scale. The over-all aim of the system was to provide the means by which a mobile robot could autonomously navigate from one location to another. In that case the system required the capability to recognise obstacles as well as the current location. According to the report the robot utilised magnetic sensors to determine the presence of an obstacle, however no mention is made of the specific sensors in use.

Although the cleaning system did require knowledge of its current location, the Cricket system would not have been appropriate. On the small-scale test area of 240cm X 240cm the group made use of nine Cricket beacons in order to accurately determine the position of the robot. The cost of installing the same proportion of beacons in a hospital environment would be very large and would as a result rule out the option of making use of a similar set up. The authors briefly mention that the system was tested on a mobile platform, where it was found that the error in correctly determining the location of the robot was less than 10cm. Since the location of the robot was based on trilateration illustrated the effectiveness of utilising the function on the Cricket device called TDOA (time difference of arrival). As the focus of the work was on accurate distance measurement by making use of the Cricket hardware, it has proven that the technology can be used in a system requiring linear distance measurement, but it is the opinion of this author that the Cricket Indoor Location System is limited in its applicability in a realistic situation.

2.1.3 Object tracking

Early 2009 saw the publication of a document titled "Building a mobile robot with optical tracking and basic SLAM" from Luleå University of Technology [9]. The author, Marklund, introduced the project by stating that a commercially available remote controlled unit would form the chassis for the project with an optical targeting & tracking system incorporated to enable the robot to follow the object of interest; in this case the spot from a laser pointer. In order for the robot to be able to track an object, a camera was necessary, however in this case a CCD (Charged Couple Device) rather than a digital camera. Marklund utilised the principle of colour separation in an attempt to segregate a particular object within the image. As a means of distinguishing noise, the image was also portioned into an evenly spaced grid so that once a certain number of relevant pixels were detected in a single square, that square was marked as part of the object of interest. In order to eliminate false readings the number of squares and pixel density were taken into account as a means of ensuring the correct object was being identified by the software.

One method of marking an object to be visually tracked was by means of a laser pointer. As would be expected, some unforeseen results did occur during the testing of that particular concept. The intensity of the laser spot as detected by the CCD resulted in a “halo” type effect being displayed on screen. This intense bright spot with a slightly more dim shadow failed to allow the software to incur the correct location of the laser spot, which is a phenomenon that was observed at a separate point in a the development of the cleaning system; that will be discussed later in the report. As a secondary solution, the brightness value was used as a means of detection with a threshold implemented. However, as stated in the report, and agreed by this author, that solution has the potential for numerous false readings throughout any well lit environment; for example a reading lamp facing towards the camera, direct sunlight or even indirect sunlight on a brightly coloured surface. Marklund indicated that the first half of the research, which dealt with the object detection as outlined above, was considered a success. The initial project aims of the cleaning robot did not include any requirements for mapping and as a result the latter half of the document, “Building a mobile robot with optical tracking and basic SLAM”, was not deemed appropriate until a later stage in the development of the cleaning system.

Marklund introduced a set of sonar sensors utilised on the robot for the purposes of mapping and obstacle avoidance. It is the opinion of this author that the chosen Maxbotix EZ1 sonar sensor would add sufficient detection capabilities to enable a robot to successfully avoid an object in the forward facing region of the mobile platform. This method of map generation would not, in theory, create a very accurate map of a region. A sonar sensor of this type would operate on the principle that a distance measurement value returned to the sensor would be the closest object in the area affected by the ultra-sound. As a result the true contours of a surface would not be illustrated on a map in the same manner that a 2D laser scanner would. However it appeared that for the project in question the sonar sensors appeared to suffice.

In conclusion, the map produced by the robot was rudimentary and could not, in its current format, be utilised in a navigational system, however time constraints were included among the reasons for this. The earlier optical tracking algorithm appeared to have operated successfully, both using laser tracking and colour separation techniques which provided potential features to be considered for implementation in the automated cleaning robot. Marklund briefly mentioned the common problem associated with attempting to maintain an ongoing measurement of the distance travelled by the robot: wheel slippage. While attempting to combat this problem an optical encoder from a computer mouse was installed independently rather than trying to monitor the movement of the wheels directly. This would eventually be a problem also encountered with the Roomba vacuum cleaner. The development of this mobile robot with optical tracking provided some relevant insight to the potential problems that may have arisen during the cleaning robot development while also initiating some ideas for implementation in the cleaning system.

2.1.4 Automated vacuum cleaner

"An Autonomous Vacuum Cleaner" [11] detailed the development of a number of algorithms for ensuring that the robot was "capable of efficiently and comprehensively vacuuming the floor of an unmodified unknown room". Although this optimised cleaning pattern was not necessary for the completion of the tasks laid out in the design brief for the hospital cleaning system, this document written by Harding was examined as an area where development could be carried out once the initial goals had been met.

Harding was part of an ongoing research project where the cleaning robot was assumed to be placed in a room that was in need of cleaning, as opposed to the hospital cleaning robot, which was required to autonomously arrive in the room without human input. The comparison to be taken into account here is that two automated cleaning systems focus on entirely separate areas of research within the realms of a similar concept.

Chapter two of the report described the potential methods of surface coverage available for use by a vacuum cleaner. A planning approach entails keeping a world map from which movement must be planned, a behavioural approach that involves the robot reacting to the outside world using sensors such as an insect and finally a random motion approach. Within the heading of a planning approach are a number of sub-categories, which enable a variety of cleaning patterns to be implemented. Figure 4 below illustrates two patterns in a planning approach: part A represents a simple strip filling pattern with a red base line shown which defines the beginning and end of the strips for that region. Part B shows a serpentine pattern with overlapping trails to cover areas missed on the first pass.

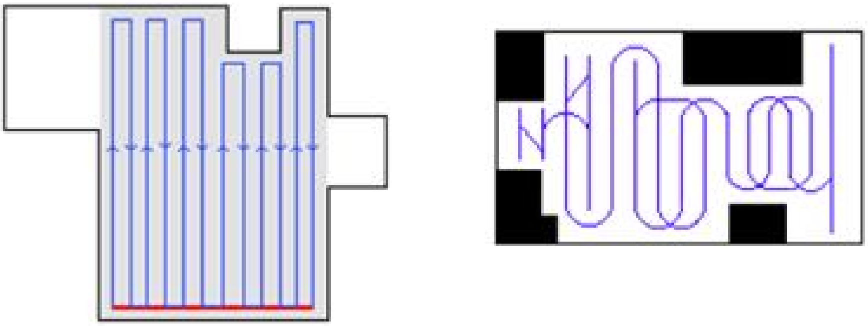


Figure 4: Cleaning Patterns A & B [11]

As was correctly mentioned by Marklund during the development of the optical tracking robot, wheel slippage becomes an issue while trying to operate a cleaning algorithm based on a map formed from absolute coordinates. External ranged sensors are necessary for a system such as that to operate reliably.

The “RoboVac” utilised a behavioural approach to cleaning in an attempt to develop a reliable method of covering the entire area of an unknown room without the use of any world map. Harding discussed the various approaches to compensate for a cavity that was detected, an area that was missed and the required wall following procedure. In order to be able to follow a wall, a set of sonar sensors were faced towards the surface in question and the software algorithm was instructed to maintain a consistent measurement in relation to the wall. The testing conducted during trials indicated that the sonar sensors in use were not sufficiently accurate to allow a consistent straight line to be followed. Figure 5 below is a record of the results produced by Harding after two consecutive tests occurred; the aim of the testing was to determine the error present when the “RoboVac” endeavoured to follow a straight wall at a distance of 2 metres.

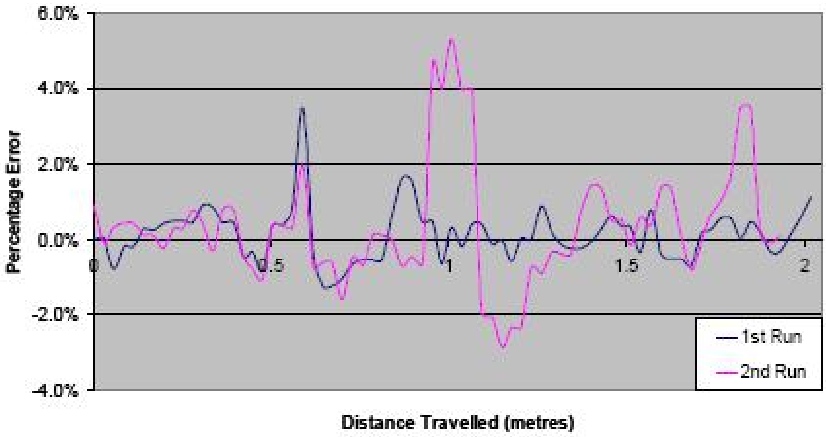


Figure 5: Sonar Percentage Error [11]

Both the above test, and another test measuring the deviation from a straight line when not following a wall, proved that the robot hardware could often not return a performance necessary to effectively execute the software programming.

The results of this report confirmed that progress had been made in the development of a successful cleaning algorithm in the chosen field, however not all theoretical solutions were implemented due to time constraints. Those practices that were implemented were hindered due to a lack of hardware consistency and an insufficient time for the author to complete the intended work. The detailed progress did provide a contrast between the intended IWARD cleaning module and the “RoboVac” as developed by Harding. The sonar testing also served to highlight the limitations intrinsic within the sensor while also reiterating the fact that mapping or navigation based on the movement of robot wheels is inherently tremendously difficult.

2.2 Chapter Review

This chapter has highlighted and reviewed other systems researched where some technologies of interest were implemented. This critical evaluation provides some background information on the devices/software utilised prior to research being conducted on this automated cleaning system.

Limitations present within all mobile robots is the difficulty in maintaining an accurate reading on current position in order to reliably pin-point a location on a world map unless an external system is introduced into the system such as GPS or the Cricket Indoor Location Tracking system. This shortcoming directly relates to the difficulty in structuring a fully efficient cleaning pattern in cleaning robots.

Visual analysis and recognition software has proven, according to previous researchers, to be a reliable and effective software component in a number of tasks in mobile robots due to it’s versatility and ease with which it can be adapted to changing needs.

3.1 Preliminary Works

This section will deal primarily with the earlier investigations of the technology intended for use on the robot. The feasibility testing of these solutions was partially based upon concepts derived from the literature survey carried out prior to the commencement of construction.

3.2 Roomba

Prior research had been carried out in a project titled “Hospital Robot Swarm (Project 3: Cleaning Module)” [11], where a study was conducted on a variety of available automated cleaning systems with a view to purchasing one for this research. The iRobot Roomba XE was chosen and justification provided as to why that particular system was purchased. Physical dimensions, cost and current availability were listed as some of the reasons for purchase. That same document detailed the initial, preliminary testing carried out using the Roomba vacuum cleaner. This testing was conducted using the Serial Command Interface (SCI): a freely available Graphical User Interface (GUI) written specifically for use with the Roomba. The purpose of those tests was to ensure that the Roomba via Bluetooth successfully received all commands.

Using the “Serial Command Interface Specification” [12] document, experimentation was carried out for the purposes of replicating the SCI GUI used in the previous project mentioned above [11]. The reason for this was to investigate and confirm that any secondary software could be utilised to control the robot and thus use this other software to provide the Roomba with a certain degree of intelligence based on a predetermined algorithm. The software chosen for prototyping was National Instruments Labview.

Labview is a graphical programming environment utilising a simple “drag and drop” method to programming claiming that “regardless of experience, engineers and scientists can rapidly and cost-effectively interface with measurement and control hardware” [13]. The aim was not to use Labview as a primary method of controlling the Roomba, but merely to utilise this software as a prototyping environment in the early stages of research. It provided a quick and easy method of interfacing with the hardware while also confirming the findings as stated by the author who conducted the initial trials upon purchase. However prior to programming, a method of interfacing the Roomba with a desktop PC was required since Bluetooth capabilities were not inherent on the computer in use at the time.

3.2.1 Transporting Roomba

During the early development of both the core robot platform and the cleaning robot system, the subject was broached of the main robot containing a compartment, which would be large enough to carry the cleaning system on board. Two suggestions that were discussed were as follows:

The primary robot would require a hinged shelf on the rear of the platform that would have a motorised mechanism to lower and raise 90^{o} to allow the Roomba to drive onto it. Figure 6 (part A) displays the shelf in the lowered position, which would enable the vacuum robot to enter and exit the storage shelf. Figure 6 (part B) shows the storage shelf in the raised position with the Roomba vacuum cleaner being transported.

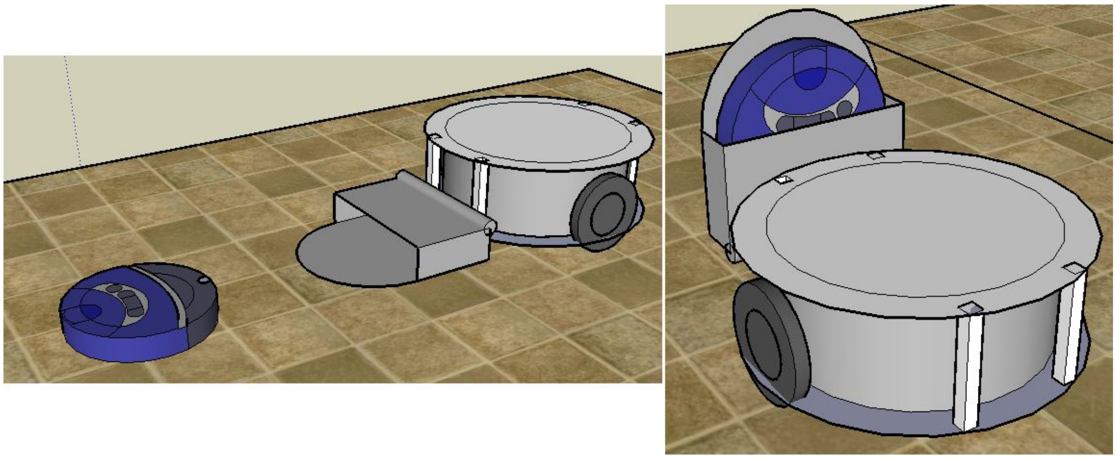


Figure 6: Sketch of Roomba Transport, Part A & B

The second solution raised for discussion involved a compartment in the very base of the main robot where the Roomba could simply drive into and be transported. That option involved less mechanical design however the solution was still impractical

Both of the above solutions were eliminated due to a number of reasons that were highlighted by the design team of the core modular robots once further discussion had occurred. The primary factor was the limited space on the base robot. The lower portion of the robot has the primary drive stepper motors, the rechargeable batteries and the motherboard. In addition to those components are the laser scanner, sonar sensors and the front caster wheel. The addition of a permanently attached shelf at the back of the structure would have inhibited access to the lowest rear-facing modular block while also causing an extra drain on the power. The combination of those factors resulted in a decision being made that the cleaning robot was required to independently follow the lead robot from a short distance.

Of the two ideas suggested the former has already been put into practice in a domestic cleaning robot as shown below in Figure 7. However, as is visible, the robot is quite large and merely serves to reinforce the point that addition of a compartment to house the Roomba results in a larger than necessary over-all structure. Images courtesy of “Blog about Robots life in our world” [14].

Figure 7: Existing Home Cleaning Robot [14]

3.2.2 Serial Cable

Appendix A contains the wiring schematic that was used to construct a serial cable used for direct communication between a desktop PC and the Roomba vacuum cleaner. Since the Roomba operated on a DC power of 14.4VDC and the serial port in a PC operates at 5V a voltage regulator was also required to be incorporated into the cable. The wiring diagram was found online [15] and solved the problem of 2-way communication and the varied voltage levels.

Initial trials proved unsuccessful however and the expected transfer of commands from PC to robot was not occurring. Electrical testing illustrated that the schematic provided by the website [15] was incomplete. The connection missing from the diagram online is to connect pin 5 on the DB-9 serial cable to Ground. This missing wire has been included in Appendix A. Figure 8 below shows a photo of the completed voltage regulator/communications circuit.

Figure 8: Photo of Power Regulator/Serial Cable

3.2.3 Labview

A sequence of steps was required to initialise communications with a serial device, issue commands, receive feedback and terminate the serial communications with the device. The following are the communications protocols as supplied by the manufacturers of the Roomba to customers:

Baud Rate: 57600 Date Bits: 8 Parity: None

Stop Bits: 1 Flow Control: None

The block diagram, which was put in use for this purpose, is supplied in Appendix B with any relevant information regarding that particular program.

3.3 Distance Measurement Devices

This section is a description of the two separate linear distance measurement devices that were intended for use within the system and the details regarding why each particular system was, or was not integrated. Following this is a minor introduction to the chosen device after being coupled with the vacuum robot and the progress made there.

3.3.1 Radio Frequency Identification

RFid (Radio Frequency Identification) was briefly investigated as a means to reliably and consistently determine the distance between the navigational robot and the vacuum robot. This was intended as an addition to the Roomba, should the testing have yielded positive results. The RFid system consisted of, in this particular case, an active tag, a tag reader with antenna and a computer to interpret the results.

RFid was tested as a means of distance measurement based on the success achieved by other systems available on the market. RFid-radar [16] is a system where the distance and angle of multiple tags can be tracked in real time for the purposes of asset or personnel tracking. Based on the success of this system replication of the results was attempted to determine whether a less sophisticated array of hardware could be utilised.

3.3.1.1 Operation

The basic operation principle of an RFid system is that an active tag (considered active because it contains a battery and actively emits a constant signal) transmits a radio signal containing information unique to that particular tag. This encoded information requires a tag reader & relevant power supply to output data to the computer regarding the tags that had been detected. Software on the PC is then capable of decoding the tag data and listing which, if any, tags are within range of the tag reader. Multiple readers used within a networked system enable the user to approximately triangulate the location of a particular tag relative to the known positions of the readers.

As with the Cricket location system, triangulation and exact location of a tag was unnecessary and as a result only one reader was purchased. As mentioned above, the presence or absence of a particular tag was determined and this in turn would have been used to tell whether the robot was within a particular circular range of the vacuum. The radius of that circular detection zone was based upon both the reader and the tag since different models of tags transmitted the RF signal up to different distances. The presence or absence of the robot within, for example, 5 metres was insufficient to be used in any sophisticated decision-making process so another aspect of the RFid system was briefly investigated: the RSSI (Relative Signal Strength Indicator) value. The RSSI value, as the name suggests, corresponded to the strength of the radio signal being detected from the tag in question and it was intended that this value would be proportional to the distance the tag was from the reader. Figure 9 below shows the 6 active RFid tags utilised in the following experiments.

Figure 9: Photo of RFid Tags [16]

3.3.1.2 Testing & Results

To determine whether or not the RSSI value could be utilised for distance measurement in this system some testing was conducted by a colleague who required RFid for a different area of the IWARD research project. The results for the preliminary experiments were obtained from a published document [17] where the experiment conditions and graphical results were detailed. The particular test of interest took place in an indoor setting with no obstacles between the tags and the reader.

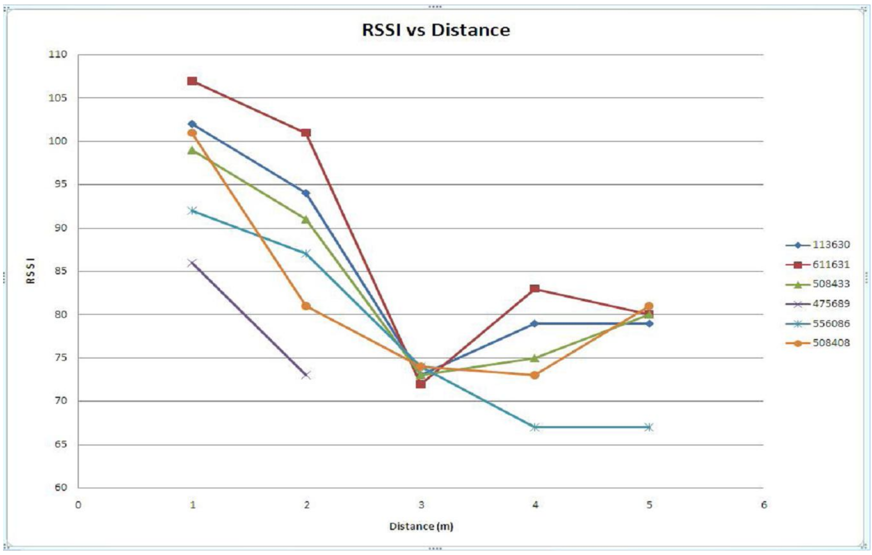


Figure 10: RFid Tag Performance [16]

Above in Figure 10 are the graphical results for a test carried out using 6 different RFid active tags in the same testing environment. The experiment consisted of manually moving each tag individually along a single axis away from the reader from 1 metre up to 5 metres while RSSI values were continually being recorded. Each line on the graph corresponds to a different tag, the identification numbers of which can be seen on the left hand side of the graph.

The expected results were a set of lines moving uniformly from a high RSSI value at 1 metre to a low RSSI value at 5 metres. As illustrated above the actual results did not match the expected results and proved that a linear relationship between distance and signal strength was not present. Further testing was carried out, the results of which can be found in the document titled “Developing a patient guidance module for hospital robots” [17]. The other tests consisted of rotating the tag reader and also introducing an obstacle to the test environment, however the results still returned irregular readings meaning that the RFid system was dismissed as a reliable method of determining a linear distance between two robots. This conclusion regarding the unreliability of the RSSI values was one that was also formed by the research team involved in developing the RFid-radar. This technology was used in no further part of the cleaning system.

3.3.2 Cricket Indoor Location System

The Cricket System consists of a number of identical hardware devices operating in conjunction with one and other. Originally the system was designed to be used as a means for locating a particular object while stationary or in motion. Using the supplied software an individual device is set as a beacon or listener. Ideally the beacons are placed on walls or ceilings within the desired operating environment where they periodically broadcast their positional information. Any listeners within range can detect this information and based on a relatively simple algorithm can determine the position of the listener within the environment. That expected method of operation was previously implemented by a group of students [8] where the Cricket "network" was installed within a scaled down environment. The devices were used, in conjunction with magnetic sensors for obstacle detection, to track a moving object in real-time & display the position of the object on a map. The error in correctly relating the position of the object on the map with the actual position was listed as less than 10cm. One particular attribute within the system is the act of measuring linear distance between one listener and one beacon, and it was this ability that allowed the Cricket to be used on the cleaning robot.

3.3.2.1 Operation

As mentioned above, the beacon periodically transmits a signal. This signal consists of two individual parts: Radio Frequency (RF) and Ultrasound. Since the speed of light (RF) and the speed of sound are both known, this property plays the integral role in the over-all system. Once the listener receives the first part of the RF signal it begins to actively listen for the Ultrasound signal. The time delay between the two signals is then used to compute the linear distance between the beacon and listener. If multiple beacons were detected a listener could determine the exact location by means of triangulation, however this aspect of the technology was not utilised. Figure 11 below shows an individual Cricket device as illustrated in the Cricket manual alongside an American quarter for size comparison.

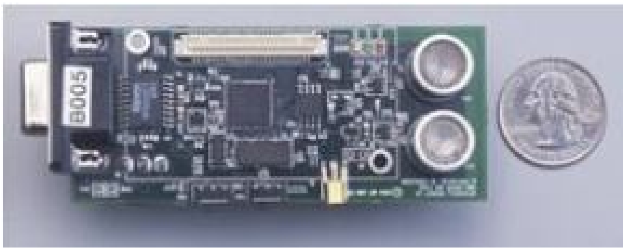


Figure 11: Cricket Device [18]

3.3.2.2 Experimentation

The accuracy of the linear distance between beacon and listener was briefly tested to determine how much error was present under normal conditions. To investigate this, a simple experiment was laid out as shown in Figure 12 below: the listener is set at a fixed point and connected to a computer where the distance values can be read. A standard measuring tape is laid out, as represented by the grey strip, and the beacon is moved linearly back and forth along the measuring tape. The actual values obtained using the measuring tape and the expected values obtained from the Cricket devices were compared to check the error between the results. Based on that simple test the Cricket devices were deemed acceptable despite a small error being present. For example up to 1.5m the difference between actual and expected results was a maximum of 4 cm. In some instances this would be a huge percentage of error, but for the role that these devices would play in the cleaning system it was thought to be within reason.

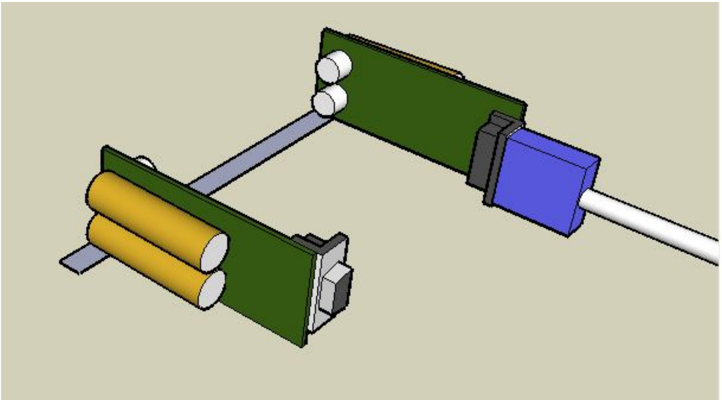


Figure 12: Illustration of Cricket Testing

A simple Labview program was written to obtain, in real-time, the full set of data transmitted on the output channel of the Cricket listener device. The following is a sample of the raw data transmitted from the Cricket listener to the PC through Labview.

“VR=2.0,ID=01:0e:39:39:11:00:00:cc,SP= ,DB=30,DR=956, TM=1170,TS=13888”

Figure 13 below, taken from the Cricket User Manual [18], shows the Serial Port Command Interface necessary for successful communication between PC and Cricket device. Each iteration contained a set of data, as shown above, that was unnecessary for the user but was, however, used in automatically calculating the distance. Examples of some of that data are the software version in use on the Cricket device as well Ultrasound time of flight (both corrected and un-corrected). The information of interest was the calculated linear distance; "DB = "which was returned in centimetres. In order to communicate via serial cable to the Cricket device from Labview the same program was utilised as was required to communicate with the Roomba (See Appendix B). However that program merely served to establish a connection to the device; further manipulation of the raw data was necessary to segregate the distance value from the remainder of the output string in each iteration.

Transmission speed	115200 bits/second
Data format	8 bits, no parity
Flow control	Xon/Xoff ("software")
Stop bits	1

Figure 13: Serial Port Command Interface [18]

3.4 Cricket & Roomba Combination

A series of simple experiments followed to ensure that each separate part of the work carried out thus far would work in conjunction with one and other. The Labview programs from the Cricket and the Roomba were combined along with a basic decision making process involving the Cricket measurement values and the bump sensors from the vacuum robot. Once the linear measurement was below a certain threshold value the robot was instructed to stop, otherwise it should drive forward at a constant speed. The bump sensors were integrated so the cleaning robot would turn should it impact any obstacle. Downward pointing infrared sensors, commonly known as cliff sensors, ensured that the robot did not stray off the edge of the work area such as falling down a set of stairs. Once a large increase in the distance measurement is detected, the sensors assume a large drop and prevent the robot from progressing any further in that direction. The purpose of those brief experiments was simply to ensure that all components were still fully operational following each step of development. This consisted of the final step where National Instruments Labview was utilised. There was no further progress to be made with the Roomba and Cricket devices with the current software.

4.1 Vision System

Thus far the Roomba vacuum robot consisted of the ability to be controlled from a desktop PC via serial cable or by means of a Bluetooth connection once a laptop PC was introduced to the scenario. For the purposes of prototyping within the confines of this project the laptop computer would be placed on top of the vacuum robot to substitute a purpose built motherboard and CPU to carry out all additional computational tasks. To this laptop would be connected the Cricket listener device and the Roomba itself, however the robot had no means of tracking the lead robot, receiving commands or locating any object of interest. Although technologies exist that would enable a secure, easy, long distance communication between the vacuum robot and the lead robot (for example Bluetooth or Wireless Local Area Network) it was decided not to make use of these devices to receive instructions by the Roomba. Since it was decided that the cleaning system would make use of a visual component to isolate the lead robot from the video stream, a further decision was made that the visual analysis software would be incorporated into as many aspects of the project as possible. The author of the report titled "Design of Distance Monitoring Algorithm for Robotic Applications" mentioned the same sort of conclusion in the report, stating that the visual component would be used in two separate components of the system: distance measurement and providing feedback to the operator.

4.2 RoboRealm

RoboRealm is described as" a powerful robotic vision software application for use in computer vision" [19] which immediately made it an attractive software package to be utilised for the purposes of this project. The package is specifically designed for image processing and analysis while also advertising an easy to use interface. Having seen that this software had previously been used to communicate with an iRobot Create mobile robotic platform [7] it was decided that a short investigation should take place to determine how applicable RoboRealm would be for the tasks outlined for this research. In keeping with the low cost requirements of the project this software is freely available for download by users in an educational role. RoboRealm would serve as the primary software component for the automated system.

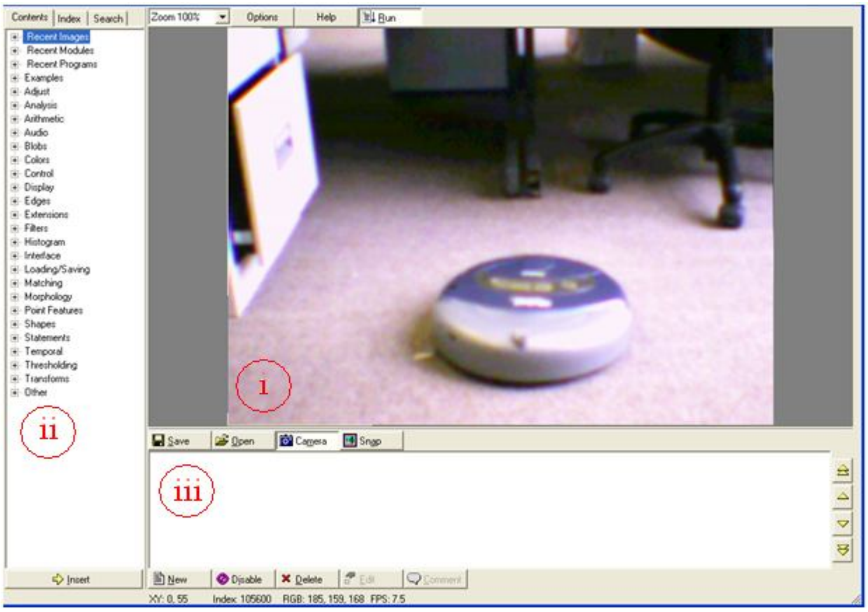


Figure 14: RoboRealm Software

Figure 14 above is a screen-shot taken of the RoboRealm software while in use. The area labelled “i” on screen is the view from the camera with the current step of analysis/manipulation available for viewing by the user. In this particular view no steps to manipulate the video stream had been added so the stream is as seen by the video camera. Area “ii” in the photo is the list of available functions able to be used once a photo or video is present. Once a relevant function has been chosen from the list a simple click imports it to the area labelled “iii”. This is known as the processing pipeline where the sequential manipulation of the video stream occurs according to the blocks selected by the user. An in-depth description of each function is available on the RoboRealm website under the tab labelled “Documentation”

The reason for using this software was that it was described in the report introduced in section 2.1.1: “Design of Distance Monitoring Algorithm for Robotic Applications”. The developers of that project successfully utilised the software to isolate a particular coloured item within the image. Based on the location of that object other information was derived and fed into the system.

The main role of RoboRealm was to analyse the video input stream obtained from a camera and extract an object of interest by means of manipulating the stream. This object of interest would allow the Roomba to centre on it and attempt to navigate from point to point within the given environment. The programs used in the various capacities will be discussed in this chapter.

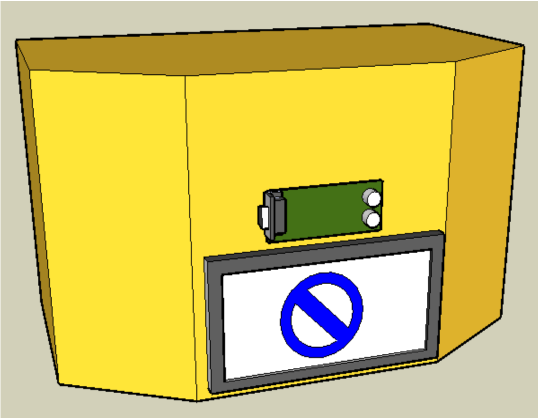
4.3 Early object detection

Initial trials involving the vision analysis software tracking on object of interest consisted of the user moving a particular object in front of the camera and noting the output responses displayed on screen. Using the web-camera on a laptop PC & the RoboRealm software an object was successfully tracked left & right within the laboratory conditions. A simple Visual Basic Script file was included into the program pipeline where the centre of the detected object was compared using the X & Y coordinates of the centre point. Three zones were initially set on screen and depending on where the centre of the object was located a message was displayed to simulate a command being sent to the Roomba. The three “commands” were to turn left, turn right or continue driving forward. The lighting, however, played a huge part in this scenario; testing took place in a variety of areas where lighting conditions were quite different from one to the next. This posed severe difficultly for the system as the object was not detected the same in each area. The cause of this was the direction and intensity of the light reflecting off the object, which changed its shade of colour. Seeing as the software was set to detect a particular shade of colour this resulted in a system that was not robust enough outside of ideal lighting conditions.

A number of objects were tried, all of which yielded similar results, proving that, for example, three objects could work perfectly in three separate areas but none would return satisfactory detection in all three areas of operation. To that end, a solution was required which was less dependent on ambient lighting conditions to provide a favourable scenario for ample detection of the object in question. This solution came in the form of an object that also emitted light meaning that low light conditions would no longer be problematic.

4.4 Computer Display

As illustrated in section 1.1 (Project Background) the core group of robots consisted of a tall skeletal structure constructed above the primary driving components such as motors and control circuitry. In addition, the lowest level of the main robot consisted of components for navigation such as a semi-circular array of sonar emitters and receivers and a laser scanner to measure the distance at a huge number of points along a single horizontal axis. The purposes for the tall structure were to primarily accept the insertion of pre-constructed aluminium boxes. The boxes were constructed identically and modified at a later stage to cater for the individual needs of the task for which they were intended within the realms of the IWARD project as mentioned in chapter 1. Other tasks to be carried out by the main robot are jobs such as the delivery of medicines which required a secured partitioned box, the monitoring of environmental conditions which necessitated a number of sensors mounted on the exterior of the aluminium casing and finally patient guidance which was a task in need of linear distance measuring such as a Cricket device to identify that a patient was in pursuit of the mobile robotic platform. Figure 15 below illustrates the module box as designed by a member of the IWARD project group. The addition of the monitor and Cricket measurement device were added postproduction for this specific project. As visible in the image on the right hand side, the box consists of a circular “self-centering” power attachment, a data transmission connector and in the centre of the back panel is the small receiver for a locking mechanism. The design of the box was to aesthetically follow the general style of the core robot while also providing a functional, secure, interchangeable compartment to contain all components necessary to complete a task. This removed the necessity for every robot to carry all components to participate in every task within the scope of the IWARD project. This ability to customise a robot for the required tasks was one of the primary features of the robots in the initial design brief.



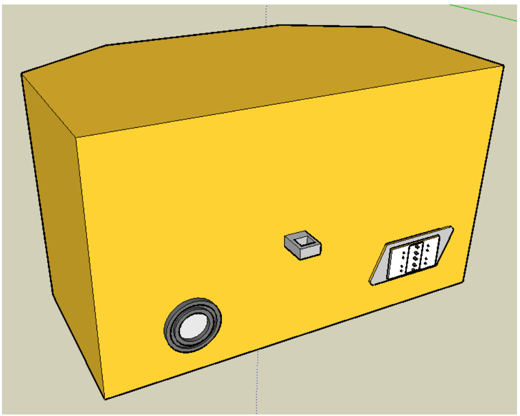


Figure 15: Illustrations of Module Box Concept

The module box for the cleaning system consisted of a small monitor recessed into the front of the module box as shown, with the interior of the box securing all power and data cables. As with all other modular boxes, this would enable any authorised person to merely insert the box into the labelled compartment on the core robot without the need for an engineer to connect all components individually.

Restrictions put in place by the developers of each module restrict which of the four compartments the relevant module box could be placed. The delivery module, for example, was restricted to the top layer of compartments so that people loading or retrieving from the box had easier access. The module concerned with patient guidance was to be placed at the rear of the robot in order to ensure that the Cricket distance measurement device was pointed towards the person carrying the emitter device.

Similarly the position of this modular box was restricted to the rear of the robot on the lower level in order to enable the camera of the vacuum robot to see the monitor.

4.5 Justification of vision

Under normal conditions robots would be constructed with an ability to transfer data using a wireless system in order to utilise existing technology and speed up the transmission of commands and information. During the design and construction process of the cleaning system, integration of Bluetooth technology was discussed among a peer group and the requirements of the system assessed. A problem with the base robot computer became quite serious; the number of USB devices connected on the robot was causing the system to shutdown due to the amount of conflicting signals. Input/output devices such as camera, touch-screen monitor, microphone and a number of other components were deemed necessary for the functionality of the base robot in primary tasks and communication for the cleaning system was labelled as secondary. As a result, a Bluetooth dongle was not permitted to be connected to the computer of the lead robot until such time as the software instability was solved.

The IWARD robot, prior to the inclusion of the cleaning system, already consisted of a dual-purpose camera on board. That camera was to allow the robot to recognise and identify a person lying on the floor in a situation, for example, if a patient had collapsed. The second purpose of the camera was to allow a doctor to perform a remote consultation from a workstation present elsewhere in the facility. Since the cameras had been successfully integrated into the project, there was encouragement to utilise similar systems in multiple applications. The addition of a wireless data transmission would have enabled the cleaning robot to receive instructions, however it would not have provided any means by which those tasks could be carried out. The camera and visual analysis software were an essential part of the cleaning system, without which the vacuum robot could not operate. Examples of such necessity are outlined below:

- While the Roomba was stationary in an area, perhaps after completing a cleaning cycle, the programming instructed that the robot periodically conduct a 360-degree rotation as a means of searching for the lead robot, or more precisely any symbol displayed on screen. If a wireless network system were in effect then the lead robot would arrive in the designated area and subsequently issue the command to follow. However, the Roomba must first establish a visual connection with the lead robot in order to determine a direction in which it must travel. A wireless network cannot be used to issue directions without knowing the precise location and heading of the vacuum robot in relation to the main robot. The cleaning robot would be aware that it had been requested to carry out a task and would, in an attempt to acquire the expected visual object, conduct periodic rotations to find a heading in which it must travel. Therefore, without the camera identifying the appropriate object, the robots would be unable to move in unison.
- Once the two robots had successfully begun the transport cycle, the vacuum robot operated utilising two separate technologies: the visual recognition system and the Cricket linear distance measurements. Once a clear line of sight

had been established, the two robots could successfully navigate through the hospital environment by means of the navigational software programmed into the lead robot. Commands were not continuously issued to the Roomba to request it to follow; the cycle was dependent on decisions made on-board the vacuum robot. Therefore the addition of Bluetooth or a similar wireless technology would not aid in the process of one robot following the other. In instances where line of sight was lost, a wireless signal would not allow the vacuum robot to continue to travel, as it would effectively be moving blindly throughout the environment. The lead robot had no means by which it could direct the secondary robot and therefore could not issue commands regarding angular turns or speeds.

- Once both robots had successfully reached a destination, the secondary robot would be behind the main robot in a clear line of sight. This assumption is based upon the fact that the vacuum robot had maintained visual contact from the starting point to the current position and would have been continuously able to view the symbol displayed on the rear of the robot. If the line of sight had been disturbed for a long period of time then the Roomba would not have reached the destination with the lead robot. The visual recognition software would recognise the change of command on the screen and would subsequently ignore the lead robot and either begin to search for the appropriate area for spot cleaning or would have initiated a standard cleaning cycle of the entire area. Regardless of which cleaning regime had begun, wireless capability would not provide any better means by which the cleaning would occur.

As has been illustrated, the visual aspect of this system played a larger role in the operation of the system and as a result was given a higher priority in the project. The vacuum robot could not successfully carry out any task without the inclusion of a visual component. Tasks such as locating the spillage and maintaining a heading whilst in transit would not be within the realms of Bluetooth alone. A system such as the Bat Ultrasonic Location System [20], which operates on a system not dissimilar to the Cricket measurement systems, could offer a solution to aid the visual component. The vacuum robot would carry two receivers at fixed points and the base robot would contain one emitter. The angle and location of the emitter would be determined based on the time difference of arrival of the sonar signal to both receivers. The Bat location system requires a significant distance between both receivers to measure an accurate distance and this was not possible on the robots due to their small size. The inclusion of a visual component was however, essential for the system to operate.

5.1 Command Recognition

Early indications from the software displayed the ease with which an object could be isolated through the medium of RoboRealm, however shortfalls existed within the physical equipment in use at the time. The introduction of the computer monitor on the main robot was to rectify the less than ideal results found up to that point in time. The inclusion of the monitor resulted in an extremely clear & recognisable shape being extracted from the video stream in the form of a binary image. Variations in lighting conditions no longer had such a detrimental effect on the detection capabilities of the system; regardless of whether the camera was facing towards or away from a window, or indeed in an area of limited illumination the system was continually fully functional.

As was stated, the camera was required by the Roomba to orientate itself in order to be able to pursue the lead robot from one location to another. Without the visual aspect incorporated, the cleaning robot would have had the capability to detect the distance between the robots (by means of the Cricket system) but would consist of no means to dictate in which direction to move. The isolation of a dedicated object on the lead robot provided the directional heading in which the cleaning robot was requested to travel. Testing illustrated, upon inclusion of the computer monitor, that a shape could not only be extracted from the video stream but also recognised as a particular shape by the user. The question was raised as to whether the software could be programmed to autonomously recognise one shape from a list of possible shapes?

Words were displayed in the appropriate colour and were duly detected and converted to a binary image viewed by the software. “Clean”, “Follow”, “Spot” &

“Pause” were used and related to the task the base robot was requesting to be carried out. The pause merely related to the sequence of one robot following the other where a momentary respite was required, possibly due to an obstacle etc. Although the software was appropriately trained to detect the words, the system still provided incorrect matches to words on occasion. The words, regardless of how different they appeared to a human user, still apparently provided sufficient similarity to the software that words were interpreted incorrectly and thus resulted in a system that acted erroneously.

In order to reduce the level of error in the recognition portion of the program the words used were replaced with a series of very different symbols with as little similarity as possible. Figure 16 below illustrates the four symbols used to signify the various commands in use by the system. Labelled A-D the commands are pause, spot clean, regular clean and follow respectively.

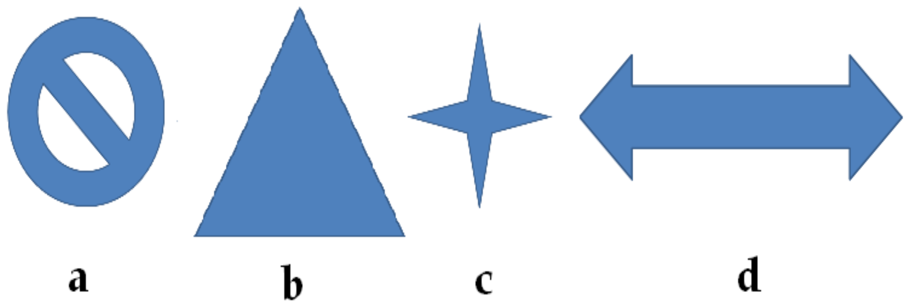


Figure 16: Command Symbols

To enable the system to operate at full potential the system was trained using images in an ideal environment. A perfect binary image of each shape was stored and used as a comparision for the “shape matching” function within the RoboRealm software. Within the settings of the shape matching, filters were applied so that objects approximately matching the recorded symbols would not interfere with the operation of the over-all system. The shapes were filtered according to size, angular rotation and then the confidence with which the image on the video stream corresponded to the ideal recorded image. A minimum of 85% confidence by the analysis software, after filtering by size and orientation, was required in order for a command to be accepted and the next stage of the programming algorithm to be initiated.

Once the corresponding command was accepted the program pipeline used conditional IF statements to load a new sequence of blocks designed to carry out the required task. Upon completion the system was instructed to return to a state of readiness to accept the next command issued from the base robot.

5.2 Following

The sequence of steps to execute the task of maintaining a reliable line of sight on the symbol displayed on the lead robot is as follows:

- Serial block to connect to the Cricket location listener device
- RGB filter to isolate the colour of the designated symbol
- “Open” the image to remove any small unwanted solitary pixels
- remove any temporary sporadic pixels (flicker)
- determine the centre of gravity of the object
- apply the Visual Basic Script to rotate the robot as necessary

Below is an image taken from the RoboRelam software once the symbol for the "follow" command has been successfully detected. Included in the image are the surrounding boxes for the centre of gravity of the blog (required in the Visual Basic script file) and the confirmation box that the symbol has be correctly identified. Appendix C contains the RoboRealm pipeline program used in the sequence to enable the Roomba vacuum robot to follow the main robot.

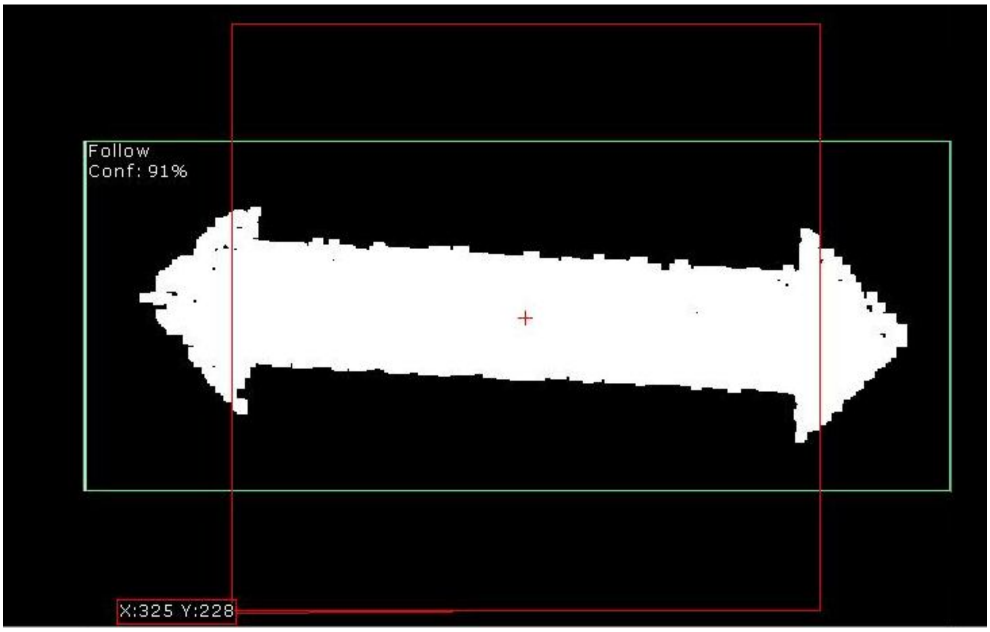


Figure 17: Command as Recognised by RoboRealm

5.3 Obstacle Impact

Once the two robots were in convoy there should, in theory,have been no object or obstacle to impact the bumpers. The lead robot, with sophistacted navigational and obstacle avoidance capabilities, should negotiate all interferences and as such sucessfully lead the Roomba around said objects. Should the main robot halt abruptly for any particular reason, the “pause” symbol would have been immediately displayed requesting the Roomba to do so. In the event that the command was not issued in sufficient time, the visual analysis software in conjunction with the Cricket measurement device would have resulted in the drive motors stopping prior to an impact occuring with the rear of the other robot. The software algorithm, written to allow the vaccum robot to follow the target symbol, was designed so that only a small linear distance existed between the two robots; the reason for this was to prevent personnel from walking between the two robots and obstructing the line of sight and secondly to enable the Roomba to clearly view the monitor recessed into the module box.

In the unlikely event that an impact should occur, the software would have recognised the sensor activation and reacted in kind. A frontal impact would require the vacuum robot to stop and wait for a short period of time allowing the object an opportunity, if possible, to move i.e. if it had been a person. Static objects which had accidentally fallen in front of the Roomba would not move and the vacuum robot was not programmed to deal with unforeseen obstacles such as those. The reason for this was that there was no on-board capability to determine the object, it’s size or in which direction the robot should rotate in order to navigate around the barrier. Successfully passing the obstacle would require turning and as a result most likely losing sight of the lead robot. Without the visual informtion the vacuum robot had no method of tracking the lead robot and would therefore act as if no other robot was present and stop while simultaneously emitting a sound to draw attention in the hope that the obstacle would be moved by a passer-by, thus allowing the Roomba to continue.

Should an impact occur on the left or right sides of the Roomba then it was hoped that the obstacle only partially blocked the path in front of the Roomba. Due to the nature of the construction of the Roomba there was no method available to determine the exact location of the impact; the bumper consisted of two spring loaded micro swithes, one on either side and should an impact occur at the front then both sensors activated. The course of action taken by the vacuum robot was to rotate a small angular distance, while endevouring to maintain a visual link with the lead robot. This simplistic sequence of events was included in order to account for any small error that may occur in the “following” algorithm in the event that a wall was impacted, an edge was bumped during cornering or some other unforseen circumstance. In the event that the Roomba has rotated too far in an attempt to avoid an obstacle the lead robot may no longer be in view and therefore the visual rocognition software would be temporarily out of use.

5.4 Testing

Although testing did occur, it was proven over a period of time that the communications link with the RoboRealm software and the Roomba impact bumpers was tenuous at best. There were numerous occassions where an impact was forced in order to ensure that the correct response would occur. Although the software was capable of receiving information from the sensors, the hardware seemed unreliable in it’s ability to transfer the signal to the laptop mounted upon the robot. The bumpers operated as expected during the regular cleaning cycles proving that the fault did not exist within the micro-switches; as a result the error seemed prone to occur during the communications stage with the laptop PC. This was an error where a solution did not present itself throughout the course of the research and as a result remained a periodical problem.

As a means of evaluating the performance of the cleaning system during the “following” sequence a laptop was mounted on a small mobile platform as a means of simulating the main robot. This was to ensure that a consistant height was maintained and the platform could be manually moved at a steady pace. The testing occurred in an environment with common obstacles such as beds, chairs, tables and corners at 90 degree angles, much like a hospital environment. The experimentation involved displaying the relevant symbol and allowing the Roomba to travel behind the simulated lead robot. Speed differences, turns, sudden stops and gradual curves were all performed and the respones of the Roomba noted. The results of testing illustrated some hugely important points of interest:

- The lead robot must ensure that when a corner must be turned that it does not stop and rotate in postion and continue straight; the robot must make a gradual curving turn and utilise as much of the space as possible to make the turn. The reason for this is that one the monitor rotates and the camera on the Roomba no longer had a clear view of the symbol. The maximum rotation allowable in either the clockwise or anti-clockwise directions were approximately 35 degrees away from the axis perpendicular to the camera on the vacuum robot.

- The optimal distance be maintained between the two robots while in transit was found to be 1 metre. This allowed for a clear view of the lead robot, with very little risk of obstacles falling between the two robots to obstruct either the view or the path of travel. This distance also enabled sufficient time for speed changes and sudden stops to be accounted for by the secondary robot.

- Gradual arcs performed by the moving platform along a straight corridor or hallway presented no difficult for the cleaning robot while in transit.

- Sudden stops both with the “pause” command and without were tested to ensure that the vacuum robot could react and stop without any collision occuring which may risk damage to one or both robots.

- Issues occurred once the distance between the two robots became too large due to rapid increases in speed on the part of the lead robot. This, however, would be unlikely as it was discovered during testing of the lead robot, by the developers, that the lead robot could not travel too fast due to a risk of toppling.

Appendix C also contains the program details for the standard cleaning cycle.

6.1 Spot Cleaning

This chapter deals with the particular task that was mentioned in the introductory chapter regarding the ability of the robot to isolate and clean a particular area within a specific room or corridor.

6.2 Intended Scenario

In order to correctly portray the spot cleaning cycle in the correct manner, a theoretical scenario for operation is described here to illustrate the intended method of practice.

A member of staff is notified regarding a spillage that has occurred within the hospital facility and the location of the spillage. The member of staff notifies the swarm of modular robots and includes details of the task and location. A robot fitted with the appropriate module box travels to the location in which the Roomba is currently present. The appropriate command is illustrated to enable the Roomba to follow the main robot to the appropriate location.

6.3 Operational Information

While endeavouring to create a solution to reliably clean one small area, a number of solutions were investigated. Below is a description of a number of areas where experiments took place to ascertain the feasibility of utilising some of those methods to achieve the intended results.

Virtual walls are small devices designed to be placed across doorways or in front of areas where access was restricted and the Roomba was not permitted to enter. The principle of operation is that an infrared beam is transmitted that is capable of being detected by the Roomba and once it detects this beam it will stop as if a physical barrier has impacted the bumper. As the illustration suggests, the initial suggestion was to make use of the existing technology within the vacuum robot rather than attempting to introduce a new feature. Figure 18 below shows the concept where four virtual walls were placed to surround a spillage and the green cone indicated where the spillage was. The red beams indicate the IR barrier, however in reality the beams extended in a conical shape from the front of the barrier units.

However the concept was discontinued for a number of reasons; for the Roomba to enter the area to clean the spillage the IR barriers would need to be deactivated upon approach of the vacuum and activated once the Roomba was within the required area. This would have required that some additional components be added to enable the barrier system to be able to detect the presence of the Roomba. The purchase of a minimum of three virtual wall emitters would have raised the cost, and would have been deemed excessively complicated to enable a small area to be cleaned. The additional problem was a means by which the robot would still detect the area of the spillage and travel towards it.

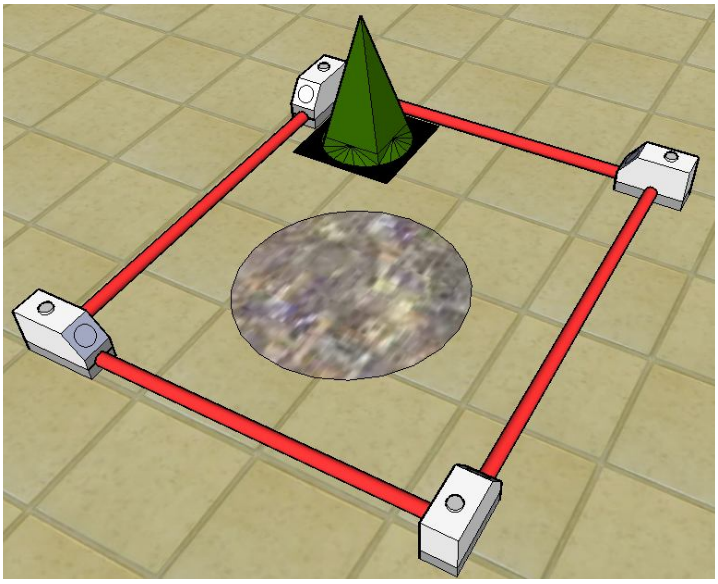


Figure 18: Spillage Marked for Attention

Prior research in two projects, mentioned in the literature survey, illustrated that a laser spot could be detected using visual analysis software and as a result a similar solution was investigated to determine viability of using such devices. By making use of a function within the RoboRealm software, specifically included to detect a laser spot, some preliminary testing was carried out. The camera did indeed detect a laser spot within the video stream but there were a large number of false readings also present during the tests. In the document titled “Building a mobile robot with optical tracking and basic SLAM” [9] the author described the problem of a spot only being detectable in a laboratory environment under ideal conditions. The exact problems listed included the presence of a “halo” around the spot, which distorted the image as well as some surfaces not being conducive to reliable detection due to the reflective properties of that surface. In this project the “halo” effect was not noticed, however the surfaces upon which the laser was pointed did influence the results dramatically. Under conditions where one would expect a vivid red point to be clearly visible, the actual results did not match. Varying lighting conditions, such as proximity to a window or external light source and time of day, all influenced the results greatly. With no change to the software, the detection capability of the program was not robust in changing conditions.

While a red dot was successfully located in the project “Design of Distance Monitoring Algorithm for Robotic Applications” [7] the system did not require the same versatility with which the spot-cleaning algorithm was required to operate. The distance measurement system was designed to locate the brightest pixel within a very particular region of the video stream at relatively small distances on a surface roughly perpendicular to the camera. The intention with the spot-cleaning scenario was to use a laser pointer mounted on a raised structure that was angled towards the ground. The location of the laser spot on the ground would be used as a marker for the area that required attention. This involved trying to isolate a small brightly coloured group of pixels at a distance, up to and including 5 metres, across a variety of surfaces and realistic locations. This proved unsuccessful and as a result was not put into practice for further research due to the unreliability of the detection in the earlier, more ideal stages of testing. A solution was required where the marker for the area to be cleaned was more easily detectable.

To allow an item to be detected from a reasonably large distance a source of light illuminating the object would reduce the variance in different lighting conditions.

Once a light source was present the colour of the object would also be much more vivid and, in theory, create more of a contrast between it and surrounding colours. Taking a brightly coloured yellow cone and placing a light source within it investigated this concept. The software was trained to isolate objects matching a particular RGB (Red Green Blue) value as seen by the camera. The results were unexpected and unusable within the scenario. The object was indeed illuminated, however once the camera attempted to detect and isolate the object and convert it to a binary image, the on-screen result was not as expected. The light source saturated the image, thus giving a false reading. The right hand image below (Figure 19) illustrates the resulting image, which is similar to the "halo" effect noticed by another researcher in trying to detect a bright red spot. The left hand image is merely for comparison

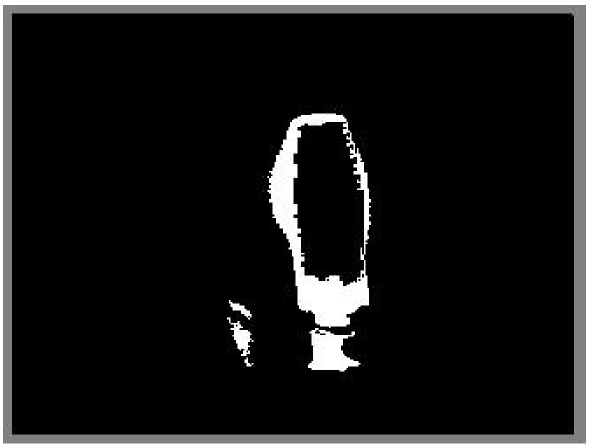


Figure 19: Anomaly as viewed normally (left)& by RoboRealm (right)

The light source used was not only causing a "halo" to form around the object of interest, but once the object came close to another surface the camera was falsely detecting that secondary surface as an area of interest. This was due to the particular shade of light being cast on the surface falling within the RGB values used by the software. As with the previous experiments, this solution was deemed unsuccessful.

Based on the success achieved with the two robots, a similar solution was employed for the spot-cleaning scenario. This was initially avoided due to the hardware required for the application of this system. The aim was to keep the cost as low as was feasible while still achieving the desired goals, which resulted in the lower cost solutions being investigated prior to the addition of more costly measures to this scenario in the project. The intention was to use a small movable structure that would support any hardware necessary to allow a small monitor to display a symbol in exactly the same manner as the lead robot did while the Roomba was in pursuit.

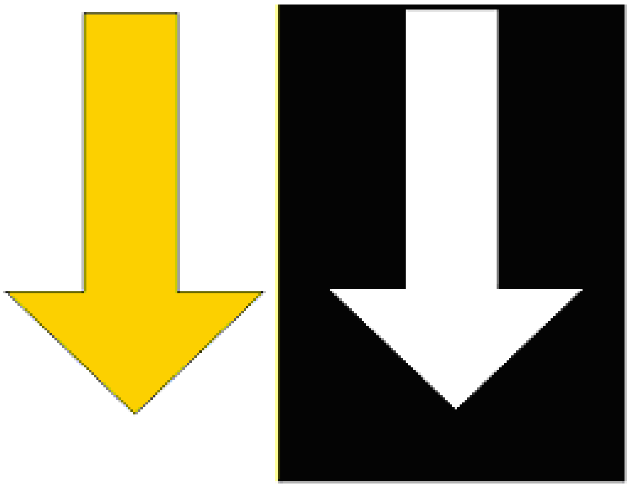


Figure 20: Symbol Prior to (left) and Post (right) Detection

Figure 20 above shows the yellow symbol displayed on the screen to be used for tracking and shape matching in order to determine the location of the area in need of attention. A separate colour was chosen to be filtered from the image in order to remove the possibility of the vision system mistakenly tracking the incorrect object. Once the system accepted the command for spot cleaning the RoboRealm software loaded a new pipeline program, which disregarded the colour, and symbols used for following the lead robot and would focus only on the designated yellow colour and then attempt to match the recorded shape.

The relevant software for the spot-clean algorithm can be found in Appendix D, which contains the RoboRealm pipeline program, any appropriate visual basic script file descriptions and attached settings for individual steps.

6.4 Testing

The Roomba spot cleaning was tested to ensure it could successfully clean a spillage that had occurred within the operational environment. Maintaining a similar testing method as the "following" sequence, a second computer was used to simulate the marker used to denote the position of a spillage within a room or hallway. The vacuum robot was deposited within the area of the spillage and the appropriate program was activated and no more human interaction was provided. Assumptions for this testing were that the user had followed instructions and placed the marker with the computer monitor facing the door in order to enable the camera to pick out the symbol. Experimentation took place in a number of rooms, which contained typical furnishings to simulate hospital environments containing rooms of average size. Testing of the spot cleaning functionality yielded results that are summarised below:

- The camera and RoboRealm combination had very little difficulty in correctly assessing the size of the object in question and correctly stopping a correct distance in front of the computer monitor. This was necessary to ensure that the vacuum robot began the cleaning cycle in the correct area, which was in very close proximity to the spillage. RoboRealm could successfully view the image and measure the size of the surrounding box and based on limits within the VBScript files determine a correct distance.

- Once the spot cleaning cycle was activated the robot began to move in an increasingly large spiral pattern, however due to the motors not performing equally the spiral pattern had a tendency to drift and therefore did not finish in the same position as starting from, which was expected. In an uninterrupted area the robot finished approximately 1.5metres from its initial starting point. This merely resulted in a larger cleaning area.

- In a small number of cases the simulated spillage was placed in an area of a room where there was no line of sight the marker and the doorway. If the core robot deposited the vacuum robot at the doorway then the camera would not be able to recognise any symbol and would fail to clean the spillage. The suggested location for the lead robot to stop would be a central area in the room where an improved view of the room was available.

- Spillages in large traditional wards within a hospital could cause issues for the cleaning system. The lead robot does not contain the ability to locate a specific bed within a room and as a result the default position would be to stop in the centre of a ward. If the ward room consisted of, for example, ten beds then the cleaning system would not find the spillage. The reasons for this are that the number of obstructions would prevent a reliable line of sight and the distance would potentially be too large for the camera to correctly identify the object of interest. In conclusion, the spot cleaning system was better suited to smaller rooms such as individual patient rooms, which would be furnished much like a domestic bedroom.

7.1 Mapping

Once it was apparent that the Roomba could successfully be deposited within a particular room for cleaning, the process of successfully cleaning an area with more efficiency was briefly approached. There were, however, constraints and as a result the solution was never implemented. This section will discuss the brief investigation conducted and the intended path of progress. The initial intention of this area of research was not to alter the cleaning cycle that was pre-programmed into the Roomba vacuum cleaner, but merely to record the path that was taken during cleaning. Upon notification of completion, the software system would subsequently determine which areas had been missed and redirect the vacuum to return to those areas and complete the task.

A series of tests were run to determine the effectiveness of the standard cleaning cycle with the route recorded manually of the entire cycle to visually assess areas that had not been cleaned. What became apparent after a short space of time was that the robot, as expected, was quite inefficient and cleaned certain sections of the test area repeatedly while other portions got cleaned once. Figure 21 below illustrates the accessible floor area of a room cleaned. Each green line traces the path taken by the Roomba in one particular recorded test. The line simply denotes the central point of the robot, whereas the effective cleaning range of the vacuum robot is 25cm across. The cleaning of this area took place numerous times with similar results being shown. Left in an average sized room to operate, the Roomba appeared to complete a satisfactory level coverage throughout the entire room, however due to the random nature of the pattern, 100% coverage could not be guaranteed.

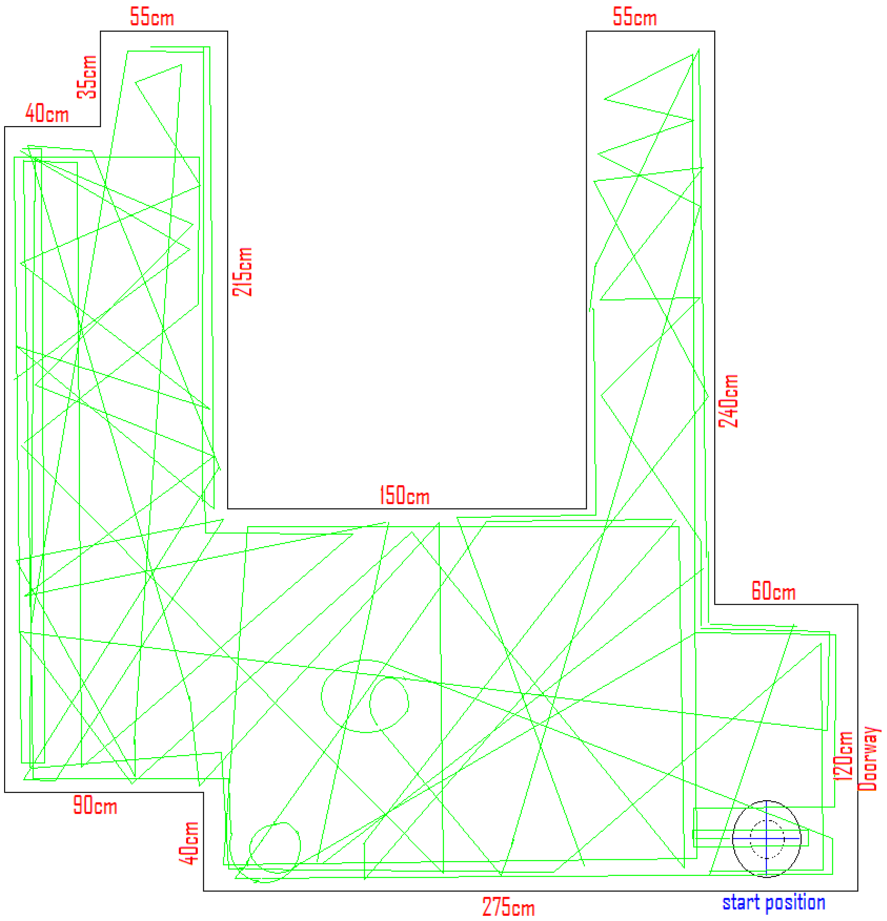


Figure 21: Tracking path of Roomba

To compare the cleaning of a standard room with a section of uninterrupted hallway, testing was repeated elsewhere. Since the area of operation to be tested was significantly smaller, the time required for a successful clean was limited. The results for the hallway testing were more successful than the testing in a bedroom. The longer, straighter surfaces resulted in all areas being cleaned during all five tests ensured greater freedom for the Roomba to operate with ease. The entire area of the hallway was cleaned each time, however efficiency of the pattern was still of concern due to numerous area being repeatedly covered.

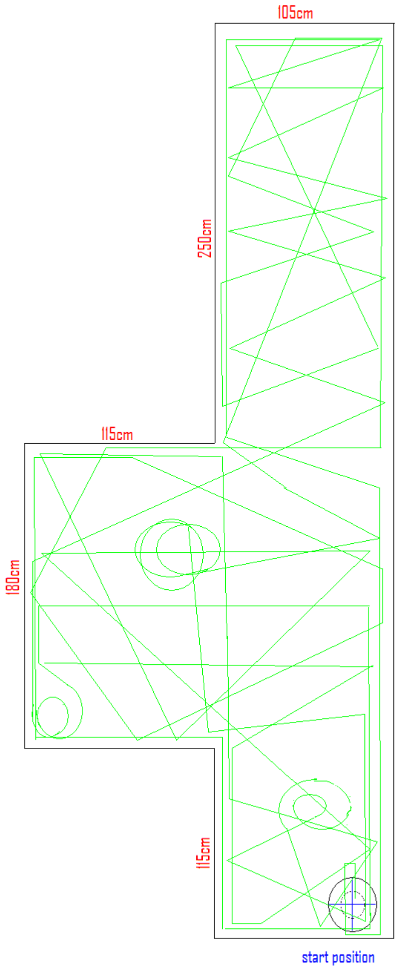


Figure 22: Hallway testing of Roomba

As mentioned by Harding [11], the method of cleaning employed by the Roomba vacuum cleaner is considered a random approach; the robot drives around until it bumps into an obstacle at which point it turns randomly and drives until the next impact. If the software were to record the path travelled by the vacuum, certain information would be crucial to perform this task, namely angular rotation and distance travelled. The Roomba is equipped with the capability to return this information to the user upon request. The distance, returned in millimetres, is the sum of the distance travelled by the two wheels divided by two. Forward or reverse direction can be specified. The angle is returned in degrees or radians and can be returned in clockwise or anti-clockwise directions.

A suggested form of tracking involved the use of two different software programmes working in conjunction with one and other. Since the RoboRealm software was in communication with the Roomba, this was the medium through which the odometry was to be returned. The data provided, as an output by the Roomba robot was angular turns in radians or degrees and the distance travelled in millimetres. With all values at zero the Roomba would start to move and periodic measurements were to be requested. With the receipt of each data set, RoboRealm would utilise a previously established link with “The MathWorks Mathlab & Simulink” software. The Mathlab programme would plot the angle and distance in a simple two-dimensional diagram and save it; each set of new distance and angle measurements would be updated on the diagram. Once the cleaning cycle was complete the diagram would be returned to the RoboRealm software with the current location of the robot saved. Based on a simplistic colour scheme, RoboRealm could easily distinguish between areas that were cleaned and not cleaned and from that the Roomba could be directed to an area of a particular colour.

The main problem involved in this scenario was the hardware and the lack of precision involved. In a series of tests conducted, the Roomba illustrated that it is unable to traverse an area using straight lines. To test the degree of error inherent in the robot it was driven forward 100cm; the end position was 25cm to the left. The test was carried out a number of times with the result being similar each time. In addition to simply measuring with a standard measuring tape, the feedback from vacuum robot was recorded and the values fluctuated inconsistently allowing for no reliable measurements to be taken from the encoders. Clockwise and anti-clockwise rotational values returned readings of values approximate to 65,000 despite the fact that the program requested the angle in degrees, which proved that the hardware was incapable of returning useful measurements for use in a mapping process.

As was correctly stated by Marklund and Harding in the respective documents, a map is difficult to construct using positional information based on the robot's own sensors. The error due to wheel slippage can render any such estimation useless and entirely inaccurate. The solution to this is to utilise an external system to return the current location of the mobile platform, such as was implemented in Hallym University when a Cricket Indoor Location System was included for asset tracking. Even in situations where the sonar sensors were used for tasks such as maintaining a constant distance to the wall, the hardware resulted in an error approximately 2cm at 2metres which would be deemed acceptable for applications such as this.

In order to effectively create a map a number of additional components would have been essential for the robot. Primarily the robot would require rotary encoders; ideally absolute encoders would be utilised since they provide a unique code for each position and they do not require a home cycle, even if the shaft of the encoder was rotated while the power was off. If an encoder was mounted externally on the robot at either side and was not connected to the drive wheels then they could accurately measure distance without the problem of wheel slippage occurring. The addition of equipment along the outer circumference of the Roomba could interfere with the pre-programmed algorithm within the robot. A second method would be to mount a number of sensors such as a laser scanner in conjunction with sonar sensors and attempt to locate features such as corners or doorways. That method would require a great deal of computational power in order to constantly analyse the surroundings and cross reference the current readings with the reference points recorded within the system. Numerous solutions are available for integration into a mobile robot platform however most consist of expensive equipment, which is contrary to the initial request to maintain a low cost system. As a result, the additional mapping hardware and software was sacrificed in order to keep the cost to a minimum.

8.1 Discussion

As stated in the introductory chapter, the objectives laid out as guidelines for the duration of the research stated that, initially, a method of communication was to be established between the two robots involved in the automated cleaning system. Subsequently the main IWARD robot was to be provided with a method by which it could successfully transport an auxiliary cleaning unit to a designated area within the confines of the hospital environment. Once the communications link had been deemed operational, the main robot was to be capable of issuing a number of commands pertaining to the orders derived from the robot management system present within the core robot. The final task to be completed was a method by which the cleaning system could automatically isolate a particular area of interest within a room and clean a specified area should a spillage of some sort occur.

8.2 Tasks

Without orders to dictate the method in which the tasks were to be completed, a number of concepts were investigated throughout the course of the research to provide a solution to the individual objectives. Upon completion of the allotted time made available for the project work to be undertaken, the tasks, as dictated upon initialisation of the research, had been successfully carried out. During the testing phase, utilising the RoboRealm software and the camera mounted on-board the cleaning robot, the four designated commands were successfully and repeatedly transmitted to the cleaning robot. Subsequently those commands were interpreted, leading to software algorithms being loaded to initialise the appropriate function.

Within the RoboRealm software, a number of conditional statements were included as a method of loading separately saved algorithms. Since the conditional statements relied completely upon the detection and recognition of the individual symbols, this task was of the utmost importance and during testing it was found that the detection capability of the Roomba robot was satisfactory. Although the communication was unidirectional and the cleaning robot required a clear line of sight to the main robot, the Roomba was capable of detecting the symbol and activating the appropriate cycle. As a result, the first requirement of the cleaning system was deemed to be successful since instructions were issued across a small distance and received and acted upon by the recipient; hence communication was occurring.

In order for the cleaning robot to autonomously activate the regular cleaning cycle within the desired location, it was the task of the IWARD robot to successfully transport the cleaning device to said destination. As was intended, the core navigational system on the cleaning robot was comprised of, in the majority, the visual analysis software. RoboRealm was the key component required to locate the object of interest on the main robot while simultaneously utilising the sequential pipeline program to decide upon the course of action to be taken. In this instance the software enabled the Roomba to follow the main robot from point A to point B within the hospital environment without the assistance of any personnel working within the facility. Based on the position of the object of interest along the X-axis within the field of view, the size of the object of interest and the linear distance obtained from the Cricket measurement device, the cleaning robot had the ability to travel in convoy behind the lead robot. Testing proved that the visual analysis system was capable of carrying out the task under ideal conditions and as a result this requirement as laid out in the initial stages was considered successful.

As a supplementary requirement, which continued from the initial task, the third objective was to enable a series of commands to be issued to the cleaning device. As has been previously stated, this task was a success. Although limited to four individual commands, the robot system was indeed capable of transmitting any of the pre-recorded commands. The vacuum robot had to follow the lead robot, pause while in transit, clean a particular area/ spillage or clean an entire room. Each command was displayed on the monitor, which was recessed into the rear of the lead robot and was detected by the Roomba. The decision regarding the commands was made by the robot management system present within the IWARD robot. As was found during testing in the laboratory setting, the RoboRealm software was capable of distinguishing one symbol from the other and loading the appropriate pipeline program.

The project guidelines stated that the system must "Issue a variety of commands to the cleaning robot and ensure task is completed", and this was attempted. However, the latter half of this requirement was not met. Although the lead robot consisted of the ability to send a variety of commands to the Roomba, there was no additional capability for the core robot to receive any updates on the status of the cleaning system. This shortcoming within the system had consequences that extended to every aspect of the operation. There was no method by which the lead robot could identify whether the cleaning robot was in pursuit, or whether an obstacle had prevented the transit process. Similarly there was no data to inform the IWARD platform whether there had been a successful cleaning cycle carried out or not. For the purposes of simulation an audible signal was produced during parts of the testing to denote the appropriate occurrences where a response was to be communicated to the main robot. These signals were observed by the user, whom, during trials, acted as a replacement for the lead robot within the laboratory facility.

The fourth and final requirement, as specified in the introductory chapter, dealt with the ability to isolate an object of interest within a room and travel towards it for the purposes of cleaning a small area. As discussed in chapter Y, the visual analysis software successfully segregated a yellow object from the background and matched it with the recorded shape saved in the database. Once the shape was positively identified by means of a similar methodology as was employed during the transport cycle, the robot was capable of positively identifying a marker and autonomously activating the spot clean cycle. As such, this task was also considered to be a success within the boundaries of the project guidelines.

8.3 Critical Evaluation

Although the majority of the tasks laid out for the successful completion of the project were met, there was no definable value against which a satisfactory performance by the system could be measured. Each area of operation possessed a number of flaws or shortcomings, which would be expected in the prototype phase of any system. One detail requested upon initiation of the project was that the cost of the project be kept at level conducive to the system being reproduced a number of times. One would argue that the inclusion of a computer monitor in the module box pertaining to the cleaning system acts contrary to that request, while also applying the same argument to the solution for spot cleaning. Although the solution presented here was not the cheapest option, it did indeed prove to be the more superior of the trials that were conducted using a variety of alternative techniques.

Upon integration of computer monitors to the cleaning system, the problem regarding object detection in very high or very low lighting conditions was severely diminished. This issue did not entirely disappear and was noticed during a small number of trials carried out as the system developed. The camera in use in the system remained in “auto exposure” mode as a means to adapt to changing lighting conditions which enabled more versatility in the system in rooms of differing luminance; unfortunately this led to the software failing to detect the symbols at certain points. If the camera was faced towards the rear of the lead robot which had a very bright light source in front of it then the auto exposure would compensate in order to provide the best quality footage if the video stream was being recorded. The RoboRealm software enabled certain colours to be isolated based on a certain bandwidth of values as seen by the camera; if the camera adjusted for the intense light then the object of interest no longer fell within the specified bandwidth in relation to the remainder of the image. This phenomenon was only observed on a small number of occasions but was not adjusted for as the auto exposure acted as more of a help than a hindrance.

An unexpected negative result of utilising a monitor was observed during the rotational testing conducted in the laboratory. The monitor was placed on a desk at the appropriate height in relation to the camera mounted on the Roomba. The software on the cleaning robot was fully capable of isolating the required image while the robots were in line. However, during operational conditions the two robots would not always be able to maintain this position, regardless of how the RoboRealm software attempted to ensure that this was the case. Once the monitor was rotated past a certain angle in the positive or negative direction the Roomba struggled to match the on-screen symbol. The edges of the symbol appeared to dissolve and no longer provided a binary image with sufficient clarity to correspond to the recorded image on file. In order to solve this, the lead robot would be required to have adjustments made to the path taken during the transport cycle; rather than turning 90° at a corner in order to maintain a short distance to the edge of the corridor, the main robot would be required to make a more gradual arc while cornering so that the Roomba was always capable of maintaining visual contact. Testing to determine the more efficient method of cornering would be required once both robots were available for experimentation.

The unidirectional communications was a deficiency in the system, which, outside of a laboratory experimental environment, would make for an unreliable cleaning tool should any problems occur during operation. Under the current configuration, the prototype was still reliant on a certain amount of human input although the system was intended to operate autonomously. The solution to this omission could be present within the current system with a small amount of editing within the software. As has been illustrated, the camera on one robot has the ability to recognise a command displayed on the monitor mounted on the second robot. This application could similarly be utilised to provide feedback from the Roomba to the main robot. In this hypothetical scenario, a small display monitor would be mounted on the vacuum robot facing the front, while a generic web-camera was mounted rear-facing on the same module box carried by the lead robot. Once the RoboRealm software was programmed to isolate a colour and symbol in the manner already used on the cleaning robot, the system would consist of bi-directional communication. The communications would remain dependent on limitations such as a clear line of sight between the robots, and the rare occurrence where lighting conditions were not favourable for detection. The introduction of a wireless LAN (Local Area Network) would be much more reliable and would not be restricted in the same manner as visual communication, however the inclusion of a new communications system would require the development and integration of further devices to the cleaning module. The use of bi-directional visual communications would require very little in terms of development since replication of the unidirectional communications would suffice.

The Roomba vacuum robot, as sold by the iRobot company, was, as detailed, constructed upon to act as a chassis for the cleaning system. Initially the size and shape of the vacuum appeared to be ideal for the desired application. The size, shape and inherent cleaning cycles formed a platform, which had the potential to be expanded and further developed into a more advanced robotic device. During testing and development, the shortcomings within the Roomba became apparent. As was briefly mentioned in Chapter 5, the micro-switch bumpers on the front of the robot resulted in a lack of information being transmitted at periodic intervals. The problem was not successfully diagnosed, but the vacuum failed to successfully transmit impact data to the laptop computer in use. This has been assigned as a fault to the particular unit is use, rather than a widespread flaw in Roomba model.

Based on the random motion approach to cleaning, the Roomba appears to be rather inefficient during a cleaning cycle. Beginning with a spiral motion, the robot cleans the area in which it began and continues until an impact occurs and following that, the vacuum operates in a random motion: driving until it hits an obstacle, turning a random angle and continuing forwards again. According to the manufacturers, this method of cleaning should result in every part of the floor being covered approximately three times. There is no guarantee though, that all areas have been cleaned! To achieve a reliable method of cleaning, a cleaning algorithm would be required to be developed for this purpose. The cleaning module, in its current configuration, does not contain the necessary hardware in order to initiate a reliable method of mapping or tracking.

During a realistic testing scenario, the Roomba vacuum would be required to be located at a charging station while not in use. This is to ensure that the vacuum robot has a fully charged battery once called upon to clean an area. Although not indicated in the section regarding command recognition, earlier testing had proven that the Roomba was capable of returning to, and being retrieved from the charging base station. The “force docking” command issued, during a cleaning cycle only, commanded the robot to cease cleaning and locate the charging station by means of tracking an infrared signal and mount itself in a manner where charging began automatically. In order to retrieve the cleaning robot a cleaning command was required to be issued; this resulted in the robot reversing off the charging station and beginning to clean the immediate area. Subsequently that command was then required to be superseded by the command to follow the lead robot to the desired location. Due to time constraints, the scenarios regarding the docking station were not correctly implemented into the testing procedures utilizing the visual analysis software.

9.1 Conclusion

This report has detailed the development, testing and results of an automated cleaning system prototype in its opening stages of research. A set of requirements that the system was intended to perform was supplied along with a number of restrictions applied. The restrictions included the required inclusion of the cleaning system into the existing IWARD robot platform as well as the issues regarding the installation of certain technologies due to the operating environment. A prototype was shown to be successful within the given parameters, but further development is required in order to improve upon the progress which was achieved. The conclusions summarise the successful aspects of the system, the areas in need of attention should further research be conducted, and the flaws discovered throughout the duration of the research period.

9.2 Thesis Contribution

Although cleaning systems have been previously developed, with a number of examples detailed in the Literature Review, most systems appeared to deal with map generation or the cleaning cycles once an area had been selected by the operator. In the study conducted, the robots programmed with the ability to autonomously navigate throughout an environment utilised systems such as the Cricket Indoor Location Tracking. However, in the environment intended for use for this automated cleaning system, such a solution was impractical. The IWARD robot had been developed with navigational abilities included and therefore attempting to replicate such results would have proven to be ineffective time management. A two-tier system was then developed: the lead robot carried out the existing functions of navigation and task scheduling and the cleaning module was assigned the task of vacuuming.

The project evolved to consist of two separate robots to form one automated cleaning system. The vacuum robot was provided with the means by which it could accept commands from the lead robot and successfully accomplish the task at hand. RoboRealm; a visual recognition software, was put to use as the core component within the vacuum robot where, upon isolation of a particular object, the command displayed by the main robot was recognised and it subsequently activated a sub-program. The majority of the requirements for the research were fulfilled and the cleaning system operated successfully during testing. Although testing was conducted in a laboratory environment with a substitute present for the lead robot, the cleaning system was considered a successful prototype.

The aforementioned work consisted of, mainly, utilising the visual analysis software to isolate particular objects in a variety of operating conditions. Shapes, colours and sizes of objects were taken into consideration while the software was being trained to successfully interpret the incoming communications. Secondly, external hardware was integrated into the system under the umbrella definition of sensor fusion. Proximity to the lead robot coupled with the size of the on-screen object resulted in an accurate input for decision making in order to protect both sets of hardware from impact; Roomba and IWARD robots.

Rather than introduce extra equipment for each task, it was decided upon by the author, that the technology already in use on the robot would be incorporated for multiple tasks. Although the solution presented for each task within the project was not always the optimal one, it was more appropriate in this case to complete each required function. Enabling the RoboRealm software and the externally mounted web-camera to participate in a multitude of tasks aided in maintaining a lower cost prototype, while also ensuring the weight carried upon the robot was minimised. A lesser amount of equipment results in a lower mass that the motors must carry, which in turn extends the battery life of the robot. With a smaller number of components, troubleshooting and maintenance became easier once the prototype had been completed and would provide the same advantage once a system had been further developed for hospital use.

The cleaning system operated within the facility in which it was developed, and had limited testing in environments external to that location, however to produce a more effective prototype system further development would be required in a variety of aspects relating to the robots.

9.3 Future Development

It is the opinion of this author that one of the primary tasks, for the continued success of this automated cleaning system, should be a redesign of the chassis for the external vacuuming. A number of tasks to be performed include the integration of all components into the design at an early stage to construct a practical, yet aesthetically pleasing platform where components are less exposed and have a measure of protection. The redesign would negate the need for a laptop computer to be carried, as was the case for this prototype system. A smaller amount of mass on the robot would increase battery life and enable a faster response time for speed adjustments.

In order for the vacuum robot to clean more efficiently, a two-stage solution would be required to be implemented in series. Stage one would involve the development of a system that could reliably track the movements of the robot. The method of robot tracking would be at the discretion of the operator, depending on the concept intended for efficient cleaning. The software development would be the second stage in that process. The combination of stages would, upon completion, enable an efficient, reliable and complete cleaning cycle to occur with a map visible to an operator upon completion.

Should a redesign of the chassis occur, it would be advisable to examine the vacuuming and brushing mechanisms. The Roomba robot does not possess any capability to clean an area where a fluid has been spilled on the ground. The intent of this cleaning system was to address the problem of dust in wards within a hospital environment; this was to aid in general hygiene standards while also combat the spread of infectious diseases present in dust particles. A wet cleaning cycle would also provide the same amount of cleanliness, but would also allow for a more expanded range of possible tasks to be performed, such as wet spillages in a concentrated area.

The integration of bidirectional communications to the system would enable the system to carry out the desired tasks more effectively. Examples would be the ability, by the vacuum robot, to inform the lead robot when a cleaning cycle has been completed to a satisfactory standard. Other areas of communication being particularly useful would be during transit where the cleaning robot may become obstructed and unable to continue behind the lead robot. A command on the vacuum robot could request assistance, inform the lead robot that no forward movement is possible at that time or any other pre-recorded command. This form of communication would also ensure that the other robot successfully received commands issued from the first. The system would therefore operate with a higher degree of certainty rather than having to use assumptions.

Most crucial to the system, in terms of future development, would be more extensive testing. As stated in numerous chapters, each process integrated into the system was tested and, in addition, experimentation took place on the completed system. The majority of the development procedures occurred in a laboratory setting and did not consist of the mobility required for more in-depth fault finding. The main robot was not present and as a consequence it was substituted for by using a desktop PC, which, as expected, only allowed for a limited degree of manoeuvrability.

9.4 Project Summary

The automated cleaning system for hospitals can be summarised by the following points:

- Successful unidirectional communications was established between two robots
- Bidirectional communications was not developed in practice
- The Roomba was capable of being led from one location to another for the purposes of cleaning

- Spot cleaning was deemed successful
- RoboRealm proved a huge success and was utilised with great success in almost all aspects of the system
- Two robots were combined to form an automated cleaning system, which was integrated into a larger project of which cleaning only formed a small portion
- Time constraints prevented a system consisting of further evaluation and integration of all potential attributes, which have been included in the “Future Development” section

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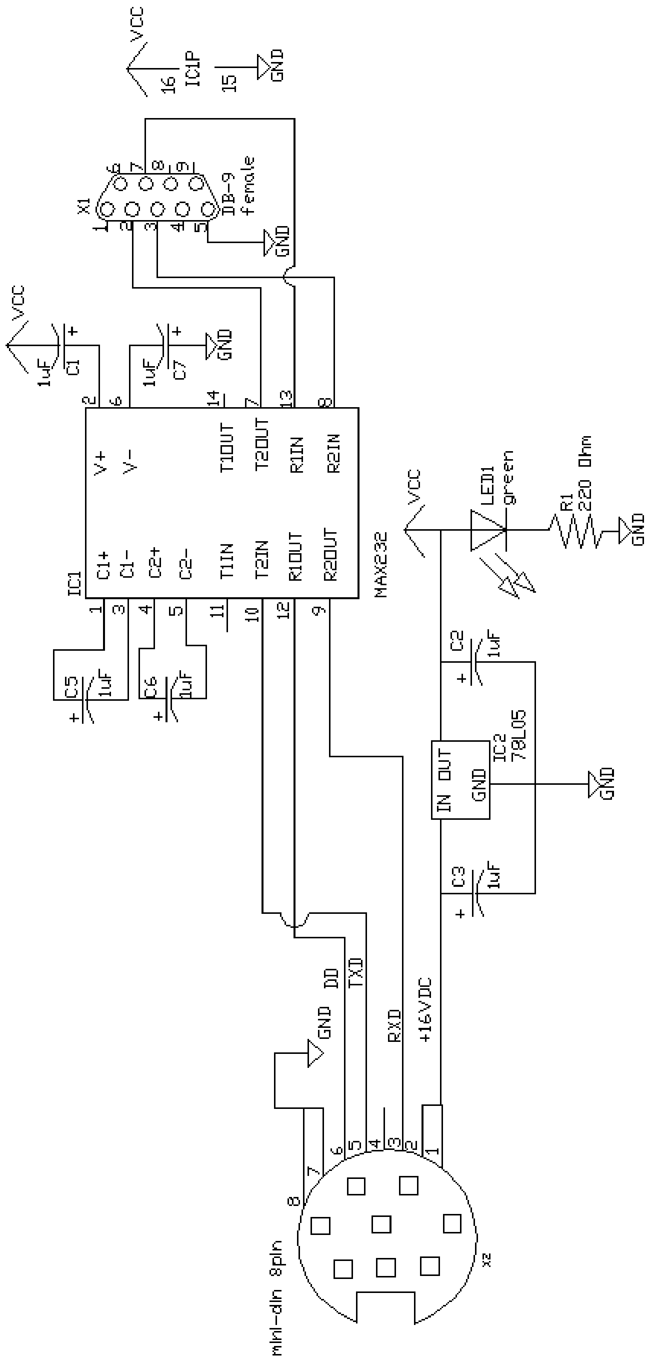
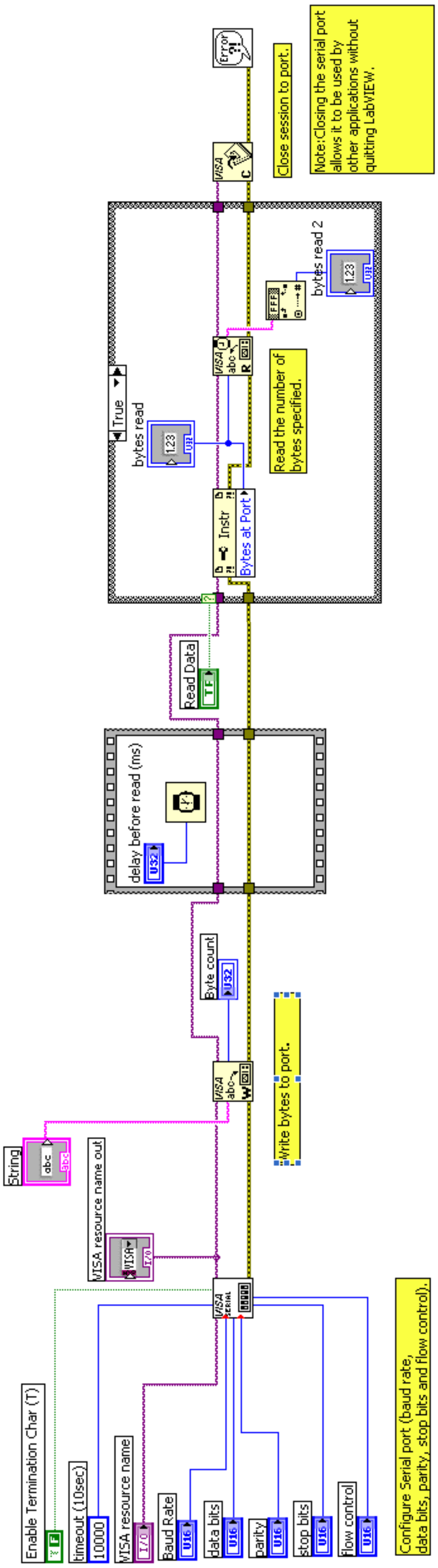
Appendix A: Circuit Diagram for power regulator / Serial Cable



Appendix B: Labview Serial port communications



Appendix C: RoboRealm “following” Program

Please note that a level of familiarity with the RoboRealm software is assumed.

- Serial

  Bps/Par/Bits = 115200 8 N1
  Hardware & Software flowcontrol disabled
  In field marked “Receive Sequence”; insert ”DB = [distance],”

- RGBFilter Blue

  Min Intenstity = 29
  Min Hue = 182
  Hue Hysteresis = 28
  ⦿ *White Mask*

- Shape_Match

  4 pre-saved images loaded for comparison

- VBScript Program

  Program contains instructions to return named of matched shape and confidence with which it matches the saved file

- If SHAPE_NAME contains “spot” then
- ..Load Program spot-clean.robo
- end_if

- If SHAPE_NAME contains “clean” then
- ..Load Program cleaning.robo
- end_if

- IRobot_Roomba

  Connect software to Roomba via Bluetooth

- If SHAPE_NAME contains “pause” then
- ..VBScript Program

Instructs Roomba motors to stop temporarily and immediately.

- end_if

- Centre of Gravity
- If SHAPE_NAME contains “follow” then
- ..VBScript Program

  Program contains parameters which must be met in order for the Roomba to successfully follow the main robot. The speed of the robot is determined by the size of the symbol as detected by the camera on the Roomba, the value as read by the Cricket deviceand how far away from the central vertical line the symbol centroid is. Rotation is based on the distance of the symbol to the left or right away from the central axis.
- end_if

RoboRealm “cleaning” Program

- IRobot Roomba

  Connect software to Roomba via Bluetooth

- VBScript Program

  This program is responsible for activating the cleaning cycle.

- Shape_Match

  2 pre-saved images loaded for comparison

- VBScript Program

  Program contains instructions to return named of matched shape and confidence with which it matches the saved file

- If SHAPE_NAME contains “follow” then
- ..Load Program follow.robo
- end_if

Appendix D: RoboRealm “spot-clean” Program

- IRobot_Roomba
- RGBFilter Yellow

  Min Intensity: 102
  Min Hue: 90
  Hue Hysteresis: 46
  ⦿ *White Mask*

- Flicker 3,70%
- Erode 2
- Shape_Match
- Centre of Gravity
- VBScript Program

  This program establishes the parameters needed in the remainder of the program such as the box size surrounding the symbol, the confidence in the detected symbol and the X & Y coordinates of the centroid of the symbol.

- If SHAPE_CONFIDENCE > 70 AND COG_BOX_SIZE > 180 AND COG_BOX_SIZE < 340 then
- ..VBScript Program

  This program allows the Roomba to navigate towards the symbol that has been previously matched in the RoboRealm sequence

- end_if
- if COG_BOX_SIZE < 180 OR COG_BOX_SIZE is null then
- ..VBScript Program

  While no correct symbol is detected the Roomba will periodically rotate on the spot in an attempt to acquire the relevant symbol or await the base robot to return

- End_if