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Control Engineering

An environmental sensor system for an autonomous litter collecting robot

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Summary

Every day more people live in cities. People consume and produce litter. So, when more people live in cities, more litter is produced. Litter generates litter: when there is already litter on the ground people seem to more easily contribute their litter to it. Keeping the streets clean all day will reduce this effect and, as a result, will have a double effect on the amount of litter on the streets. The cleaning robot, called JaClean, will assist street cleaners in the future by looking for litter and remove it when any is found.

The JaClean robot is divided in several modules. This project is on the environmental sensor system for the JaClean robot. The sensor system should provide sufficient information to perform the tasks of detecting obstacles and recognising litter. In addition, this information should be made accessible to the rest of the system.

A sensor combination has been selected for the robot that is able to perform the tasks they were selected for. It was proved with a demonstration that a SLRF is capable of detecting objects and that effective recognition can be done with a camera. During the may 2009 demo it became clear that a high quality camera is required to be able to cope with differences in ambient light. Overall the robot performed satisfactory although work needs to be done on robustness.

Based on this work several improvements are suggested for the continuation of the JaClean project. First of all, close range obstacle detection was not implemented due to the time budget available. However, for proper behavior of the robot it is necessary to have a similar sensor system present. It is recommended that this system is (further) developed in the continuation of the project. Secondly, the camera currently used for the JaClean robot has a too low resolution to enable recognition at larger distances. This way the robot is not able to comply with the wishes of the stakeholders. As a result a different camera should be used in the continuation of the project, one with a much higher resolution. Thirdly, the proof of principle pointed out that work needs to be done on the robustness of the JaClean robot.

Contents

1 Introduction

1.1 Context

Every day more people live in cities. People consume and produce litter. So, when more people live in cities, more litter is produced. Litter generates litter: when there is already litter on the ground people seem to more easily contribute their litter to it. Keeping the streets clean all day will reduce this effect and, as a result, will have a double effect on the amount of litter on the streets.

"Spot cleaning" is done manually by street cleaners. It is a heavy and unpleasant job. This situation can be improved. To achieve cleaner streets and make the job of street cleaners more pleasant and efficient a cleaning robot is designed. The cleaning robot, called JaClean, will assist street cleaners in the future by looking for litter and remove it when any is found.

A machine like JaClean requires some special attention since it is designed to operate among people. For this reason aspects as public acceptance and safety are extremely important in addition to the more common demands like robustness and cost efficiency.

1.1.1 Project structure

The JaClean project is divided into several modules, the modules are divided between the students that are working on the project. Figure 1.1 gives an overview of the modules.

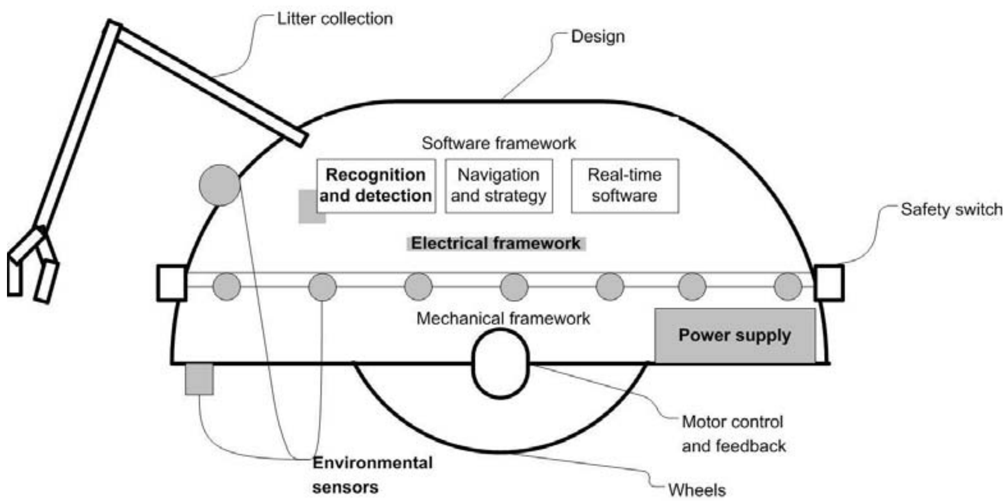


Figure 1.1: Project structure with the modules discussed in this report bold and marked grey

The modules discussed in this document, bold and marked in grey, are:

- Environmental sensors
- Recognition and detection

The students working on the other modules are:

- Rogier Kauw-a-Tjoe (Industrial design, MSc final project): Design, Market research, systems engineering
- Alexandros Frantzis Gounaris (Mechatronics, internship): Integration, Environmental sensors, Wheels, motor control and feedback
- Menno Bouma (Electrical Engineering, Bsc final project): Navigation and Strategy
- Hans de Boer (Mechatronics, pre MSc project): Wheels, Motor control and feedback, Real-time software

- Koen van der Heiden (Computer Science, MSc final project): Recognition and detection, Software framework
- Ruben Nahuis (Mechanical engineering, MSc final project): Litter collection, Mechanical framework

Several students from different disciplines participate in the project, making it a multidisciplinary project. In addition to the students working on the project various partners are involved in the project with different roles:

- University of Twente: Students at the University of Twente perform the preliminary design phases.
- Stichting Nederland Schoon: Litter is a subject that has gathered a lot of political and public interest, Stichting Nederland Schoon initiated the project. In addition Nederland Schoon sponsors the project.
- Demcon: Demcon is a company specialised in the design of mechatronic solutions, they support the design team with their practical experience and knowledge.
- HAKO: HAKO is a company specialized in street cleaning equipment, they will perform the last design stages and eventually produce and distribute JaClean. Hako Sponsors the project by means of parts.

1.1.2 Final requirements for this part of the project

A list of requirements has been put together in cooperation with the involved parties. The complete list is presented in Kauw-a Tjoe (2009). For the modules discussed in this document the following requirements (of the final product) are of importance:

- The robot needs to work among people and may not cause any hinder
- The primary areas of deployment will be city centres and malls
- The robot will not encounter cars
- The robot only collects plastic bottles, glass bottles, cans and paper
- The robot will run for 8 hours continuously
- The robot will work under the following environmental conditions:
  - -15 to +40 °C
  - Any weather condition in which a street cleaner would continue to do his job
- The design of the robot will be cost effective

1.2 Goals

As introduced in section 1.1 the modules discussed in this document are:

1. Environmental sensors
2. Recognition and detection

The first module aims at selecting a proper sensor system for the robot. This sensor system should provide sufficient information to perform the tasks of detecting obstacles and recognising litter under the environmental conditions mentioned in 1.1. In addition this information should be made accessible to the rest of the system.

The second module focuses on processing the data from the sensors and subtracting useful information. In this document only the implementation for the first prototype is discussed. This prototype is build for a demonstration in May 2009. This module should provide information on where the obstacles and litter is located with respect to the robot.

1.3 Approach

The goals mentioned in the previous sections are approached by means of a iterative design as described by figure 1.2.

The iterative design is based on multiple iteration steps in order to constantly improve the result. As a result multiple prototypes are created and evaluated. For the JaClean project the

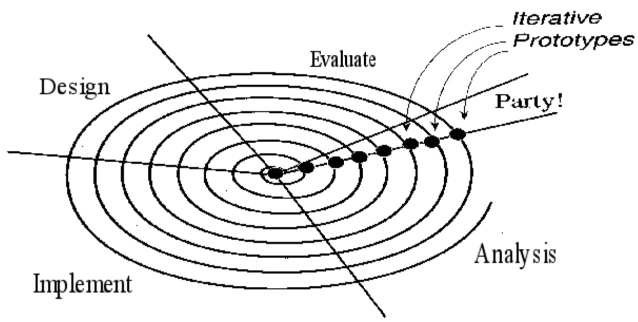


Figure 1.2: Iterative design, inspired by (Douglass, 1999)

delivery of these prototypes is centered around events in cooperation with the partners of the project. The original planning is:

- In May 2009 a demonstration on the Reinigings Demo Dagen.

  The main goal of this demonstration is to show the public our intentions.
- In October 2009 a proof of principle.

  The aim of this proof of principle is to show the stakeholders that the project is feasible.

1.4 Competitors and related work

Other people working on similar project will, most of the time, not use use the same requirements as this project. However, one can always learn from their successes and failures. For this reason several similar projects are briefly discussed in this section.

- OSR: The Outdoor Service robot, also called OSR (shown in figure 1.3), is a Japanese initiative for the development of a spot cleaning robot. The project has the same aim as the JaClean project. Since they have the same aim as the JaClean project they need a sensor system as well. Nishida et al. (2006) have chosen to use several Scanning Laser Range Finders (A sensor that measures distances of multiple points) and cameras. They achieved successful litter recognition, but need a large database of template images.

Figure 1.3: The Japanese Outdoor Service Robot (Nishida et al., 2006)

- Planetary vehicles(shown in figure 1.4): Planetary vehicles are designed for autonomous use. They are send to a planet to collect data, this data is transmitted back to earth. Object avoidance is an important task of these autonomous vehicles. In Se et al. (2004) area mapping using a 3d Scanning Laser Range Finder and using Cameras is discussed.

Figure 1.4: An Planetary rover Se et al. (2004)

1.5 Report structure

The report is structured according to the prototypes and goals of the project. In chapter two the first two goals for the May 2009 demonstration are discussed. These are reviewed in short from section 1.2:

- Selection of a competent sensor system
- Subtract the required information from the sensor system

Chapter three covers the selection of a sensor system October 2009 proof of principle. Chapter 4 discusses the performance of the robot at the proof of principle. Chapter five concludes the report with the conclusions and recommendations. The appendices include relevant information for future work that is too detailed for the report.

2 Environmental sensors, recognition and detection for the May 2009 Demonstration

The first part of the assignment was done for the May 2009 demo. The main goal for this demonstration was to show the public our intentions. It was important that there was something to show, not that everything was finished.

This chapter is structured according to the systems engineering approach described in section 1.3: Analysis, Design, Implementation and Evaluation.

2.1 Analysis

As described before, the May 2009 demo was more on showing our intentions to the public than having everything finished. Therefore, a reduced set of requirements was determined. The team did not go for the complete set because there was little time available to create a complex prototype. It was decided to go for a less complex solution. The reduced set of requirements concerning the modules *environmental sensors* and *recognition and detection* was: The sensor system needs to be able to

- recognise objects based on specific colors
- determine the distance (d) to these objects
- determine the angle (α) to these objects

This way still a robot that avoids one kind of objects and collects and other type of objects was shown. This is the aim for the final product.

The next section covers the design phase for the sensor system and the obstacle detection and litter recognition algorithm.

2.2 Design

Designing a sensor system that meets certain requirements is more on selecting a proper set of sensors than designing them. Therefore, an investigation was done to determine which sensors are best suited for the task. Although a reduced set of requirements was decided on, this investigation was still done with an eye on the final requirements, for time-efficiency reasons.

The investigation included the following sensors:

- (Scanning) Laser range finders (abbreviated as SLRF)
- Ultrasonic transceivers and Ultrasonic range finders
- Infra-red range finders
- Various principles with CCD-cameras
- Switches
- Thermal cameras
- Temperature sensors
- Inductive sensors
- Microwave radar

These sensors have been evaluated according to the following characteristics:

- Relevant information they can provide
- Purchase costs
- Particular conditions that can reduce the performance (if any)
- Can the sensor be used while moving / to detect dynamic objects
- Maximum sensing range
- Power consumption

In appendix A, all working principles are discussed and all characteristics are presented. In the next section only the result of the investigation is discussed.

2.2.1 Sensor types

Table 2.1 shows a summary of the results of the investigation on sensor types. The information in this figure is obtained from data sheets supplied by the manufacturers and websites from distributors.

	Operational temp range (degrees)	Restricting weather conditions	Cost estimation (€)	Info provided	Can be used while moving / with dynamic objects	Range (m)	Power consumption
Switch	-40 ~ +100	N	0,5	Distance	+	0	~0W
Laser range finder	-10 ~ +55	B	400	Distance	+/-	40	~3W
Scanning laser range finder	-10 ~ +50	B	1000	Distance	+/-	4	~10W
Ultrasonic transceivers	-30 ~ +80	N	10	Distance, (shape)	-	3	Unknown
Ultrasonic range finder	-30 ~ +80	N	30	Distance	-	6	~5mW
Infra-red range finder	-10 ~ +60	B	10	Distance	+/-	0,3	~150mW
Mono vision	-40 ~ +85	B	500	Colour, shape	+/-	NA	~2,6W
Stereo vision	-40 ~ +85	B	1000	Colour, shape, distance	+/-	NA	~5,2W
Mono vision with laser	-40 ~ +85	B	500	Colour, shape, distance	+/-	?	~4W
Mono vision with actuator	-40 ~ +85	B	500 + ?	Colour, shape, moveability	-	NA	Unknown
Thermal camera	-40 ~ +55	T	14000	Temperature, shape	+/-	NA	~4,8W
Thermal array sensor	+4 ~ +100	T	75	Temperature	+/-	NA	~25mW
Temperature sensor	0 ~ +70	T	15	Temperature	+/-	2	~25mW
Inductive sensor	-25 ~+70	N	25	Metal/ non metal	+	0,4	~4,8W

Abbreviations:
P : poor visibility (e.g. Heavy snow)
T : Environment = Body temperature
N : None

Table 2.1: Summary on sensor types

In the next subsection this information will be used to compose a number of combinations that are in theory capable of suppling the required information on object colour, distance and angle.

2.2.2 Sensor combinations

One of the things that was determined in section 2.2.1 is what relevant information the sensors can provide. In this section, this information is used to compose several sensor combinations. Every one of these sensor combinations can, in theory, provide all the required information on colour, angle and distance. For each combination the mayor issues with respect to their use in the project are presented. With this information the best solution can be selected. Since cost efficiency is a final requirement the estimated costs of the combinations is used in the decision as well.

One of the issues mentioned in the combinations is a Multi sensor system. A multi sensor system is a sensor system in which multiple measurement principles are used. It is considered to be an advantage due to the fact that if one measurement principle fails an other may still be operational. This provides graceful degradation of performance.

Colour sensor	Camera
Angle sensor	SLRF / Camera
Distance sensor	SLRF
Issues	Multi sensor system
	SLRF robust and proven
costs	€1800,-

Table 2.2: Sensor combination 1

Combination 1: Single camera with Scanning Laser Range Finder

The first possible combination (table 2.2) uses a (colour) camera to be able to distinguish between colours. Although a camera can also be used to determine the angle it can only be used for distance measurements under certain conditions (see appendix A), with limited robustness. For this reason the scanning laser range finder is added to the design. Since an SLRF can also determine angle to an object, this information can be used to combine the distance and object color.

Combination 2: Single camera with laser range finder

Colour sensor	Camera
Angle sensor	Laser range finder /Camera
Distance sensor	Laser range finder
Issues	Multi sensor system
	Pan system required: introduces additional mechanics
costs	€660,-

Table 2.3: Sensor combination 2

This combination (table 2.3) has a significant lower cost than the first. However, this is at a penalty. The laser range finder needs some mechanical construction to be able to create the SLRF functionality. This introduces additional mechanics and uncertainties in the performance.

Combination 3: Single camera with ultrasonic range finder

Colour sensor	Camera
Angle sensor	Camera
Distance sensor	Ultrasonic range finder
Issues	Multi sensor system
	Ultrasonic range finder is not bothered by weather conditions
	According to Cai and Regtien (1993) ultrasonic transceivers have problems to distinguish object that are close to each other
	Pan system required: introduces additional mechanics
	Slow refresh rate
costs	€190,-

Table 2.4: Sensor combination 3

In this combination (table 2.4) the range measurements are done with an ultrasonic range finder. The camera can provide information on colour and angle.

Although this is a low cost solution it has some significant problems. JaClean will work in crowded areas. In this case, the ultrasonic range finder will not be able to distinguish between different objects. As a result, it will not be able to find litter any more. In addition, the configuration will need some kind of mechanical construction to rotate the ultrasonic range finder.

Combinations 4: Single camera with infra-red range finder

Colour sensor	Camera
Angle sensor	Camera
Distance sensor	Infra-red range finder
Issues	Multi sensor system
	Range limitations
	Pan system required: introduces additional mechanics
	No implementations have been found costs
€170,-	

Table 2.5: Sensor combination 4

In this combination (table 2.5), the range measurements are done with an infra-red range finder as described in appendix A. The camera can provide information on colour and angle.

This is a cost-effective sensor combination. However, infra-red range finders have one significant disadvantage. Appendix A explains that infra-red range finders have serious range limitation which make them either suitable for longer range, or shorter range. This can be solved by using multiple sensors. However, distance measurements will still be limited to 4cm . . . 150cm. This implementation may be feasible. However, no implementations were found. Some risk will be involved.

Combination 5: Stereo vision

Colour sensor	Camera
Angle sensor	Camera
Distance sensor	Stereo vision (using 2 cameras)
Issues	Single sensor system
costs	€200,-

Table 2.6: Sensor combination 5

Stereo vision (table 2.6) is widely applied for distance measurements in experimental setups. The working principle is explained in appendix A. Although stereo vision has only one sensor type, it still is a good option for a reasonable price.

One should notice that in this combination one camera is used for two purposes. One as part of the stereo vision, one as sensor to sense colour and angle.

Combination 6: Camera with laser pointer

Colour sensor	Camera
Angle sensor	Camera
Distance sensor	Laser pointer with reflection to camera
Issues	Single sensor system (Only information from camera)
costs	€300,-

Table 2.7: Sensor combination 6

This combination (table 2.7) can be seen as a kind of home made laser distance sensor. As described in Appendix A several very successful implementations have been found.

The combination of a camera with a laser is in terms of sensor usage efficient. The camera can both be used as a sensor for colour and angle and in combination with the laser to measure distance.

Decision

From the six combinations described above, combination 3 has serious limitations. The combinations that remain (1, 2, 4, 5, 6) seem all suitable.

Since the sensor system needs to be cost-effective the next selection step is done based on costs. Selecting based on this criterion combinations 4, 5 and 6 remain due to the much lower purchase costs compared to 1 and 2. It was decided to implement combination 6 due to expected difference in implementation time. To repeat, combination 6 consists of a camera with a laser pointer.

However, when the laser that was ordered arrived, it turned out to be not strong enough. As it seems, this problem will occur with any eye-save laser. Unfortunately, by the time this was found out the remaining development time was too short to go for a different sensor combination. Therefore, it was decided to patch the problem with an other restriction: the objects have to be fixed size. The distance measurement can now be made with an algorithm as described in the following section.

2.2.3 Algorithm

This section covers the design choices on the algorithm used to interpret the data from the sensors. Due to the short development time that was available the decision was made to base the color recognition algorithm on an algorithm already implemented in the Twente Humanoid head and no further research was performed.

Colour recognition

The colour recognition implementation that is implemented for the May 2009 demo is based on manipulation of RGB (Red, Green, Blue) channels. By emphasizing the differences between a specified color and the other colors, a Black/White image can be created. In this image the pixels that have, for example, more red than green and blue will become white and the others black. A contour finding algorithm implemented in OpenCV (For more information: Willowgarage (2009)), an open-source software library for computer vision, was used to locate the coordinates of these white spots.

Angle estimation

The tasks colour recognition finishes with the finding of the coordinates of the object with a specific color. The horizontal location (pixel) coordinate can be used to estimate the angle, together with the following information concerning the camera:

- Camera angle(α)
- Number of horizontal pixels(p)

the focal length can be computed according to:

$FocalLength = l = (p/2)/tan(\alpha/2)$

The focal length can be described as the distance from the focal point to the lens. In this case, for a sharp image, the focal point is at the image sensor. As a result, the focal length is equal to the distance from the lens to the image sensor as represented in figure 2.1.

When the focal length is known the angle corresponding to a pixel can be calculated according to:

$angle = atan(x/l)$

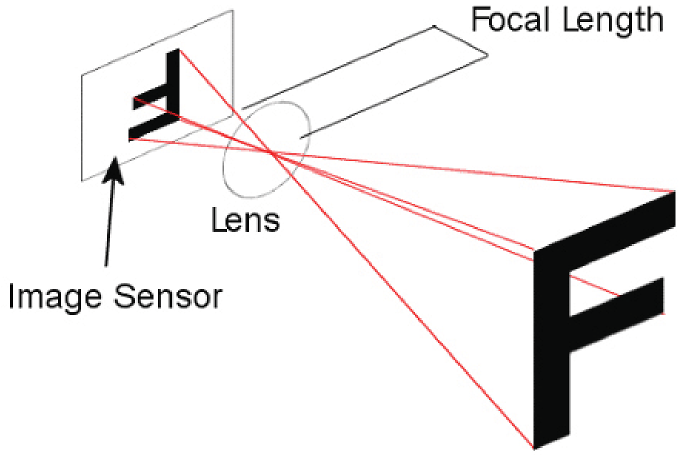


Figure 2.1: Focal length (Source: (itc, 2009))

Where x is the horizontal pixel number. In the case where $-p/2 < x < p/2$ and $-\alpha/2 < angle < \alpha/2$ pixel 0 (= -p/2) will correspond to $\alpha/2$ and pixel p (=+p/2) to $-\alpha/2$. This algorithm is commonly known as triangulation.

Distance estimation

The contour finding algorithm that is used for the localization of objects with a specific colour calculates a bounding rectangle. Of this rectangle all parameters are known (corner position, width, height). With this information, it can calculated at what angle the object starts and stops (Section 2.2.3) as shown in 2.2.

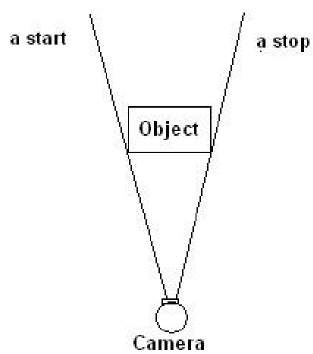


Figure 2.2: Start and stop angles of an object

The following formula provides the distance to an object with width w.

$distance = (w/2)/tan((maxangle - minangle)/2))$

The formula is based on triangulation. A drawback is that there is a minimum distance. This distance is determined by the opening angle of the camera and the size of the object. When the object width covers the entire width of the screen then maxangle is at its maximum and minangle at its minimum. When the object moves closer, this cannot be detected. Instead the minimum range is given as a result.

2.3 Implementation

As said in the previous section, the software is based on software already written for the Twente humanoid head. This software already contained an algorithm to detect yellow objects. In the implementation for JaClean this algorithm was simply replaced by the one described in the previous section.

During implementation, it became clear that it is not easy to get only a few, distinctive objects from an image. This is mainly caused by the many colour nuances in the image. In addition to this, there are also ‘stray‘ pixels with the same colour that to not belong to the object. To work around these problems, several smoothening filters and a threshold on the width of the binding rectangle were applied. Appendix B contains the pseudo code for the software.

While working with the camera, it became clear that the model that was chosen, which is the same as used for the humanoid head, is sensitive to ambient light. As a result, it is hard to get a reasonable repeatability in any uncontrolled environment.

2.4 Testing and evaluation

It was already mentioned that the distance measurement with an eye-save laser fails in this setup. This is due to the fact that the laser is not powerful enough. As a result, it cannot be detected on the camera over distance. In the chapter 3 the choice will be reviewed. It was also noted that the camera suffers a lot from ambient light. For this reason, an other camera will be used in the future. The colour recognition, angle estimation and distance estimation algorithms have been tested and work as they should in controlled circumstances.

2.5 Use in the may 2009 demo

For the demonstration in may 2009 a crash programme was followed due to problems with integration of the different modules. This crash programme resulted in the exclusion of the Environmental Awareness module. Instead, the robot followed a pre-programmed program. The technical goals were not met. However, the main goals of demonstrating the intentions was successfully completed and the audience was pleased.

Both the colour recognition and distance estimation algorithms cannot be use in the continuation of the project. This is due to the fact that the specifications on which they are based are no longer sufficient. The angle estimation algorithm can be used in the future. The software was written on short notice, as a result it is messy and undocumented. Since the bulk was not used in the continuation of the project the code was discarded and not added to the documentation.

3 Sensors for the October 2009 proof of principle

The second part of the assignment was done for the October 2009 Proof of Principle (PoP). The main goal of this proof of principle was to show that the concept of an autonomous litter cleaning robot is feasible. For the proof of principle it is important that we show all the functionality but the design does not have to be final yet.

This chapter is structured according to the systems engineering approach described in section 1.3: Analysis, Design, Implementation and Evaluation.

3.1 Analysis

As said before, should the robot have all functionalities it will eventually have. However, the functionalities do not have to be implemented in their final form. Or in other words: Everything should work, but it can work partially e.g. for one specific piece of litter.

The final requirements for the environmental awareness module, as discussed in section 1.1.2, is repeated for completeness:

1 The robot needs to work among people and may cause limited hinder
2 The primary areas of deployment will be city centres and malls
3 The robot will not encounter cars
4 The robot only collects plastic bottles (0,5l), cans(0,33l)
5 The robot will work work under the following environmental conditions:
   - -15 to +40 degrees
   - Any weather condition in which a street cleaner would continue to do his job

For the PoP some adjustments have been made:

- Requirement 4 is reduced to collecting cans only
- the temperature condition is ignored for now since it can be solved with heating and/or cooling elements
- The following requirements were added based on further insight and design choices that affect multiple modules of the project:
   - The sensor system should provide information to estimate angle and distance to litter and obstacles
   - The sensor system should work when the robot is moving and with moving objects

For this proof of principle the robot has to recognise and collect a specific kind of litter (cans, as mentioned before). All other objects should be avoided.

The following section covers the design phase of the sensor system.

3.2 Design

For the demo in may 2009 the design alternatives were already discussed. The results will be used as a basis for this chapter. Some changes need to be made since the requirements for the PoP are different from the *may demo*. Furthermore the evaluation of the demo pointed out that some of the techniques need revisiting.

First the sensors “camera” and “camera combined with laser” are revisited, then the possible sensor combinations for the October 2009 POP are compared and a decision is made.

In addition to localization and recognition, also close range obstacle detection is included.

3.2.1 Cameras - revisited

In the evaluation of the may 2009 demo, it was mentioned that the camera that was used was too sensitive to ambient light. This is a problem that needs to be solved in order for a camera to be a realistic sensor for JaClean.

Cameras are available in various qualities and pricing. The camera that was previously used is a relatively cheap type. It appears that there are cameras available reliable enough for the cleaning robot (around €500). Which one is the best price / quality ratio can only be determined after an extensive investigation.

The extensive investigation on cameras was not performed for the October 2009 POP. At the *may 2009 Demonstration* a manufacturer of cameras for outdoor-automotive purposes contacted the team. The company, Orlaco, offered one of their cameras to use for the POP. For both financial and schedule reasons it was decided to use this camera for the proof of principle and to evaluate the choice afterward. The camera that was selected has the following properties:

Property	Value
Restricting Conditions	Poor Visibility
Cost estimate	€500
Information provided	Various
Can be used while moving	+/-
Range	Not applicable for cameras
Power consumption	Max 2,6W

Table 3.1: Properties of the selected Orlaco camera

3.2.2 Camera combined with laser

In the evaluation of the *may 2009 demo*, it was mentioned that the distance measurement with an eye-save laser failed. This is due to the fact that the camera could not see the laser on the screen. This section discusses some solutions for this problem. Based on the research done for the *may 2009 demo* it is assumed that an optical line generator will be used to enhance performance.

A difficulty with this technique is that the maximum power per square centimetre must be always limited to prevent eye injury. A line generator divides the laser point over a line in a certain angle, this way more measurements can be taken simultaneously. A result is that as the distance increases, so does the line in length. The longer the line, the less power per unit length.

Solution 1: Use a more powerful laser

To be able to see the line over distance, a very powerful laser is required. However, a very powerful laser cannot be used on short range due to the risk of eye injury. So, using a stronger laser is not an option due to the safety aspect.

Solution 2: Use an optical band pass filter

To overcome the problem with the laser intensity, an optical band pass filter can be used. With this filter, only the specific red tint of the laser is passed through. The result is reduced background noise and better detection of the signal.

This solution has the following pro's and con's:

1 - The camera becomes dedicated to distance measurements
2 + The camera does not need very high specifications

Estimated costs, for ranging only are shown in table 3.2.

Part	Cost
camera (Unibrain)	€100
laser module (Farnell, FP-65/3LF-50)	€200
Optical bandpass filer (Newport, 2009)	€200
Total	€500

Table 3.2: Costs of ranging with a laser and a camera

Here the same camera is applied as used for the May 2009 Demo.

Various projects, (robotics, 2009; University, 2009; Robotics, 2009), implement this technique. Some professional implementations were found, but these implementations use an eye-unsafe laser. Although triangulation is a well known technique, the implementation in this setting needs some development time and performance with an eye-safe laser is uncertain.

Comparison and design choice

Since solution one has unacceptable drawbacks, the use of an optical band pass filter is the only acceptable solution mentioned.

3.2.3 Sensor combinations for recognition and detection

Just like in chapter 2 several sensor combinations are composed that could be fit in terms of providing the required information. The difference is that the demo in may 2009 aimed at recognition trough colour. This time the feature type used for recognition is not specified and this results in more possibilities. In Appendix A, the several sensors are discussed for use in the JaClean robot. The following combinations are based on this information:

Combination 1: Single camera with Scanning Laser Range Finder (SLRF)

Litter recognition	Camera
Angle measurement	SLRF / Camera
Distance measurement	SLRF
Issues	Multi sensor system
	SLRF robust and proven
costs	€2000,-

Table 3.3: Sensor combination 1

This combination (table 3.3) uses a camera to provide the information necessary for litter recognition. Although a camera can also be used to determine the angle, it can only be used for distance measurements under certain conditions, with limited robustness. For this reason, the scanning laser range finder is added to the design. Since a SLRF can also determine the angle to an object this information can be used to link a distance to a recognised piece of litter. In addition, the distance map created by the SLRF can be used to detect obstacles.

Combination 2: Single camera with laser range finder

This combination (table 3.4) has a significant lower cost than the first. However, this is at a penalty. The laser range finder needs some mechanical construction to be able to rotate it, this way a scanning laser range finder is created. This introduces additional mechanics and uncertainties in the performance.

Litter recognition	Camera
Angle measurement	Laser range finder/ (Camera)
Distance measurement	Laser range finder
Issues	Multi sensor system
	Pan system required: introduces additional mechanics
costs	€1060,-

Table 3.4: Sensor combination 2

Litter recognition	Camera
Angle measurement	Camera/ (ultrasonic range finder)
Distance measurement	Ultrasonic range finder
Issues	Multi sensor system
	Ultrasonic range finder is not bothered by weather conditions
	According to Cai and Regtien (1993) ultrasonic transceivers have problems to distinguish object that are close to each other
	Pan system required: introduces additional mechanics
	Slow refresh rate
costs	€590,-

Table 3.5: Sensor combination 3

Combination 3: Single camera with ultrasonic range finder

In this combination (table 3.5), the range measurements are done with an ultrasonic range finder. The camera is used for litter recognition and angle measurements.

Although this is a very low cost solution it has some significant problems. JaClean will work in crowded areas. Is this case the ultrasonic range finder will not be able to distinguish between different objects. As a result, it will not be able to find litter any more. In addition the configuration will need some kind of mechanic construction to rotate the ultrasonic range finder.

Combinations 4: Single camera with infra-red range finder

Litter recognition	Camera
Angle measurement	Camera / (Infra-red range finder)
Distance measurement	Infra-red range finder
Issues	Multi sensor system
	Range limitations
	Pan system required: introduces additional mechanics
	No existing implementations found costs
€570,-	

Table 3.6: Sensor combination 4

In this combination (table 3.6), the range measurements are done with an infra-red range finder. The camera is used for litter recognition and angle measurements.

This is a cost effective sensor combination. However, infra-red range finders have one significant disadvantage. Infra-red range finders have serious range limitation, which make them either suitable for longer range, or shorter range. This can be solved by using multiple sensors. However, distance measurements will still be limited to 4cm . . . 150cm. This implementation may be feasible. However, since no existing implementations were found is the performance uncertain.

Combination 5: Stereo vision

Litter recognition	Camera
Angle measurement	Camera
Distance measurement	Stereo vision (using 2 cameras)
Issues	Single sensor system
costs	€1000,-

Table 3.7: Sensor combination 5

Stereo vision (table 3.7) is widely applied for distance measurements in experimental setups, the working principle is explained in appendix A. Although stereo vision has only one sensor type it still is a good option for a reasonable price.

One should notice that in this combination one camera is used for two purposes. One as part of the stereo vision, one as sensor for litter recognition and angle measurements.

Combination 6: Dual camera with laser pointer

Litter recognition	Camera
Angle measurement	Camera
Distance measurement	Laser pointer with reflection to camera
Issues	Single sensor system (Only information from camera)
	Uncertainties on performance and development time, unproven
	Laser is not guaranteed to operate at low temperatures
Costs	€1000,-

Table 3.8: Sensor combination 6

This combination (table 3.8) uses the sensor discussed in section 3.2.2 for ranging and an additional camera for recognition. Several very successful implementations have been found.

Combination 7: Two scanning laser range finders above each other

Litter recognition	Two Scanning Laser range finders above each other
Angle measurement	SLRF
Distance measurement	SLRF
Issues	Scanning laser range finder are robust and proven
	Only estimates size
	Can never detect flat paper
	Single sensor system (Only information from scanning laser range finders)
Costs	€3000,-

Table 3.9: Sensor combination 7

When litter is most likely to be smaller than a specific size and obstacles are likely to be larger it can be used to “recognise” litter. The drawback is that the system provides little information to use for recognition. In addition the combination is somewhat costly. The properties of this technique are summarized in 3.9.

Note: This principle can also be achieved with ultrasonic and infra-red range finders. This will limit the performance as indicated earlier but also suppresses purchase costs.

Combination 8: Scanning laser range finder with tilt mechanism

During the investigation at some of the researches (Se et al., 2004), 3D scanning laser range finders are mentioned. These scanners can graph an accurate 3D map of the environment based on distance. However, they seem only available to space agencies. As an alternative, one scanning laser range finder could be mounted on a tilt mechanism (universitat Cheamnitz, 2009).

Litter recognition	3d SLRF (shape)
Angle measurement	3d SLRF
Distance measurement	3d SLRF
Issues	Scanning laser range finder are Robust and proven Accurate information on the shape of the surroundings, much like camera information The Scanning laser range finder needs to be best in angular resolution, accuracy and speed to be able to reconstruct a similar image and still have a high enough refresh rate. Can never detect flat paper Single sensor system
Costs	Unknown

Table 3.10: Sensor combination 8

Summary

The table 3.11 is used as an aid in decision making for the sensor system. In this table rating is applied subjectively. A combination either meets the criterion, fails it or there are uncertainties. These three ratings are represented by the numbers 0, 3 and 1. The grades noted are relative to the maximum grade possible.

Please that an original traffic light diagram uses colours instead of numbers.

Decision

The sensor combinations containing ultrasonic sensors score rather low in the summary. This indication is confirmed by the problems described previously in this chapter. These sensor combination are first discarded.

Although it could be possible to perform object recognition based on shape, no papers were found that mention an successful implementation. Due to the uncertainties on this point, the combinations that can only recognised based on shape are discarded.

Five combinations seem feasible for the proof of principle and do not introduce a lot of risk:

1 Camera with SLRF
2 Camera with panned LRF
3 Stereo vision
4 Camera with panned infra-red range finders
5 Dual camera with laser pointer

For the proof of principle limited time is available in combination with a solid deadline. Therefore, it was decided that combinations four and five introduce too much risk.

Of the remaining three combinations, combination one is the most robust combination. Based on this criterion, this combination 1 is chosen for implementation for the proof of principle.

	Single camera with scanning laser range finder	Single camera with panned laser range finder	Single camera with panned ultrasonic range finder	Single camera with panned infra-red range finder	Dual camera with laser pointer	Two scanning laser range finders above each other	Two panned ultrasonic range finders above each other	Two panned infra-red range finders above each other	Stereo vision	Scanning laser range finder with tilt mechanism
Can operate in the specified temperature range	3	3	3	3	0	3	3	3	3	3
Robust solution	3	1	0	1	1	3	0	1	1	3
No moving parts (low maintenance)	3	0	0	0	3	3	0	0	3	0
Can handle crowded scenes	3	3	0	3	3	3	0	3	3	3
Can be used on both short and longer range	3	3	3	1	3	3	3	1	3	3
Multi sensor system (Robustness benefit)	3	3	3	3	3	0	0	0	0	0
Can recognise litter	3	3	3	3	3	1	1	1	3	1
Score	**100,00%**	**76,19%**	**57,14%**	**66,67%**	**76,19%**	**76,19%**	**33,33%**	**42,86%**	**76,19%**	**61,90%**
Cost estimate	€ 2.000,00	€ 1.060,00	€ 590,00	€ 570,00	€ 1.000,00	€ 3.000,00	€ 200,00	€ 150,00	€ 1.000,00	€ 2.100,00

0 = No
3 = Yes
1 = uncertain

Table 3.11: Summary on sensor types in a traffic light diagram

3.2.4 Sensors for close range obstacle detection

Depending on the shape of the robot, additional information may be required to prevent the Cleaning Robot form riding into anything during turning and backward riding. There may be something it has not seen yet! If additional information is necessary, it will be information on relative free space around the robot similar to the information provided by parking assistants. The following sensors can provide this distance information:

Switch: Not ideal since it detects touch, the collision already took place when it is detected.

Laser range finder: Too expensive and bulky for this purpose

Scanning laser range finder: Too expensive and bulky for this purpose

Ultrasonic range finders/ Ultrasonic transceivers: Very suitable for this purpose: cheap, small and capable

Infra-red range finders: Not ideal since it fails at short range (< 4cm)

Stereo vision: Too bulky and expensive for this purpose

Mono vision with laser: Too bulky for this purpose

Based on the information provided, it is concluded that ultrasonic range finders are most suited if near-collision detection is required. This type of sensors is already successfully used in parking assistants and in some robots at the Control Lab of the University of Twente.

Short-range collision detection with ultrasonic range finders

The main task for the ultrasonic range finders on The Cleaning Robot is to double-check whether the space where the robot wants to go is actually free, as to prevent collision. Also called collision sensing. This space is defined as: 'The space where the robot would go in case of a 20° turn (left or right) and 10 cm straight riding' . In figure 3.1 this area is marked.

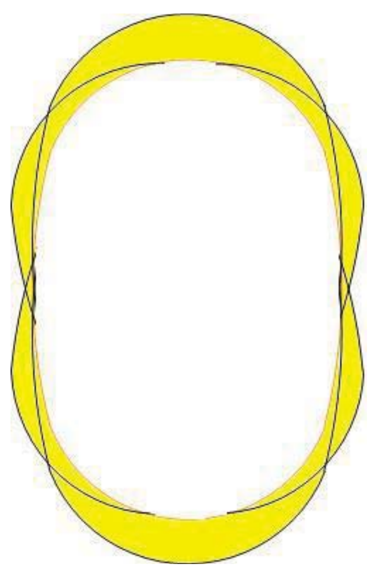


Figure 3.1: Critical zones for the JaClean Robot

As discussed in appendix A, of-the-shelf ultrasonic range finders are available. These modules can measure the distance to an objects within a certain angle under certain conditions. Figure 3.2 shows the most effective coverage of the critical areas with these sensors based on the opening angle.

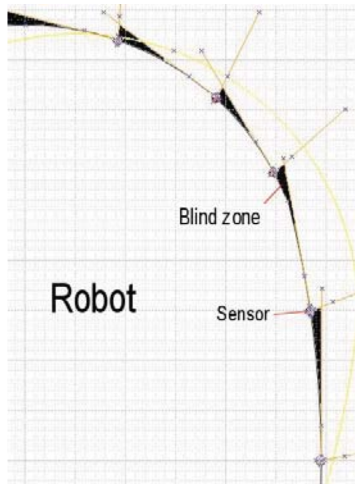


Figure 3.2: Coverage with 20 ultrasonic sensors

Two assumptions have been made for this design:

1 An obstacle is most likely not smaller than 1 cm * 1cm
2 The ultrasonic transducers on the range finders have an opening angle of 80° (Information obtained from supplier)
3 The robot has an approximate size of 90 * 60 cm and is ellipse shaped.

With these assumptions, five sensors are needed to cover a quarter of the area around the robot. If assumption one can be further loosened, this amount can be reduced. This configuration results in a total amount of twenty ultrasonic range finders around the robot. The Parallax ultrasonic range finders are about €20,- each, resulting in a total cost of €400,-.

It should be noted that the opening angle of the ultrasonic range finders as a module is only 40°. In addition to this, there is an other problem: ultrasonic range finders need an angle of more than 45 degrees with respect to an object to be able to detect it. This is illustrated in figure 3.3.

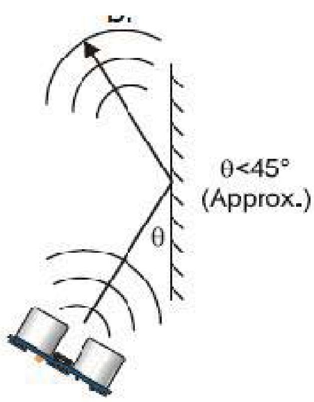


Figure 3.3: Detection problem due to deflection

To solve the problem of deflection and to be able to use the full opening angle of the ultrasonic transducers, crosstalk between different range finders can be turned into a benefit. Crosstalk can occur when two modules operate at the same time at the same frequency. None-the-less the other range finders can detect the signal, in some situations where the one that send it cannot detect it due to deflection. By using this phenomenon, it is easier to cover the area and the problem of deflection can be compensated for. Figure 3.4 illustrated this.

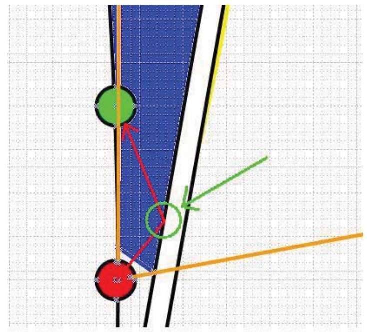


Figure 3.4: Solution to the deflection problem and performance optimization

The marked area marks the deflection of the signal send by the lower sensor. It cannot be detected by the lower sensor, as no reading can be done in this case. By also listening on the upper sensor the signal can be detected and the obstacle will become visible to the robot.

The detailed design of this principle, can be found in appendix C. Although the system should be present in the final model, it is not necessary for the proof of principle. Therefore, the design has not been implemented.

3.2.5 Where is the information used

As discussed in chapter one, the functionality of the robot has been allocated to a number of modules. The environmental awareness module is, as its name implies, responsible for the majority of the sensors. This module derives the information required for navigation from the sensor system.

The information from the close-range collision sensing (ultrasonic sensors) part is used directly by the navigation module. This part of the sensors is capable of quickly acquiring the required data and indicate whether the next move chosen by navigation is allowed. The information from these sensors is processed almost real time.

Figure 3.5 gives a schematic overview of the distribution of information.

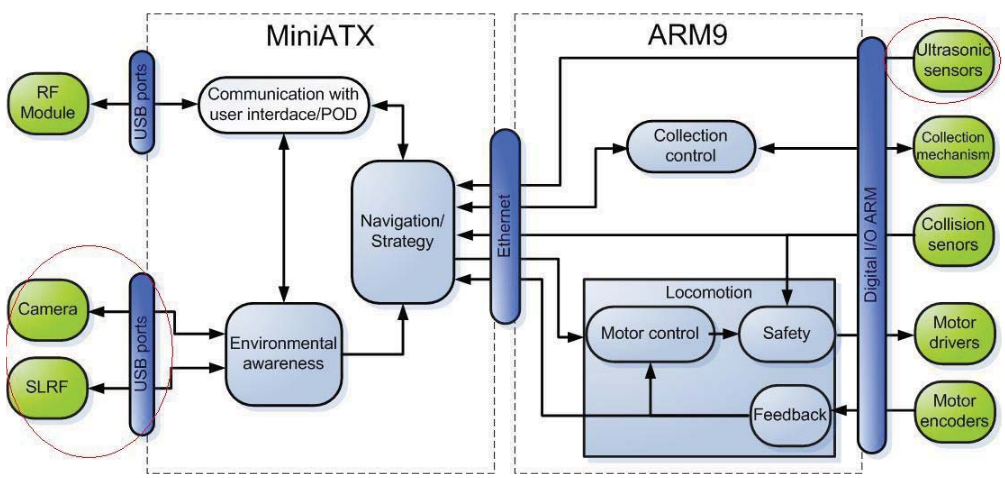


Figure 3.5: System information distribution with the part discussed in this report marked by circles

3.3 Implementation

Obtaining information (frames) from a camera and SLRF is no knowledge that is required for understanding the rest of the text. It is useful information for those who continue with the JaClean project. The topics are discussed in appendix D and E.

This section discusses the measurement error that can be present in the distance and angle measurements.

3.3.1 Measurement error for SLRF

To be able to give an indication on the measurement error of the scanning laser range finder some information on the device is required. The manufacturer provides the following information:

- Accuracy: 20mm − 1000mm ± 10mm, 1000mm − 4000mm ± 1%
- Angular resolution: approx. 0.36°

It is not specified whether the accuracy includes non-linearity, hysteresis, offset, zero-drift and noise. It is assumed that the specified accuracy is the overall accuracy or maximum deviation.

The operating temperature is specified at −10 − +50°C. Therefore, it is assumed that deviation caused by temperature change within this range is incorporated in the accuracy.

Based on the information provided, the following can be said on the measurement error:

- Distance measurement error: maximum at 4m is 40mm
- 'Vertical' error caused by angular resolution: max 12mm

The navigation module uses a map with tiles of 10 * 10 cm. This causes discretisation of the measurement values, making the measurement error acceptable.

3.4 Evaluation

3.4.1 Test results

As mentioned, close-range obstacle detection was not implemented. As a result no tests were done yet.

The camera has been tested for performance under different light conditions. These conditions were not characterized quantitatively since one would need a completely controlled environment. The tests were done under the following light conditions:

1. Only artificial light (tubular light)
2. Only daylight
3. A combination of 1 and 2

The tests indicated that the performance of the camera is extremely good compared with the performance of the model used for the demonstration in May. However, the camera is not completely immune to different kinds of light. Especially direct light effects the camera performance.

Tests on the camera in combination with the litter recognition software pointed out that the resolution and opening angle of the camera quickly limits the range for recognition. With an opening angle of 115° and a resolution of 795(H) x 596(V) pixels the recognition range is limited to 0.5m.

The SLRF that is used for the proof of principle is designed for indoor use. The manufacturer indicates that the device may have problems with direct light. This has not been verified. The performance of the SLRF is specified in the technical documentation, no tests were done. The SLRF has met all expectations while testing in combination with other parts of the system.

The software written to access the information form the camera and the SLRF has been tested on a stand alone basis and in combination with other parts of the system. Some general testing en experimenting showed that the software is performing its job properly.

3.4.2 Evaluation

The tests pointed out that the camera is somewhat effected by different kinds of light, especially direct light. Therefore, the camera should be shielded as much as possible. Since the robot will be used in urban areas, this shielding occurs partly by surrounding buildings (shade). Furthermore, the camera does not have to look upward. By directing the camera downward most direct light is avoided.

Due to the fact that the opening angle and resolution of the camera quickly limits the recognition range it should be considered to use a camera with a relatively small opening angle and high resolution. The consequence will be that the robot can see less at the same time.

4 Results: performance of the Proof of Principle(PoP)

This assignment ended with the proof of principle. Therefore the performance of the PoP is discussed in this section, this performance is based on tests done preliminary to the PoP.

4.1 Test structure

The JaClean project has been tested according to the following structure:

1. The module's were developed and tested according to the specifications
2. The module connections were tested by putting the modules together in a piece-wise manner
3. The system as en entity was tested

The coming sections discuss the systems tests. The status of the units is not discussed here. The status of sensors is discussed in chapter 3, the status of the electrical framework is discussed in appendix F. Other units are discussed in other documentation on the JaClean project.

First the the system tests are described. Secondly the results of the tests are presented. The chapter closes with a discussion of the results.

4.2 System testing

During system testing, the system as an entity has been tested. Tests have been done qualitatively on the following robot tasks:

1. Litter collection
2. Obstacle avoidance

The tests on litter collection were conducted as follows. A piece of litter was places outside the direct view of the robot. The behavior that is expected in this case is the following sequence:

1. Drive around in a predefined manner to scan the area for objects
2. One an object has been found, move closer to recognise it
3. If the object has been marked as litter move in and collect the litter

The tests on obstacle avoidance were conducted in the following way. Several obstacles were placed around the robot. Litter recognition was disabled to be able to isolate obstacle avoidance problems. The following behavior was expected:

1. Move around the area in a predefined manner to try to find litter
2. When an object is found continue the area scan while avoiding the obstacle

4.3 Results

The tests showed that the robot is capable to do litter collection and obstacle avoidance. Both sequences were completed successfully multiple times.

However, for the final product the robot needs to be reliable. Tests showed that although the robot was able to collect litter and avoid obstacles, it is not reliable yet.

4.4 Discussion

The test results show that the robot can collect litter and obstacles. However, more work is required on the robustness of the system. Since this is the first prototype of the robot, these results are not unexpected.

5 Conclusions and recommendations

5.1 Conclusions

The main goal of this project was to select the environmental sensors. The environmental sensors chosen for the robot are able to perform the tasks they are selected for. It was proved with a demonstration that a SLRF is capable of detecting objects and that effective recognition can be done with a camera. During the may 2009 demo it became clear that a high quality camera is required to be able to cope with differences in ambient light. It should be said that in the current implementation the resolution of the camera is too low to recognise at distance and the computer used is not powerful enough to allow recognition with sufficient speed.

Overall the robot performed satisfactory although work needs to be done on robustness.

5.2 Recommendations

Based on this work, several improvements are suggested for the continuation of the JaClean project.

1. Close range obstacle detection was not implemented due to the time budget available. However, for proper behavior of the robot it is necessary to have a similar sensor system present. It is recommended that this system is (further) developed in the continuation of the project.
2. The camera currently used for the JaClean robot has a too low resolution to enable recognition at larger distances. This way, the robot is not able to comply with the wishes of the stakeholders. As a result, a different camera should be used in the continuation of the project, one with a much higher resolution.
3. The proof of principle pointed out that work needs to be done on the robustness of the JaClean robot.

A Environmental sensors: design alternatives

In chapter 2 and 3 it was mentioned that the design alternatives for the environmental sensor have been investigated. This information is the basis for the sensor combinations that were composed to possibly meets the requirements. This appendix contains the results of this investigation.

A.1 Switch

Switches can be used to provide information about contact. They are switches that can be connected to output a digital signal: '0' on no contact, '1' on contact. Or the other way around.

Figure A.1: A typical example of a switch

The characteristics of a typical switch are shown in table A.1.

Characteristic	Value
Operational temperature range	-40 to +100 °C
Restricting Conditions	None
Cost estimate	€0,5
Information provided	Contact
Can be used while moving	+
Range	0m
Power consumption	About 0W

Table A.1: Characteristics (Farnell, 2009a)

A.2 Laser range finders

Laser range finders are devices that measure distance based on information obtained from a laser beam. Most models use Time of Flight or triangulation. Laser range finders are very accurate (1.5 mm)(Moduloc, 2009), have long range (0.1...40m for a black reflector surface)(Moduloc, 2009) and are reliable. Using a pan (and tilt) mechanism a distance image can be constructed.

Table A.2 shows the characteristics of a typical laser range finder.

A.2.1 Scanning laser range finders

Scanning laser range finders measure distance within their angle of view, creating a distance map of the environment. Since scanning laser range finders have centimetre accuracy (Hokuyo, 2005) some information about shape can be derived from the distance information provided. Scanning laser range finders can typically measure distance from 2cm up to 4 meters

Characteristic	Value
Operational temperature range	-30 to +55 °C
Restricting Conditions	Poor visibility
Cost estimate	€400
Information provided	Distance
Can be used while moving	+/-
Range	40m
Power consumption	About 3W

Table A.2: Characteristics (Opticsplanet, 2009)(Moduloc, 2009)(SICK, 2009)

(Hokuyo, 2005) some go up to 30m. Scanning laser range finders have a large scanning angle (240...270 degrees). The resulting information is comparable with a laser range finder with pan mechanism.

Table A.3 shows the characteristics of a typical scanning laser range finder.

Characteristic	Value
Operational temperature range	-25 to +50 °C
Restricting Conditions	Poor visibility
Cost estimate	€1500
Information provided	Distance
Can be used while moving	+/-
Range	4m
Power consumption	About 10W

Table A.3: Characteristics (Robotshop, 2009a)(SICK, 2009)

Figure A.2: A typical scanning laser range finder (Robotshop, 2009a)

A.3 Ultrasonic transceivers

Ultrasonic transceivers can send and receive ultrasonic pulses (frequency>20kHz). Ultrasonic waves are reflected by most materials. When an ultrasonic pulse is send and the time is measured until the pulse returns one has a measure for the distance between the transceiver and the object that reflected the pulse (typical from 3cm up to 3m, accuracy 1-3 centimetres). In addition to this feature more information about the shape of the object can be obtained when the distortion of the reflected pulse is studied. Several studies (Streilein et al., 1998)(Ecemis and Gaudiano, 1998)(**?**)(Liu, 2006) indicate that the information included in this distortion can be used for effective and reliable recognition of objects with a specific shape. Unfortunately there is not enough information in an ultrasonic echo to do anything else but signature matching.

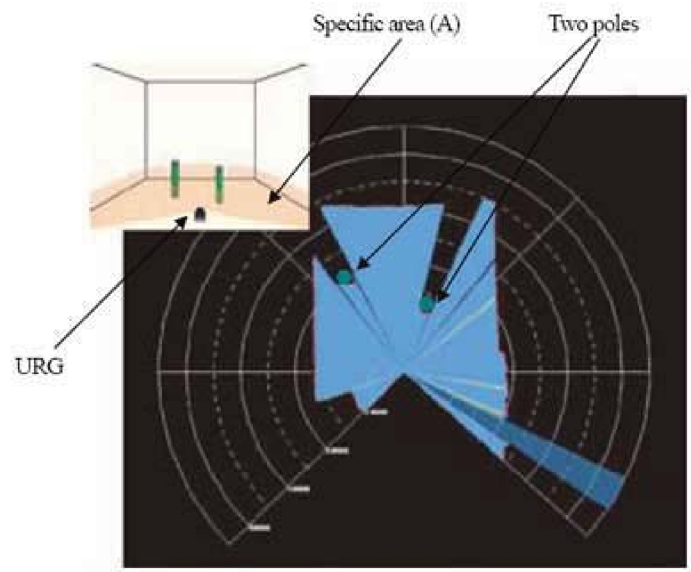


Figure A.3: Example of a distance map obtained from a scanning laser range finder (Robotshop, 2009a)

Figure A.4: A typical ultrasonic sensor (Farnell, 2009b)

The characteristics of a typical ultrasonic transceiver are shown in table A.4.

Characteristic	Value
Operational temperature range	-30 to +80 °C
Restricting Conditions	Measurement varies with temperature and humidity
Cost estimate	€6
Information provided	Distance
Can be used while moving	-
Range	3m (for distance measuring)
Power consumption	Minimal, depending on support circuit

Table A.4: Characteristics (Prowave, Unknown)(Bu, 2005) (Farnell, 2009b)

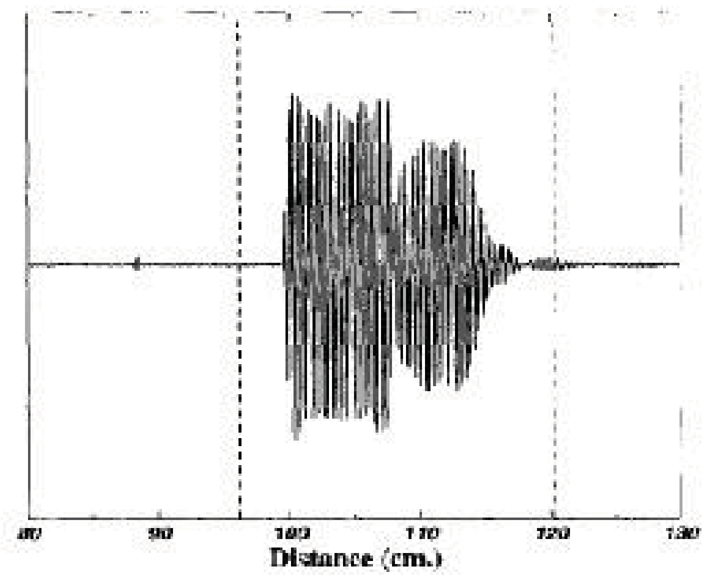


Figure A.5: Example of a distorted return pulse (Ecemis and Gaudiano, 1998)

A.3.1 Ultrasonic range finder

Ultrasonic range finders are ultrasonic transceivers with some electronics, dedicated to measuring distance. One can only obtain distance information from these sensors, but a lot of work is already done for you. Ultrasonic range finders go up to 6m and are available with temperature compensation due to the dedicated use.

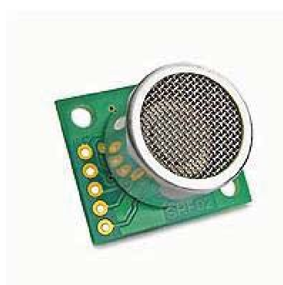


Figure A.6: A typical ultrasonic range finder

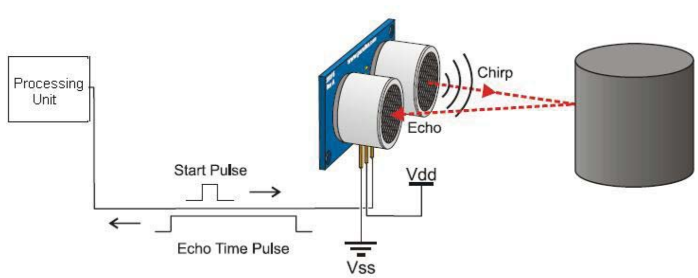


Figure A.7: Ultrasonic range finder: working principle (Parallax, 2008)

Table A.5 shows the characteristics of a typical ultrasonic range finder.

Characteristic	Value
Operational temperature range	-30 to +80 °C
Restricting Conditions	Measurement varies with temperature and humidity
Cost estimate	€30
Information provided	Distance
Can be used while moving	-
Range	6m
Power consumption	about 5mW

Table A.5: Characteristics (Prowave, Unknown)(Bu, 2005)

A.4 Infra-red range finders

Infra-red range finders use the angle of return of an infra-red beam for distance measurement. The following figure illustrates this principle. Infra-red range finders are available for different distances, examples are (Robotshop, 2009b):

- 10cm...80cm
- 4cm...30cm
- 20cm...150cm

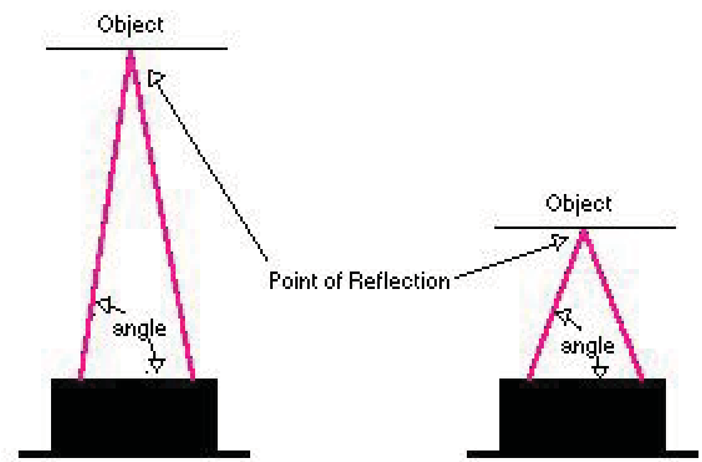


Figure A.8: Infra-red range finder: working principle

In table A.6 the characteristics of a typical infra-red range finder are shown.

Characteristic	Value
Operational temperature range	-40 to +60 °C
Restricting Conditions	Poor Visibility
Cost estimate	€10
Information provided	Distance
Can be used while moving	+/-
Range	various (described before)
Power consumption	150mW

Table A.6: Characteristics (Farnell, 2009c)

A.5 Cameras

Digital cameras are widely used in robotic applications. They take a series of 2d images of the environment. Different algorithms can be used to obtain information from these images. Digital cameras are available in colour and in grey scale.

Cameras are available in various qualities and pricing. Which one is the best price/ quality ratio can only be determined after quite a lot of research.

Table A.7 shows the characteristics of a Unibrain camera.

Characteristic	Value
Operational temperature range	-10 to +50 °C
Restricting Conditions	Poor Visibility
Cost estimate	€110
Information provided	Various
Can be used while moving	+/-
Range	NA
Power consumption	Max 1W

Table A.7: Characteristics (Unibrain example)(Unibrain, 2009)

Cameras can be used for various measurement principles. The most well known are briefly discussed.

A.5.1 Mono vision

Mono vision uses a single camera, information one could obtain with this technique is:

- colour of an object
- shape of an object
- does the object look like .... (matching)
- distance (optical flow)

Distance measurement can be done by using a single camera and taking multiple shots of a object at different positions. When knowing the exact difference between two positions the distance to object can be derived, this principle is called optical flow (Beauchemin and Barron, 1995)(van der Heiden, 2009)

Characteristics are the same as noted in the general part on cameras.

A.5.2 Stereo vision

Stereo vision uses the information of two cameras. By using a stereo vision algorithm a disparity image of the two images obtained by the cameras can be calculated (SRI, 2009). This is done on basis of similar interest points in both pictures (for example by using image features). Once objects are recognised their relative location can be determined by using the disparity image. (van der Heiden, 2009)

Characteristics are the same as noted in the general part on cameras.

A.5.3 combined with laser

When combining a camera with a laser a primitive laser range finder can be created. Distance can be measured according to the horizontal position of the laser point on the screen.

A difficulty with this technique is that the maximum power per square centimetre must be always limited to prevent eye injury.

A line generator can be added to enhance performance. A line generator divides the laser point over a line in a certain angle, this way more measurements can be taken simultaneously. An

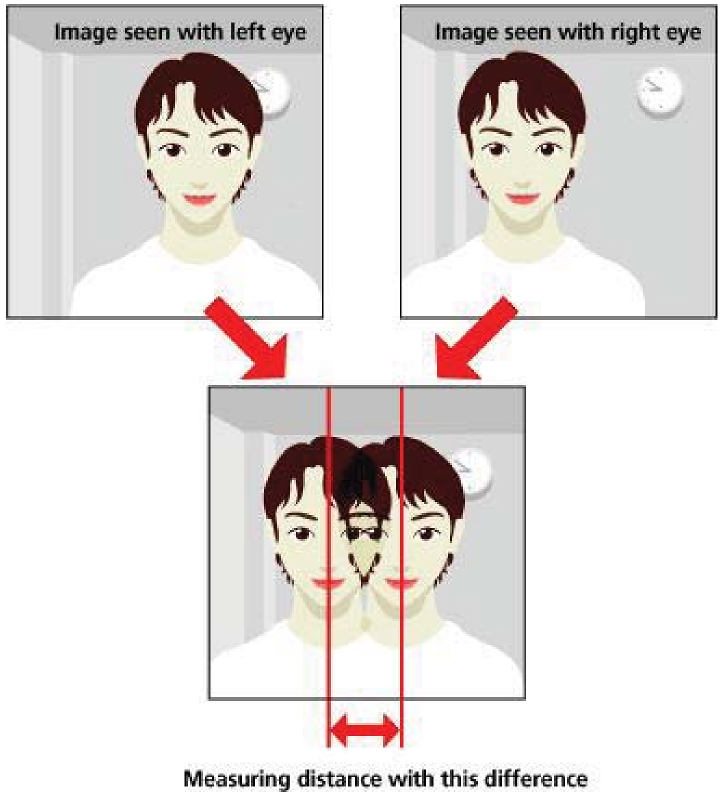


Figure A.9: Working principle of stereo vision (NEC, 2009)

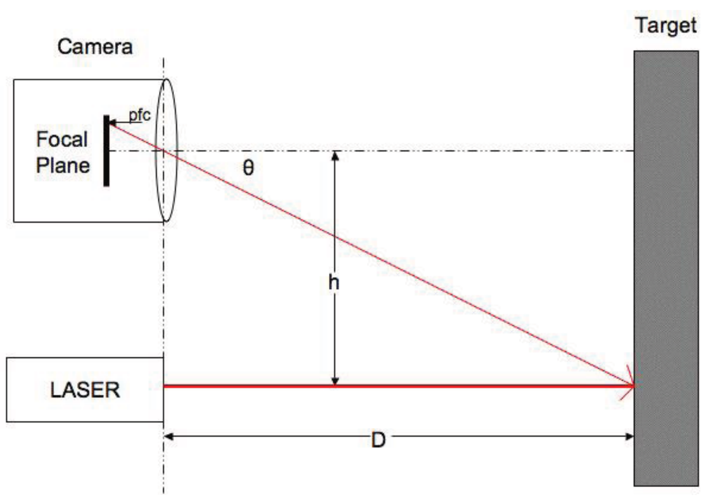


Figure A.10: Camera combined with laser: working principle

other option to improve performance is to add a pan and tilt mechanism. The technique with any of the above two improvements provides the same distance info as a scanning laser range finder.

Various projects (robotics, 2009)(University, 2009)(Robotics, 2009)) implement this technique. Some professional implementations were found (www.SICK.com), but these implementations use an eye-unsafe laser. Although triangulation is a well known technique the implementation in this setting needs some development time and performance with an eye-safe laser is uncertain.

Part	Cost
camera (Unibrain example)	€100
laser (Farnell, 3mW)	€200
Total	€300

Table A.8: Costs

Typical characteristics of this same are the same as with the single camera, except for the price. They are shown in table A.9.

Characteristic	Value
Operational temperature range	-10 to +40 °C
Restricting Conditions	Poor Visibility
Cost estimate	€300
Information provided	Distance
Can be used while moving	+/-
Range	NA
Power consumption	Max 4W

Table A.9: Characteristics

A.5.4 combined with actuator

The combination of a camera with an actuator emerged from a brainstorm. The idea was issued as a possible solution for the problem that there is no way to measure the mass of an object without weighing.

When an actuator is used to apply force on an object the object gives a certain reaction (or no reaction at all). This reaction can be detected with a camera. From this reaction, for example a vibration, information can be derived about the mass or 'move-ability' (can the object be moved) of an object. Examples of possible actuators are:

- poke, to directly apply force
- Apply force by means of moving air

A.6 Thermal cameras

Thermal cameras give a image of radiated heath. Generally the exact temperature of a specific point is given and the rest of the image with respect to that point.

Information on the temperature of an object can be used to determine if something is likely to be living or not. Possible problems may rise when objects are present with a temperature that could be that of a living organism, furthermore the effect of insulating clothing has to be addressed.

The characteristics of a typical thermal camera are shown in table A.10.

As an alternative a thermal array sensor can be used. A specific example, (Robotshop, 2009c), can measure temperature of 8 adjacent points up to 2 meters away. A pan and tilt mechanism can be used to construct a thermal image. (Servo for panning can be controlled by the module)

Table A.11 shows the characteristics of this thermal array.

A.7 Temperature sensors

In addition to a thermal camera, temperature can also be measured with an Infra-red temperature sensor (Like (Raytek, 2009)). These sensors measure temperature wireless with an opening angle of about 14°C. Because of this large opening angle the range for accurate measurements

Figure A.11: Example of the image generated by a thermal camera

Characteristic	Value
Operational temperature range	-40 to +55 °C
Restricting Conditions	Poor Visibility
Cost estimate	€14000 (Flir recommended model)
Information provided	Temperature, shape
Can be used while moving	+/-
Range	NA
Power consumption	Max 4,8W

Table A.10: Characteristics (Flir, 2005)

Characteristic	Value
Operational temperature range	+4 to +100 °C
Restricting Conditions	Environment = body temperature
Cost estimate	€75
Information provided	Temperature
Can be used while moving	+/-
Range	NA
Power consumption	about 25mW

Table A.11: Characteristics (Robotshop, 2009c)

is limited. Infra-red temperature sensors can have different measurement ranges, but typically > 0 degrees.

Table A.12 shows the characteristics of a typical thermal sensor.

A.8 Inductive sensors

Inductive sensors can be used to detect metals based on the principles of induction. They have a short range (<50mm) and are very robust.

The characteristics of a typical inductive sensor are shown in table A.13.

A.9 Microwave radar

Radar for robotic application seems, unfortunately, only to be present in papers.

Characteristic	Value
Operational temperature range	0 to +70 °C
Restricting Conditions	Environment = body temperature
Cost estimate	€20
Information provided	Temperature
Can be used while moving	+/-
Range	2m
Power consumption	about 25mW

Table A.12: Characteristics (Raytek, 2009)

Figure A.12: An inductive sensor (Farnell, 2009d)

Characteristic	Value
Operational temperature range	-25 to +70 °C
Restricting Conditions	None
Cost estimate	€30
Information provided	Metal/non-metal
Can be used while moving	+
Range	0,4m
Power consumption	about 4,8W

Table A.13: Characteristics (Farnell, 2009d)

B Pseudo code of vision software for May 2009 demo

```
start camera

while (running) {
  grab frame
  split frame in RGB

  //find litter
  empasize litter colour in frame and store in temp image
  smoothen the image (digital filtering) to reduce noise
  find the contours
  for (all contours that are large enough (noise reduction)){
    calculate the binding rectangle
    //calculate angle to litter
    calculate angle to center of binding rectangle
    //calculate distance to litter
    calculate angle to left side of binding rectangle
    calculate angle to right side of binding rectangle
    calculate distance according to known size and angles
  }

  //find obstacles
  empasize obstacle colour in frame and store in temp image
  smoothen the image (digital filtering) to reduce noise
  find the contours
  for (all contours that are large enough (noise reduction)){
    calculate the binding rectangle
    //calulate angle to obstacle
    calculate angle to center of binding rectangle
    //calculate distance to obstacle
    calculate angle to left side of binding rectangle
    calculate angle to right side of binding rectangle
    calculate distance according to known size and angles
  }

  output all information
}
stop camera
```

C Thoughts on the implementation of close range obstacle detection

In chapter 3 the options for close-range obstacle detection were discussed. The conclusion was that ultrasonic sensors are most fit for this purpose. Furthermore some ideas on working around some problems inherent to ultrasonic sensor were discussed. Unfortunately there was no time to implement close range obstacle detection, but some thoughts were spend on the implementation. This appendix contains these thoughts for future use. Some day close range obstacle detection will be implemented.

C.1 The proposed platform

The technique will be implemented on a ARM9 - 200MHz processor board with FPGA, this board is already present on the robot to perform other tasks. The ARM9 processor is not suitable for time of flight measurements, so this task will be performed on the FPGA. The implementation of the data will be done on the ARM9 processor since software programming on a soft core processor is much more flexible than on an FPGA.

C.2 Communication

Part of the software will be implemented in FPGA and part in the soft-core processor. In addition the information that is obtained needs to be transmitted to the rest of the system. These are the (boundary) communication details:

- ARM9 processor -> Rest of the system:
  - For the rest of the system the only relevant information is if the area is free to move to, this will be the only information that is provided to the rest of the system.
  - Format:
- ARM9 processor -> FPGA:
  - To be able to implement the technique effectively, the ARM9 needs to be able to trigger a specific sensor to send a pulse.
  - Format:
- FPGA -> ARM9 processor
  - In return the ARM9 needs to know which sensor has received the sensor after what time delay. To increase the data set information all sensors should be presented every time. Since it is possible that not every sensor receives the pulse a time delay should be implemented. A good time delay would be: (length of the robot*2) / 340 m/s (speed of sound) = 6ms. If a signal takes more than this time to arrive the information will be of no relevance. For flexibility's sake the time delay could be make adjustable.
  - Format:

C.3 FPGA logic structure

Figure C.1 shows a possible implementation on the FPGA. This implementation makes it possible to sens a ultrasonic pulse from a specified range finder and check on all range finders for a received pulse. The results are stored in a matrix, the same as used for the FPGA->ARM9 communication. The 'Select transmitting sensor' block corresponds with the ARM9->FPGA communication.

Measuring Time of flight,distance, with ultrasonic transducers is already implemented in the CE 'gaming humkes'. Implementing the system using this implementation would show in significant cost reduction but higher development time.

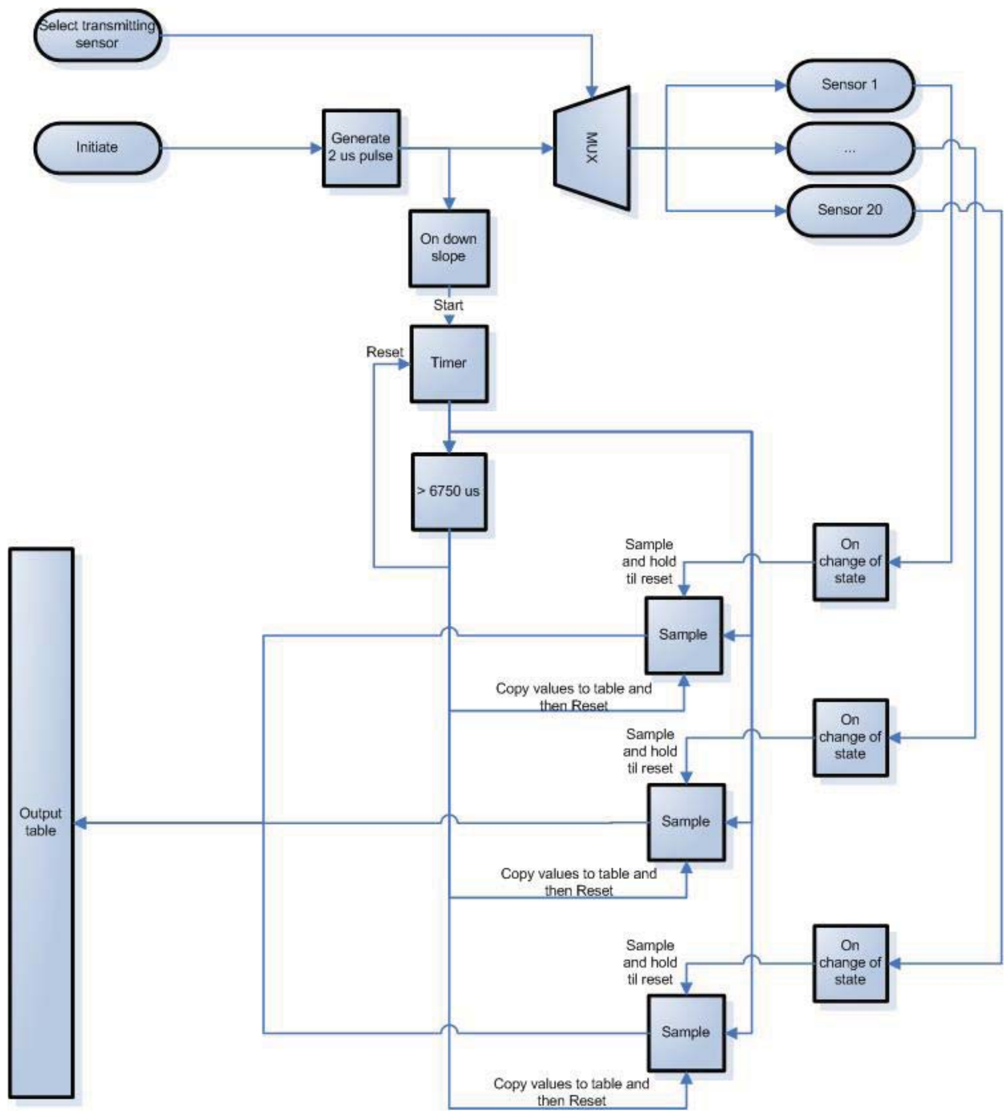


Figure C.1: A possible implementation for the FPGA

Move	Allowed
Left turn (20°)	1: Yes, 0:No
Right turn (20°)	1: Yes, 0:No
Forward riding (10cm)	1: Yes, 0:No
Backward riding (10cm)	1: Yes, 0:No

Sensor number	[]

Sensor number	Time of flight
1	[us]
2	[us]
...	[us]
20	[us]

D Additional information on the camera used for the October 2009 POP

In chapter 3 it was mentioned that an Orlaco camera was used for the October 2009 POP. The camera and the connection from the computer to the camera were not further elaborated. Therefore it is done in this appendix, for future use.

D.1 The camera

The camera, model CCC SLR, is a CCD type camera and is mounted in a waterproof enclosure. Furthermore it is shock resistant according to IEC 60068-2-27 shock test. The camera has a resolution of 442*568 pixels and is available with the following horizontal opening angles: 17, 32, 49. 78, 102 and 115 degrees (Orlaco (2009)). The camera is equipped with an analogue video output that confirms to the PAL standard. More information on the camera is available in Orlaco (2009).

Figure D.1: The camera used for JaClean

The Camera has an analogue output (PAL), while the Motherboard only has digital inputs (USB, COM, ETHERNET). Some kind of translation step needs to be performed to connect these two.

D.2 The connection

To connect the analogue output of the camera to a digital input of the motherboard a USB video grabber has been used.

A USB video grabber is a device that can be addressed as a USB camera. It has the possibility to connect a device with an analogue video output. The information from this input is presented as the 'USB camera'. The video grabber that was selected for the JaClean project has the following specifications:

D.3 Accessing the data from the camera

For the image processing software an open computer vision library called OpenCV (Willowgarage (2009)) is used. The video grabber is compatible with the OpenCV library and hence the

Figure D.2: The video grabber used for JaClean

standard frame grabbing function (cvCaptureFromCAM) can be used. OpenCV and documentation can be downloaded at no charge from Willowgarage (2009)

Specification	value
Connections	S-video, Composite, USB, audio
Supported formats	NTSC, PAL, SECAM
Max. resolution	720*576 pix.
Frame rate	30 fps

Table D.1: Video grabber specifications

E Additional information on the Hokuyo URG 04-LX SLRF

E.1 Some background on the URG 04-LX

The URG 04-LX is a scanning laser range finder manufactured by Hokuyo. It uses a class one (eye safe) laser to measure distances up to 4m. The manufacturer specifies the following characteristics (Hokuyo (2005)):

The URG-04LX has two options for connection: USB2 and serial. The USB2 connection uses a CDC implementation which means that it can be addressed as a serial connection. This way software written to be used with the USB2 connection can be used with the serial connection and the other way around. For the JaClean Proof Of Principle (POP) a serial connection is used, for this connection are no drivers required. Nevertheless the drivers will be added to the files for future use since using USB2 connection does require the use of these drivers.

Unfortunately the URG-04LX cannot be powered from USB, the manufacturer advices to use a power supply of 5V 7,5W (1,5A). The power supply can be connected to the same connector as the RS232 connection.

Figure E.1: URG 04-LX

The communication with the SLRF is based on a command set called SCIP.

E.2 The command set

The command set is described in the document 'URG Series, Communication Protocol Specifications, SCIP-Version2.0' provided by Hokuyo, the manufacturer, and included for reference.

E.3 Encoding and decoding

The document describes the following encoding algorithm that is used to compress the data obtained from the SLRF:

- split in 6 bit sequences
- add 0x30 to each sequence

This coding enables transmission of information trough ASCII characters, commonly used for communications trough RS232. By inverting this process the decoding algorithm is derived:

- subtract 0x30 from each character
- shift all characters n*6 time to the left, with n as follows: 4,3,2,1(4 ASCII values example)
- Add all values

With this algorithm the original data values can be obtained.

E.4 Resources provided by the manufacturer

To make the use of the command set easy under various operating systems, Hokuyo supplies a number of source and header files:

Header files:

- delay.h
- detect_os.h
- getTicks.h
- meth_utils.h
- scip_handler.h
- serial_ctrl.h
- serial_errno.h
- serial_t_lin.h
- serial_t_win.h
- serial_t.h
- serial_utils.h
- urg_ctrl.h
- urg_errno.h
- urg_parameters.h
- urg_t.h

Source files:

- serial_ctrl_lin.c
- serial_ctrl_win.c
- delay.c
- getTicks.c
- scip_handler.c
- serial_ctrl.c
- serial_utils.c
- urg_ctrl.c
- urg_errno.c

With these files the initialization sequence and data retrieval sequence are already implemented for usage under both Windows and Unix. Dependent on the operating system that is used the files that contain the correct functions can be included automatically using detect_os.h. In addition to the files mentioned various examples in Visual C are provided.

E.5 Implementation for the JaClean POP

For the JaClean POP an additional software layer is written based on the resources provided by Hokuyo. This software is contained in SLRF.c and SLRF.h and contains functions and definitions for easy opening (int InitSlrf(urg_t *urg);) and closing (int CloseSlrf(urg_t *urg);) of the connection as well as obtain the measures values for any range specified (int GetSlrfData(urg_t *urg, long *data, int *timestamp);).

An example using these functions and definitions is added for increased implementation efficiency. This example uses the functions and definitions in SLRF.h and SLRF.c to obtain the front three measurement points of the SLRF.

Please note the files urg_ctrl.c and urg_ctrl.h were slightly edited. The edit is commented and the files are renamed urg_ctrl_EDITED.c and urg_ctrl_EDITED.h, these files should be used instead of the original version.

E.6 How the data and time stamp returned by GetSlrfData should be interpreted

The function GetSlrfData returns both data values and a time stamp. This section summarizes some useful things to know on this information.

Data: The URG-04LX can provide a total of 768 data points (See figure E.2). Of these data points the point 0...43 and 726...768 are blind and cannot provide any useful information, the point 44...725 can.

The range 0...768 covers an angle of 270°, this results in an angular resolution of 0,35°/datapoint. This confirms the angular resolution provided by the manufacturer. The data points that are received can be specified, for example point 50 to point 100. The first received data point will now correspond to -116.9°, the second to -116.55° etc. Figure E.2 shows that step 0 corresponds to -135°, step 384 to 0° and step 768 to 135°.

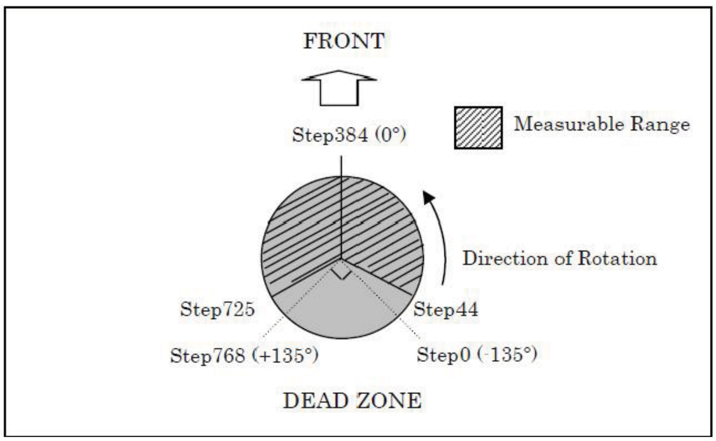


Figure E.2: Scanning range URG-04LX

The data that is connected to these points has the unit [mm], no further conversions are required after decoding.

Time stamp: Time stamp returns the value of a timer that is embedded in the URG-04LX. This timer is 24bit and has [ms] resolution. The value returned is the value of the timer at the 0th step of the scan. The returned value has the unit [ms] and in encoded according to the algorithm described earlier. No further conversions are required after decoding. Please note that the time stamp does not show absolute time, only relative. One should use a reference value to synchronise with the timer.

Characteristic	Value
Power consumption	2,5W
Accuracy	20mm − 1000mm ±10mm, 1000mm − 4000mm ±1%
Angular resolution	0,36°
Scanning Angle	240°
Communication	USB, UART
Range	4000mm

Table E.1: Characteristics

F Electrical framework and integration with other frameworks

Frameworks provide an infrastructure in which the functionality van be hooked. In the JaClean robot three frameworks have been defined: electrical framework, mechanical framework and software framework. Many of the tasks in the framework relate to the connection between the modules. Either electrically, mechanically or software. As a result the frameworks play an important role in the integration of the modules.

The framework discussed in this appendix is the electrical framework. The following tasks are included:

- Energy supply (budget)
- Wiring

The requirements on the electrical framework are mainly determined by the other modules. However, there is one general requirement that is important for the Energy supply:

- The robot will run for 30 minutes continuously

F.1 Analysis

Energy supply includes the wiring for energy distribution, while this is also included in wiring. The sections starts with discussing the energy budget and replenishment. Next all wiring will be discussed.

F.1.1 Energy supply

An important question when dealing with energy supply is: "How much energy needs to be supplied?". To answer this question three types of information are needed:

1 The amount of power consumed by all parts of the system
2 The voltages that are accepted by all modules
3 The amount of time that this power needs to be supplied

The third piece of information is known from the specifications, the robot needs to run for 30 minutes continuously.

To make sure a complete picture of the first and second kind of information was obtained a budget tree has been created. The budget tree, shown in figure F.1, is structured according to the following hierarchical layers:

- 1st: Robot level
- 2nd: Module level
- 3rd: Module part level
- 4th: Required hardware
- 5th: Chosen hardware modules
- 6th: Power (max) and Voltage requirements

The power requirements on the batteries and charger are left empty since there are the unknown variables that need to be determined.

As a summary of the information in the budget tree table F.1 shows the cumulative values.

Table F.1 shows that both the 12V circuit and the 24V circuit require a lot of power. To use one set of batteries and transform one voltage from the other would be expensive and inefficient. For this reason it was decided to use two sets of batteries: one supplying 12V, and the other supplying 24V. The 5V circuit is transformed from 12V, this can be done since it consumes little power.

With this information it, can be determined how much stored energy we need to run 30 minutes continuously (Worst case scenario). For the 12V battery set $636.6W * 0.5h = 318.3Wh$ is required. For the 24V battery set $360W * 0.5h = 180Wh$ is required.

The batteries of the robot need to be rechargeable. In appendix D the design alternatives for rechargeable batteries are investigated. The conclusion is that at the moment lithium-ion is the best choice. However, due to available time and budget it was decided to use Lead-acid batteries for the proof of principle.

Appendix H discusses important facts on Lead-acid batteries. One of the subjects discussed here is Peukert's law, which describes the relation between discharge rate and the energy that can actually be supplied. With the assumption of using Multipower MP22-12C batteries, the power consumption and the information in appendix H the amount of time the robot can run on these batteries is calculated. For the 12V circuit $T = 10(53.05 * 10/22)^{-}1,306 = 0.157h$, so for running 30 minutes continuously 4 batteries are required. For the 24V circuit $T = 10(15 * 10/22)^{-}1,306 = 0.815h$, so for running 30 minutes continuously 2 batteries are sufficient (2 are necessary to create 24V instead of 12V).

F.1.2 Wiring

When considering the wiring of a robot two things have to be considered:

1 What wiring is required

2 How much current will be flowing though the wires

To give an overview of the wiring in the JaClean robot, and thus to answer the two questions above, a N^2-diagram (Group, 2000) was created. The N^2-diagram is shown in figure F.2. In the diagram both information distribution and power distribution is included. Although the diagram is large and, as a result, the text in it is quite small it is presented none-the-less for completeness sake. The original diagram is available on cd.

In the N^2-diagram all hardware pieces that are electronically connected to other modules are noted on the diagonal. The border of the diagram represents the environment and the "remote control". All other squares in the diagrams can represent a connection, if it does the connection type in specified. By checking all squares for the possibility of a connection one makes sure that nothing is overlooked. Furthermore it should be noted that a connection always starts horizontally and finishes vertically, this way the direction of the information or power can be specified in the diagram.

The information distribution hardware, in this document called wiring, includes both wiring and protocol converters. What kind of communication hardware is required is dependent on what IO is available on all components.

In appendix D some background is provided on the protocol converter "videograbber" mentioned in the diagram.

F.2 Implementation

Implementation of the electrical framework was done in the integration stage. In this stage all frameworks and other modules have been put together in one robot. During the implementation one challange popped up: it proved to be difficult to distribute the thicker power wires in a neat way (1->more junction).

In addition to the above it was decided to use only one battery for the 12V circuit. This decision is based on the fact that the major consumer of the 12V circuit, the broom motor, will be powered less than 1/4th of the running time. This results in a much lower average power consumption. As a result one battery contains enough energy for 30 minutes up time.

F.3 Evaluation

The electrical framework has been put to the test during the entire integration stage. The robot was able to run during for 30 minutes without being completely discharged thus meeting the requirements stated.

Furthermore the use of the N^2-diagram ensured that all the required connections were in place. It has proven to be a very valuable integration tool in this project.

The time needed for the integration has been severely underestimated. This misjudgement has it origin, most probably, in the assumption that if everybody has done his/her work properly the integration should progress fluidly. In practise this is rarely ever the case. As a result there was little time for fine-tuning.

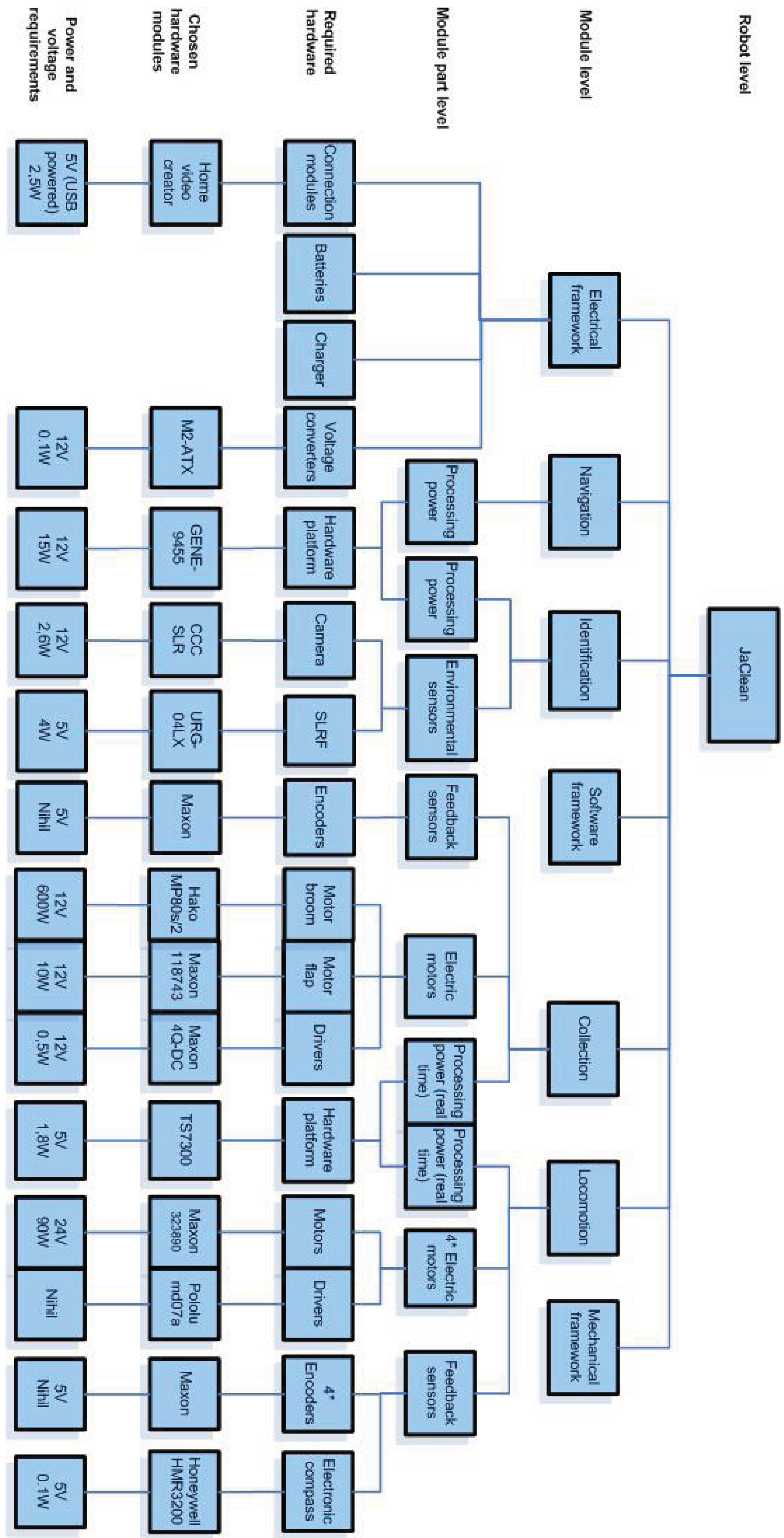


Figure F.1: Power supply budget tree

Voltage	Power
5V	8.4W
12V	628.2W
24V	360W

Table F.1: Summarized requirements

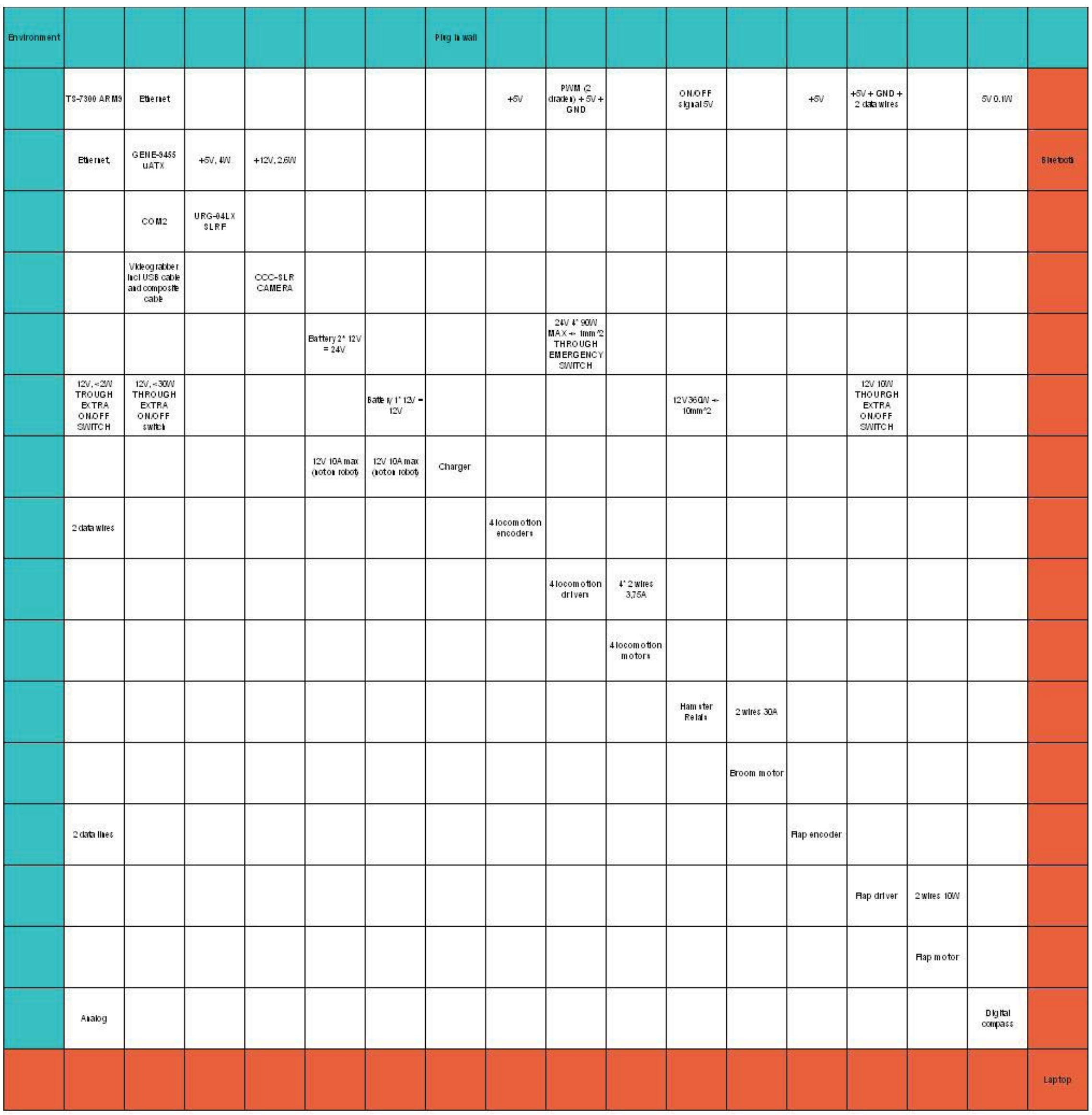


Figure F.2: N^2-squared diagram

G Power supply : Design alternatives

As part of the electrical framework discussed in appendix F the design alternatives for the power supply of JaClean were investigated. This appendix contains the results.

G.1 Battery types

A traction battery is a battery used to provide traction power to an electric or hybrid vehicle. This is the kind of battery that is required for the cleaning robot. These deep cycle batteries are used for supply of a sustainable period of time. The superior battery has high energy/ weight and energy/ volume properties: a lot of energy from a small amount of batteries.

This section compared and discusses the traction batteries available on the market today. The battery types are compared according tot the following specifications:

- Energy(Wh)/ weight(kg) ratio
- Energy(Wh)/ volume(L) ratio
- Load current(C)
- Price(€)/ Energy(kWh)
- Cycle durability(cycles)
- Time durability(years)
- Environmental load(high, medium, low)
- Charge time(hours)

All the figures you will find in this document represent the maximum result under normal conditions (not lab results, unless otherwise noted). Please note that it is very hard to get consistent information, if information at all. *As a result the information provided in this appendix should de treated as an indication only.*

G.1.1 Lead-acid (sealed)

Lead-acid batteries are the oldest rechargeable batteries on the market, the most well known example is the battery used in cars. Lead batteries can be summarized as cost-effective and mature. On the contrary they are also rather heavy and bulky for the amount of energy they can supply.

Figure G.1: Sealed lead-acid battery

Advantages according to Buchmann (2009a):

- Inexpensive and simple to manufacture
- Mature, well understood

- Low self discharge
- Capable of high discharge rates

Disadvantages according to Buchmann (2009a):

- Low energy density
- Cannot be stored in discharged condition
- Deep cycling increases wear down
- environmentally unfriendly
- Thermal runaway can occur if improperly charged

Characteristics (sources: Buchmann (2009g), Ltd (2009a)):

G.1.2 Nickel-metal hydride

Nickel-metal hydride are commonly available as rechargeable batteries in various sizes. Their modern success is mainly based on the use of environment friendly materials and relatively high energy density.

Figure G.2: High power Ni-MH battery used in the Toyota Prius

Advantages according to Buchmann (2009f):

- Potential for high densities
- Environmental friendly

Disadvantages according to Buchmann (2009f):

- Limited service life
- High maintenance

Characteristics (Sources: Buchmann (2009g), Ltd (2009a), Buchmann (2009f)):

G.1.3 Nickel-cadmium

Nickel cadmium batteries are known as the old rechargeable batteries. They can be charged fast and have a long cycle life and shelf life. On the contrary they suffer from the so called ‘memory effect’ and have a relatively low energy density. In some European counties use of nickel cadmium batteries is restricted due to the high environmental load.

Advantages according to Buchmann (2009f):

- Fast and simple charging
- Long service life
- Relatively cheap

Disadvantages according to Buchmann (2009f):

- Low energy density
- Environmentally unfriendly
- Memory effect

Characteristics (Sources: Buchmann (2009g), Ltd (2009a)):

Figure G.3: Nickel cadmium batteries applied in a vehicle

G.1.4 Lithium-ion

Lithium-ion batteries are widely applied batteries now a days. They can be found in, for instance, cameras, cell phones and laptops. The main reason for they wide application is their high energy density. On the contrary they degrade rather quick, even if they are not in use.

Figure G.4: an early lithium-ion battery

Advantages according to Buchmann (2009d):
- High energy density
- Low self discharge
- Low maintenance

Disadvantages according to Buchmann (2009d):
- Requires protection circuit
- May explode at high temperatures
- Subject to ageing
- Expensive
- Not fully mature

Due to their high potential the chemistry of lithium-ion is almost constantly improved, some types that are available today are: cobalt, Manganese, NCM and Phosphate.

Characteristics of cobalt lithium-ion batteries (Sources: Buchmann (2009c), Ltd (2009a), Buchmann (2009g)): Characteristics of maganese lithium-ion batteries (Sources: Buchmann (2009c), Ltd (2009a), Buchmann (2009g)): Characteristics of NCM (Nickel Cobalt Manganese) lithium-ion batteries (Sources: Buchmann (2009c), Buchmann (2009g)): Characteristics of Phosphate lithium-ion batteries (Sources: Buchmann (2009c), Buchmann (2009g), Ltd (2009a)): *lab conditions

G.1.5 Lithium polymer

In lithium-polymer batteries the standard liquid electrolyte is replaced by a polymer. This make manufacturing more flexible. The most significant advantage of lithium polymer batteries is a result form this flexible manufacturing: flexibility in shape. On the contrary lithium polymer cells are not capable of supplying high currents and their energy density is somewhat less than conventional lithium-ion. Due to their higher costs they find their main application in wafer-thin geometries: there where no other battery can fit.

Figure G.5: 3-cell lipo battery of racing cars

Advantages according to Buchmann (2009d):
- Very low profile
- Flexible form factor
- Lightweight
- Improved safety

Disadvantages according to Buchmann (2009d):
- Lower energy density
- Expensive

Characteristics (Source: itpower (2009)):

G.1.6 Nickel hydrogen

Nickel hydrogen batteries are mostly used in space applications. The big advantage of these batteries is a high cycle and time durability. On the contrary they are under high pressure and very expensive.

G.1.7 Nickel iron

Nickel iron batteries, also known as nickel alkaline or NiFe batteries are very robust and have a high time durability, however they have a rather low energy density.

Advantages according to Ltd (2009b):
- Very robust

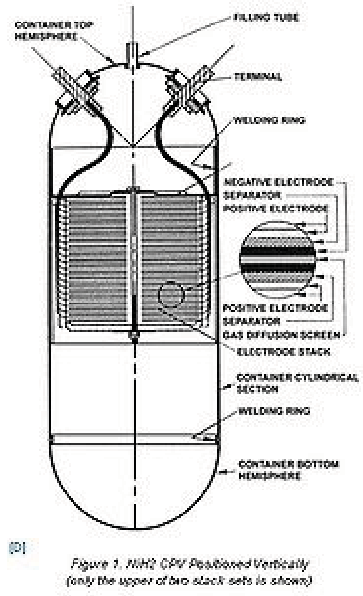


Figure G.6: Nickel hydrogen battery layout

- Long life time
- Long cycle life

Disadvantages according to Ltd (2009b):

- Low cell voltage
- Low energy density
- High self discharge rate

Characteristics (Source: Ltd (2009a)):

G.1.8 Nickel Zinc

Nickel zinc batteries were developed to replace the older silver zinc batteries used by the military. They can supply a lot of power , can be recharged fast and have a good cycle life. On the contrary they have a low energy density.

Advantages according to Ltd (2009c):

- High rate capability
- Good cycle life
- Fast rechargeable
- Low cost

Disadvantages according to Ltd (2009c):

- Low energy density
- High self discharge rate

Characteristics (Source:Ltd (2009a)):

G.1.9 Sodium-sulphur

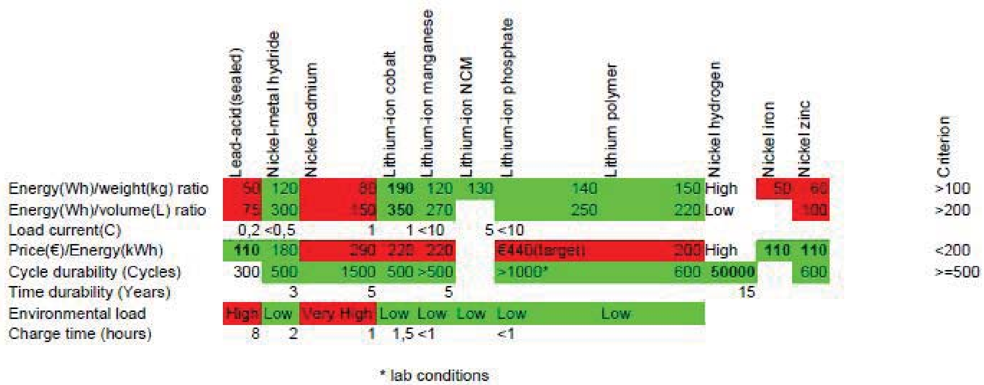
Sodium sulphur batteries are low cost, light weight and non toxic, however they can only be used in temperatures around 270°. As a result they are clearly not applicable for the JaClean robot.

G.1.10 Redox batteries

Redox batteries use a chemical reaction to generate energy, so the energy is stored in the components used for the chemical reaction. After the chemical reaction is finished no more electrical energy is available and the electrolyte needs replacement. This allows rapid recharge. Redox batteries can generate a tremendous amount of power but have a low energy density. Due to their nature redox batteries are highly impractical for the Cleaning Robot and will not be discussed further.

G.1.11 Summary on battery types

This section gives an overview of the information provided in the section before. The red and green markings are added to be able to distinguish strong and weak points quickly and without opinion, all the markings are according to the criteria noted. The bold printed figures indicate the top performers in the specific category.



	Lead-acid (sealed)	Nickel-metal hydride	Nickel-cadmium	Lithium-ion cobalt	Lithium-ion manganese	Lithium-ion NCM	Lithium-ion phosphate	Lithium polymer	Nickel hydrogen	Nickel iron	Nickel zinc	Criterion
Energy(Wh)/weight(kg) ratio	50	120	80	**190**	120	130	140	150	High	50	60	>100
Energy(Wh)/volume(L) ratio	75	300	150	**350**	270		250	220	Low		100	>200
Load current(C)	0,2	<0,5	1	1	<10	5	<10					
Price(€)/Energy(kWh)	**110**	180	290	220	220		€440(target)	200	High	**110**	**110**	<200
Cycle durability (Cycles)	300	500	1500	500	>500		>1000*	600	**50000**		600	>=500
Time durability (Years)		3	5		5				15			
Environmental load	High	Low	Very High	Low	Low	Low	Low	Low				
Charge time (hours)	8	2	1	1,5	<1		<1					

* lab conditions

Figure G.7: Battery summary

Based on the information provided the result can be summarized in the following sentence: The Nickel-metal hydride scores best according to the criteria, but beats the lithium-ion technologies only in pricing. The lithium-ion technologies always have a higher energy density than the Nickel-metal hydride. Lead-acid is the most cheap solution but has many disadvantages.

Modern autonomous vehicles use either lead-acid, NiMH or lithium technologies. Lithium-ion batteries are used less often than the other two since they are the most expensive solution and a rather young technology. Lead-acid is a cheap solution, NiMH is a solution with a high energy-density.

Lithium-ion vs lithium-ion polymer: Although it does not show in the figures all sources are consistent on the differences between lithium-ion and lithium-polymer:

- Lithium-ion has a higher energy density ratio
- Lithium-polymer has a flexible form factor
- Lithium polymer is still more expensive
- Lithium polymer is lighter since it does not need any metal casing

Note that all the information provided in this section does not include any developments and scientific claims.

G.2 Developments

Developments in the field of mobile power supply is even more interesting than the systems available today. The cleaning robot will most probably not be produced for a couple of years, therefore by the time that production starts a new development in the field of mobile power supply might be emerging. In addition the cleaning robot is an innovative product, for this reason it should anticipate changes and developments in the near future. This section discusses three mayor fields of development in mobile power supply: Lithium-ion batteries, Fuel cells and super capacitors.

G.2.1 Lithium-ion batteries

Although lithium-ion batteries already exist, scientists are constantly trying to further improve this technique and find a solutions for the current disadvantages. The following research was mentioned in the news lately:

As can be seen a lot of research is going on in the field of lithium-ion batteries. Most of them promise higher capacity and charge-discharge rates, none mention improvement for the high deterioration rate. If the scientific claims are true the distance between NiMH and Lion should further increase within five years. In favour of lithium-ion of course.

G.2.2 Fuel cells

Fuel cells are a slowly emerging alternative power source. At the moment methanol fuel cells are best suitable for mobile applications, mainly because they have no specific operating conditions (Source: Narayan and Valdez (winter 2008)). A summary of a typical fuel cell available today:

Advantages:

- Quick refill possible
- High reliability
- No exhaust gasses

Disadvantages (Sources: Buchmann (2009e), Buchmann (2009b), department of energy (2009)):

- Power is still very expensive at the moment (€3200 per kilowatt)
- Immature technology
- For now, still low energy density
- short service life

As for now fuel cells cannot compete with batteries but SECA aims at a price of €280 per kilowatt by the end of the decade (Source: department of energy (2009)) and Maxell Hitachi (Source: Hanlon (2006)) promises a new type that is both cheaper and of higher energy density. These improvements would make Fuel cells very feasible the cleaning robot. This option is certainly worth considering.

It should be noted that commercial fuel cells are already available in various shapes and sizes.

G.2.3 Supercapacitors

Super capacitors are a typical example of bold claims with little scientific background know. For a couple of years the company Eestor claims to be on the brink of commercializing a new kind of super capacitor that will make all batteries obsolete. Their claims include: charging time of 3-6 minutes, self-discharge of 0,02% in 30 days and an energy density of 280Wh/kg. According to these claims this new type of super capacitors should be superior to lithium-ion in every way. The thing is that no papers are available to back their claims. In addition they already passed two release targets without releasing anything, the most recent article found is from July 2008. Sources: Ehrlich (2008), Hamilton (2007).

It should not me overlooked that there is a second facility with claims on super capacitors: MIT. They also claim that the battery as we know it may be obsolete within the near future. Although it is clear that important developments have been made there is not yet any sign of a working implementation. The most recent article that was found dates august 2006. Sources: Bray (2006), Limjoco (2006).

Unfortunately the future of the super capacitor is still very uncertain... for now.

G.3 Conclusions

At the moment the difference between NiMH and Lion batteries is still not very large, but lion technology is still very young while NiMH is already very mature. A lot of researches indicate that the distance between Lion and NiMH batteries will most probably get larger very soon. In addition to batteries two alternatives were presented: Fuel cells and super capacitors, although both technologies are not yet suitable for the cleaning robot it may be that they will be within five years. A close eye should be kept on the developments.

For now the most secure option is litium-ion, it is already available and suitable for the cleaning robot with a prospect on big improvements. Developments on super capacitors have to many uncertainties at the moment. If the claims from SECA and Maxell Hitachi on fuel cells will be put into results in the near future they will become a very interesting alternative on lithium-ion batteries. One of the biggest advantages will be fast fuelling.

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	50
Energy(Wh)/ volume(L) ratio	75
Load current(C)	0,2
€/Energy(kWh)	110
Cycle durability	300
Time durability	
Environmental load	High
Charge time(hours)	8

Table G.1: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	120
Energy(Wh)/ volume(L) ratio	300
Load current(C)	<0,5
€/Energy(kWh)	180
Cycle durability	500
Time durability	3
Environmental load	Low
Charge time(hours)	2

Table G.2: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	80
Energy(Wh)/ volume(L) ratio	150
Load current(C)	1
€/Energy(kWh)	290
Cycle durability	1500
Time durability	5
Environmental load	Very High
Charge time(hours)	1

Table G.3: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	190
Energy(Wh)/ volume(L) ratio	350
Load current(C)	1
€/Energy(kWh)	220
Cycle durability	500
Time durability	
Environmental load	Low
Charge time(hours)	1,5

Table G.4: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	120
Energy(Wh)/ volume(L) ratio	270
Load current(C)	<10
€/Energy(kWh)	220
Cycle durability	>500
Time durability	5
Environmental load	Low
Charge time(hours)	<1

Table G.5: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	130
Energy(Wh)/ volume(L) ratio	
Load current(C)	5
€/Energy(kWh)	
Cycle durability	
Time durability	
Environmental load	Low
Charge time(hours)	

Table G.6: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	140
Energy(Wh)/ volume(L) ratio	270
Load current(C)	<10
€/Energy(kWh)	440(target)
Cycle durability	>1000*
Time durability	
Environmental load	Low
Charge time(hours)	<1

Table G.7: Characteristics

Characteristic	Value
Energy(Wh)/ weight(kg) ratio	150
Energy(Wh)/ volume(L) ratio	220
Load current(C)	
€/Energy(kWh)	200
Cycle durability	600
Time durability	
Environmental load	Low
Charge time(hours)	

Table G.8: Characteristics

Characteristic	Value
Energy(Wh) / weight(kg) ratio	50
Energy(Wh) / volume(L) ratio	
Load current(C)	
€/Energy(kWh)	110
Cycle durability	
Time durability	
Environmental load	
Charge time(hours)	

Table G.9: Characteristics

Characteristic	Value
Energy(Wh) / weight(kg) ratio	60
Energy(Wh) / volume(L) ratio	100
Load current(C)	
€/Energy(kWh)	110
Cycle durability	600
Time durability	
Environmental load	
Charge time(hours)	

Table G.10: Characteristics

Date	subject	Institution	Benefit	source
Jan. 2009	Carbon Nano tubes	MIT	Increased capacity	Www.Technologyreview.com
Feb. 2006	Battery structure	MIT	Increased charging/ discharging speed	Www.technovelgy.com
Dec. 2007	Silicon nano wire	Stanford	Increased capacity	News.stanford.edu, www.edn.com
April. 2008	LiFePO4	A123 systems	Safety	Www.popularmechanics.com
May. 2009	Titanium dioxide crystals attached to a thin carbon sheet called graphene	Pacific Northwest National Laboratory and Princeton University	Increased capacity, increased charging and discharging speed	Www.pnl.gov
March 2009	Improving lithium/ion phosphate	MIT	Higher energy density and charge-discharge rates	Www.businessweek.com, www.autoracingdaily.com
March 2009	Three dimensional nano structured anode	National Institute of Advanced Industrial Science and Technology	capacity	Www.natureasia.com

Table G.11: Characteristics

H Useful things to know about Lead-acid batteries

For the prototype of JaClean lead-acid batteries are used. Apart from common knowledge on these commonly used batteries there are some less known phenomena that are useful to know when using this kind of batteries.

H.1 Influences on the capacity

The capacity of a lead-acid battery is not fixed, but dependent on a number of parameters. The two most significant influences are discharge current and environment temperature.

H.1.1 Influences on the capacity due to discharge current

Lead acid batteries are capable of delivering enormous currents, but at a price. The higher the discharge current the lower the effective capacity and the lower the battery life time. Here only the effect on the effective capacity is considered.

Lead-acid batteries are subject to Peukert's law. Peukert's law describes the relation between capacity and discharge current:

$T = C/((I/(C/R))^n) * (R/C)$ (Source: electronics (2009b))

This can be reformulated to:

$T = R(I * R/C)^{-n}$

where:
- T = discharge time(h)
- C = battery capacity(Ah)
- I = discharge current(A)
- R = battery hour rating for the capacity C(h)
- n = Peukert's constant

Please note that this formula is a modified version of the original that was composed by Peukert.

The value for Peukert's constant can be computed given and two discharge rates and times or any two capacities at different hour ratings. The formula that can be used to compute Peukert's constant is:

$n = (log(R2/R1))/(log(C1/R1) - log(C2/R2))$

More information on Peukert's equation can be found in electronics (2009b) and electronics (2009a).

H.1.2 Temperature

The environmental temperature also has some effect on the capacity, but it is much less than the discharge current. When it is mentioned in the available data one can take notion of it, it is not further discussed in this document.

H.2 Charging

For the charge current the same counts as for the discharge current. The batteries can be charged at very high currents, but it has its price. When choosing a charge current the following should be taken into consideration:
- A Higher charge current results in a lower charge time
- A Higher charge current results in a less complete charge (<100%)
- A Higher charge current results in a shorter battery life

As a rule of the thumb it is generally said one should use a charge current of about 10% of the battery capacity, but higher charged currents (30...50%) are also commonly used.

For more information and explanation please visit electronics (2009c).

I Extension for Navigation/ Strategy

For the may 2009 demo Navigation software was written by Menno Bouma, with this software he finished his project. To be able to use this software for the October 2009 proof of principle some adaptations had to be made. This Appendix describes these changes and why they were made. In the source code all is commended to support future work.

I.1 Simultaneous add to map, find target and calculate path

In order to obtain "as intelligent as possible" behavior the robot needs to be able to "change his mind" based on new information. That is why the navigation software was adapted in such a way that it is now entirely non-blocking. While loops were removed where possible and replaced by constructions with if-statements.

I.2 Higher resolution map

In the previous version of the Navigation software the size of the tiles of the map was defined as the size of the robot. Since the robot is not exactly square or round this is not comfortable for the following reasons:

- The robot is much larger than most litter objects
- The robot may bump into obstacles while turning, this cannot be checking with the used tile size.

For these reasons the tile size is made independent of the size of the robot and adjustable.

I.2.1 the robot as a shape instead of a point

As a consequence of the change of tile size the robot cannot be represented by one tile anymore. Instead a shape was implemented that has much resemblance with the robot: an eclipse. The with and length of the eclipse are made adjustable since the outer dimensions of the robot may (and most probably will) change in the future.

I.2.2 Obstacle avoidance with a shape

With the robot now represented by a shape, obstacle avoidance has become a lot more sophisticated. Instead of just avoiding the case where the robot location is equal to the location of a obstacle point obstacle avoidance is split in two:

- Obstacle avoidance while driving straight forward or backward
- Obstacle avoidance while turning

In both cases the future (expected) path of the robot is calculated an simulated life. When one of the tiles corresponding to the robot has the same coordinated as an "Obstacle tile" in any part of the movement the path is market as blocked. With this information the turn angle required to avoid the collision is determined and the current set-point is overruled with this turn angle. Once the path is unblocked the previous set-point is maintained angle. Once the path is unblocked the previous set-point is maintained once more.

I.3 Remembering what the robot has seen

To increase the intelligent behavior of the robot that part of the map that is seen by the robot is recorded. This way the navigation algorithm always knows what part of the map is seen (and if litter is present it is known) or unseen.

I.3.1 When no litter is left on the map: look at spots that were not seen yet

When no known litter is left some kind of intelligent behavior is expected. In the old navigation software this behavior was equal to "turn 360 degrees". In the new version is is adapted to "Look where you have not looked before". In other words: the robot goes to all unseen parts of the map to ensure no litter is present.

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