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Intelligent Compaction – Autonomous Compactor Concept Evaluation

Master of Science Thesis in Computer Systems and Networks

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Abstract

Autonomous vehicles are approaching the future of our everyday life. There are many research projects going on for autonomous cars, autonomous trucks, and autonomous robots. Each of those is solving particular problems in its field. In addition to this family of vehicles, this thesis report will add one more perspective to the topic. It is presenting a concept for a construction site vehicle such as compactor and it is autonomous driving capabilities in order to facilitate work of road paving.

The current process for road paving does not consider online monitoring of the asphalt density, which makes the quality of the pavement hard to verify. Recent research allowed online monitoring based on artificial intelligence algorithms. However, there is a problem that the drivers could not react fast enough to the results of the sensors, which, on the other hand, causes over or under compacted regions. Moreover, eventually the final results are cracks and holes on the pavement in a couple of years, which does not suffice the increased demand in the standards for 20 years warranty for highways. In order to solve this problem, the current report is focusing on combining the knowledge from the autonomous vehicles area and intelligent asphalt analyzing to propose a new concept. This concept is for a product that will improve the quality of the pavement, which will follow the safety requirements and will not significantly increase the price of a compactor.

In the concept, autonomous and semi-autonomous modes for the machine will be evaluated for easier adaption in the industry. Special attention will be given to sensor fusion for facilitating positioning and maintaining movement accuracy satisfying paving process requirements.

The results from this report show that the scientific and industry requirements could be covered. Also, a system such as autonomous compactor could be implemented with the current technology in a company without significantly raising the cost of the machines.

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The Authors, Gothenburg 2015

Table of Contents

1. Introduction

The study extends the current knowledge of intelligent compaction by evaluating a concept for the autonomous compactor to achieve high quality of road layup. On the other hand, it will also extend the practical areas of autonomous vehicles together with navigation and path-finding in a complex environment. The work will also combine state-of-the-art from both areas to evaluate the proposed concept.

1.1 Problem Domain and Motivation

The main problems with the current process of pavement are uniformity of the asphalt mat and compaction quality, time limitations of the process, simultaneous tasks for the operator, and human errors. These problems could be resolved by reducing stressful tasks from human responsibilities and let the computers help the operator. These are the reasons why during the last decade after improvement of technology in the robotic area many researchers start to think about autonomous vehicles. They have implemented different types of sensors and algorithms to sense the environment like humans. The main goal of autonomous vehicles was to reduce human errors. Many car producers start to implement and test their autonomous cars in labs. Google is one of the first companies that run their car on the real environment in the US [1].

Compaction is a key point that affects the lifetime and uniformity of the asphalt mat. There are many factors that should be met to achieve the best quality of the asphalt mat. Apart from the asphalt mixture itself and the quality of the material used in mixed asphalt there are other important factors. Those factors are the temperature of the hot asphalt when it is laid down on the ground, weather conditions, operator of the compactor, crew who work around the compactor, and many other things.

The temperature of the mixed asphalt is a key point during compaction of pavement. To compact the mixed asphalt it needs to be hot (between 88 ˚C and 121 ˚C) [2]. After it is laid down on the ground, it starts losing temperature until it becomes too cold for compaction. Losing the temperature shows that the compaction time is limited, and the operator of the compactor should always take care of the temperature and adjust the compaction speed accordingly to be able to compact the asphalt on time.

The compaction process is a very slow process because the maximum speed of the compactor is up to 12 kilometers per hour [2]. So the driver gets tired or forgets to track important information simultaneously for example rolling pattern and quality of compaction [3].

Most of the problems mentioned above are caused by humans, who are drivers of the compactor; that is why the main goal of autonomous vehicles is to reduce human errors [2]. Here are some examples that could have an effect on the uniformity of the asphalt surface by the operator of the compactor [2]:

- Pressing the brake pedal hard on hot mixed asphalt.
- Change the heading direction of compaction forward/reverse very fast.
- Leave the compactor stationary on hot asphalt for long time.
- Lose track of the temperature and proper distance to the paver, which could cause the hot asphalt to become cold and lose compressibility.

The characteristic of computers helps humans to use them for tasks that are time-consuming and less interesting. The systems that use computers should be reliable and available all the time to tolerate faults and collaborate with humans.

1.2 Research Goal and Questions

The goal of our thesis is to design and evaluate a concept to fully automate a compactor vehicle by combining off-the-shelf sensors with state-of-the-art algorithms.

The idea is to introduce a system that combines the existing systems with new features to increase autonomy in Intelligent Compaction Systems (ICS) [4]. Using a normal compactor with IACA needs an operator always to look into the monitor and track the data from it to be able to keep uniformity of the pavement. The driver also needs to focus on driving to keep the working area safe for the crew, the machine, and equipment around it. So it is almost impossible to focus on two different things at the same time. The research shows that after a while he/she becomes tired of tracking the data and he/she leaves it. This results in not as accurate uniformity of the pavement as expected [3]. The new system will get data from IACA and use it along with other data collected by other sensors and/or human operator to drive compactor autonomously or partially autonomously.

In this setting we have the following constraints:

- Cost efficiency:
  The state-of-the-art is mostly focusing on the automotive industry and military facilities that need high-performance components that are usually expensive. However, the compactor compared to those cases has a stronger requirement for a low-cost solution, which is possible because of more relaxed requirements. For example, compared to autonomously driving cars the target speed of the compactor is between 2 to 4 meters per second which is much slower than cars and needs equipment with less processing power. Here the challenge is to find hardware and software layout that could suffice the requirements and ensure the cost efficiency of the solution. Another important aspect is when we have a good density of the asphalt mat and keep the uniformity of the asphalt surface, the pavement could live longer, and it can save many expenses. On the other hand making an autonomous compactor needs more expenses in relation to hardware and software improvement.

- Rugged environment:
  The sensors should be able to withstand the rugged environment in which the compactor is operating. It includes the vibrations and dust that reduce the accuracy of the sensor setup.

- Safety:
  Safety is a key challenge. The heavy machine can cause damage if it cannot operate safely. During the pavement construction, many workers work around the compactor and paver. If the driver of the compactor loses his concentration, it can cause a catastrophic accident. A good sensor layout around the compactor could ensure the safety of the crews and equipment.

- Fail-safe:
  The complexity of the fail-safe operation has to be specially treated. For example, stopping directly on the road for emergency reasons might ruin the asphalt, and it should be avoided whenever possible.

After describing goals and constraints this thesis addresses the following research questions:

- RQ1. What are relevant design considerations that need to be taken into account for a software system implementing an autonomous compactor?
- RQ2. To what extent does a software system fulfill such constraints imposed on the problem domain especially critical requirements for the compaction process?

1.3 Thesis Contribution

This thesis contributes to the area of robotics and computer science, specifically localization and decision-making.

The first contribution is to introduce autonomous compactor concept inherited from known existing research in the area of autonomous vehicles. First of all the concept is evaluated to meet the requirements for ICS provided from the industry. After that different hardware-software solutions are evaluated in terms of price and vital characteristics with respect to existing knowledge - response time, calibration time, movement accuracy, maintainability, and extensibility.

The second contribution is to define a solution that is suitable for first-time implementation of the system - autonomous or semi-autonomous. For the semi-autonomous the solution will be a system with the need for human intervention by controlling the brake pedal or throttle in the compactor. For the autonomous it will be one system in the compactor that take care of all tasks and not rely on human intervention.

The third contribution is to evaluate the concept and verify its feasibility with the defined solution over real scenario tests and simulation data. After the tests, different metrics will be used to verify that the critical compaction requirements are met. The compactor uses several different types of sensors to locate itself and follow a trajectory with respect to data gathered from those sensors. This data will also be evaluated in terms of accuracy and precision. Third party tools will be used for evaluation of the performance of the system.

1.4 Thesis Scope

The work includes the concept for software-hardware solutions that addresses different scenarios to achieve autonomous/semi-autonomous heavy duty vehicles. It focuses on the design of a software-hardware system that could meet the requirements for industrial operation and integrate new technologies for solving the presented problems in the current domain.

The prototype implementation focuses on lateral control and does not involve any longitudinal control because the demonstrating machine does not have the required technical capabilities.

In terms of machines, this thesis mainly focuses on asphalt compactors and specifically dual drum ones and will be conducted in cooperation with Cpac Company, Göteborg, Sweden.

1.5 Thesis Structure

The background of compactors, IACA, autonomous vehicles and the current state-of-the-art is discussed in section 2. The related work in the field of autonomous compactors and high duty vehicles is discussed in section 3. The concept of autonomous/semi-autonomous compactor along with a solution model is presented in section 4. The detailed description of the implementation is described in section 5. The evaluation and comparisons of raw data taken from hardware during the tests and the final results are presented in chapter 6. The conclusion and future opportunities to develop and improve the idea of autonomous compactor is discussed in chapter 7.

2. Background and Requirements

This section will cover the prerequisites from a technical perspective that allow the concept for the autonomous compactor to be practically possible. The research area for autonomous vehicles has developed a lot after the DARPA Grand Challenges held in United States in 2004-2007. Several algorithms were invented or adapted for practical use in the field of image processing, object tracking and object recognition, self-positioning on a map, sensor fusion, system monitoring, and inter-process communication. During the challenges, it was proved that autonomous vehicles are real. The results were improvements in several areas of computer science and sensor technology [5]. Among those challenges, the Desert Grand Challenge is of particular interest because it is held in a rugged environment, which is considered similar to the environment in which the autonomous compactor will operate in. The hardware and software concept, as well as the sensor fusion of Stanley, the winning car in the competition [6] provided a perfect base for creating the system concept for the compactor.

After a successful start in the autonomous vehicles area, manufacturers in the construction area decided to expand their production and give a try to autonomous heavy duty vehicles. Volvo is a well-known car manufacturer in the construction area, and it was one of the first companies that start to research about autonomous vehicles. Cpac Systems AB is one of the main companies that do different high-tech side projects for Volvo.

One of the projects that are developed by Cpac Systems AB was Intelligent Asphalt Compaction Analyzer (IACA). It is a standalone mountable device that is mounted on the Compactors and gives useful information about compacted pavement. The IACA consists of sensors that measure the location and vibrations of the drum, an infrared sensor to monitor the asphalt mat temperature, and a display to provide an operator the estimated pavement density in real time. Also, it has built-in features to display vital compaction information like coverage and density for monitoring progress during compaction [7]. These measurements show the quality of the compaction and give indications whether the compactor should move faster or slower. However, the uniformity over the whole segment is left to the operator.

The compactor is a machine that does the compaction of pavement within the process of road construction. There are three different types of compactors which are used during road construction process. First is soil compactor (Figure1.a) which usually has a drum on the front axle and tire on the rear axle and they are used to compact the soil layer (base layer) of the road. The second one is pneumatic tire compactors (Figure1.b) which have tires instead of drums, and they are usually used for smoothness of the asphalt layer surface of the road. The third one is dual drum compactor (Figure1.c) which have a drum on both axles, and they are used to compact asphalt layer of pavement.

The dual drum compactor follows a machine called paver and compacts the hot mixed asphalt that is laid down on the ground by paver to reach a certain density of the mat. Research shows that the vibration of the drum during compaction helps to get higher density on the pavement; that is why some new compactors have a vibration feature that helps to get higher density on the mat.

(a) [8] (b) [9] (c) [10]

Figure 1. Different type of compactors. On a) is presented a soil compactor, on b) - pneumatic tire compactor and on c) dual drum compactor.

From the industry point of view, there are requirements for the operation of the compactor that need to be met to allow the machine to compact the asphalt on its own [2]. The compaction speed depends highly on the vibration frequency of the drums and the size of impacts. Table 1 shows typical rolling speeds depending on the roller types and different stages of compaction. So in order to be able to accommodate all those cases the autonomous compactor should be able to handle speeds up to 12 km/h.

Table 1. Different compaction speeds in different stages of the compaction process

Roller Type	Breakdown	Intermediate	Finish
Static	3.2 – 5.6 km/h	4 – 6.5 km/h	4.8 – 8 km/h
Pneumatic	3.2 – 5.6 km/h	4 – 6.5 km/h	6.5 – 11 km/h
Vibratory	3.2 – 4.8 km/h	4 – 5.6 km/h	5.6 km/h

The asphalt density is the property that defines the quality of the compaction. The density should be around 98% of the maximum wet density obtained by the ASTM D1557 [11] standard compaction test. Also, it should not be less than 96% or over 100% [12]. Another important requirement is the temperature of the asphalt mix. Table 2 shows the range of temperatures during compaction in the different stages. The most important one is the so-called Tender Zone. After the asphalt gets below the 80 ˚C, no more density could be achieved. The Finish part of the compaction is just to make the surface smoother. In order to prevent crossing these ranges, a precision of one degree Celsius is required. It will allow enough time for compaction of all newly laid hot-mix asphalt regions.

Table 2. Requirements on asphalt mix temperatures in different stages

Paver	Breakdown	Tender Zone	Finish
166 ˚C – 144 ˚C	160 ˚C – 121 ˚C	121 ˚C - 88 ˚C	82 ˚C – 40 ˚C

Another very important requirement is the requirement for movement accuracy. During the process of compaction, the machine first compacts the area inside the road-layup and after that compacts the edges. When the compactor is compacting the main area, it should be between 15 and 30 cm from the edge. Then when compacting the edge, it should overlap with the already compacted area again between 15 and 30 cm. It implies 15 cm accuracy requirement for perfect compaction. Those requirements are relaxed for inexperienced drivers to 50cm accuracy, and a survey showed no significant quality loss [2].

The two requirements discussed above implied certain time constraints on decision-making. Since the speed is 12km/h and the accuracy needed is 50cm in that speed, the compactor takes this distance for 200ms. It means that the decision-making needs to be done at least three times faster to allow correction of previous decisions. It implies time constraint of 60ms for the decision-making, which should include communication delays, data processing delays, and decision-making calculations.

The last, but not least important requirements are requirements for safety. Unfortunately, laws and regulations for fully autonomous vehicles do not exist yet. There are trial laws in US, which are about to be rewritten in 2015, but we can use them as guidance [13]. It is the same when it comes to safety standards. Autonomous machines should be reliable and safe for themselves, the environment, and the working process. A cite from the current California law states "Autonomous vehicles must possess manufacturer certification of a mechanism to engage and disengage the autonomous technology; a visual indicator to indicate when the autonomous technology is engaged; a system to safely alert the operator if an autonomous technology failure is detected while the autonomous technology is engaged, and when an alert is given;…". This law implies that an operator should be able to take over the control at any time. The system also should be able to detect by itself if a failure in its operation has happened. In the compactor case, it means that the machine should be able to terminate its operation if there is no takeover command from the operator within a certain time frame after an alarm has been generated. The termination should happen in a fail-safe way without affecting the machine, the environment, and if possible preserving the compaction process. The last requirements were discussed and confirmed with the partner company.

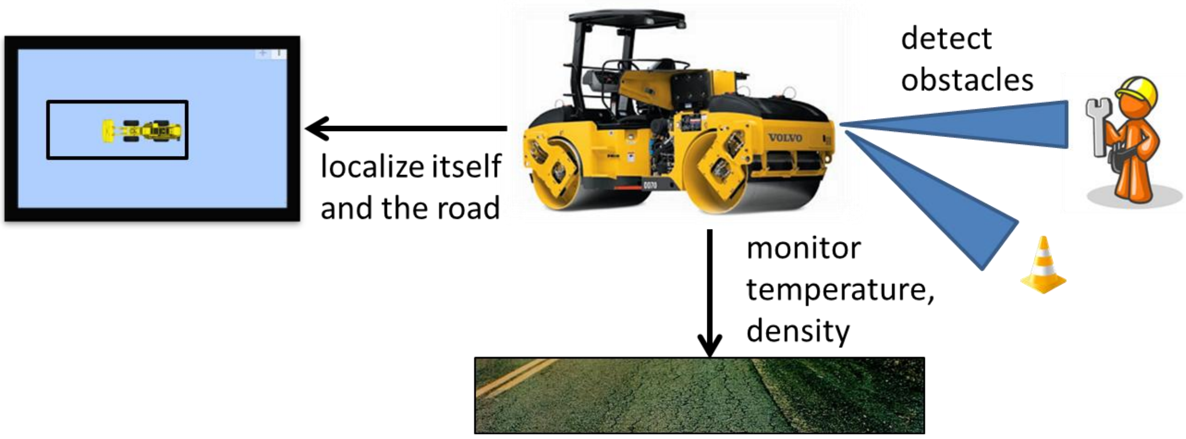


Figure 2. Compactor's technical tasks

There are several prerequisites that should be met in order to automate the process of compaction. In terms of sensor technology – an accurate measurement of the asphalt density in real time is required. Temperature measurement with accuracy up to 1 degree is required. Sensing the environment around the compactor for detecting obstacles, localizing the compactor in the environment with 50 cm accuracy, localizing the asphalt mat that need to be compacted in that environment and relate that to the compactor position are also vital requirements (Figure 2). Depending on the chosen technologies, there are several algorithmic problems that need to be solved. The following paragraphs will describe briefly what technologies and knowledge are available to suffice the requirements. Those technologies and the corresponding knowledge were found through a systematic approach discussed in the next section.

As described in Section 1 IACA was developed to analyze the density of the asphalt mat and give information in real time to an operator. This system relies on different artificial intelligence algorithms to predict the density based on the drum vibrations over the mat. The algorithms used are Fast Fourier Transformation (FFT) and Neural Networks (NN) [14]. IACA gets information from the accelerometer on the drum and temperature sensors before and after the drum, runs FFT on the accelerometer data and feeds the result plus the temperature information into the NN. The NN produces a value from 1-6, which represent six classes of equivalence. Based on those classes with a mapping function the IACA outputs the percentage of compaction in relation to perfectly compacted patch. An example output will be 96% which means very close to perfect compaction, and 101% means over compacted area [2].

Temperature measurement is not a challenge since there are many sensors that could suffice the requirements of 1-degree accuracy.

Sensing the environment around the compactor is a problem that is solved in the industry for static machines and also is addressed in the autonomous vehicles challenges. There are several sensor layouts that could solve the problem. In the DARPA Grand Challenge used sensors include but are not limited to - Lidar, Laser rangefinder, a chain of cameras and radars [6] [15]. In the industry, ultrasound sensors are used [16], as well as radars and thermal cameras. The sensors could be divided into two main categories, distance sensors, and visual sensors. When it comes to distance sensors, the software for operating them and marking obstacles on a map is pretty simple. The problem is to get a good accuracy and fast response time, which is a prerequisite for those sensors to become very expensive. They should also be able to operate in the rugged environment and incorporate the movement of the vehicle. On the other hand, the visual sensors such as all types of cameras need more sophisticated software for their operation but are rather cheap. To be able to use vision sensors to detect obstacles it might require more processing power and hardware capabilities since the data usually produced is more than the one produced by distance sensors with similar detection capabilities. It could make the solution more expensive as well.

In the DARPA Grand Challenge, both technologies were tested, but no comparison of prices has been made, and most of the equipment used is very expensive –in comparison to the price of the vehicle. An industrial machine such as a compactor could reduce the requirements for obstacle detection compared to an autonomous car a lot. There are several reasons for that. The compactor is driving much slower than a car, during construction the moving obstacles such as people and other vehicles are less than normal driving conditions. Also, the low speed gives more processing time for the processor calculating the obstacle position, which means that more time-consuming algorithms could be used, and less hardware and software optimizations are needed. In all those cases, it provides the possibility for cheaper solutions than those integrated with the DARPA Grand Challenge.

The localization of a vehicle on a given map is again addressed in the industry as well as in the DARPA Grand Challenge, but it has slightly different perspective when it comes to the compactor. In the challenge, the cars should follow a predefined map that is known prior to the driving and the accuracy needed was 1 meter [6]. In comparison to that the compactor needs to drive on a newly laid mat. The mat could be laid on an existing route, which has already been marked on a map (the same case as in the DARPA challenges). However, also it could be a completely new route that is just created. It adds the problem of locating the mat and putting it on the map. The accuracy needed is also different - within 50cm as discussed before. The important part here is that this 50cm is not just localization accuracy; it should incorporate the control algorithm errors as well as the actuators error. In order to define the path where the compactor should drive, the integrated software should be able to locate the newly laid pavement and put it on the map with respect to its relative position to the machine. It means that the accuracy of the current position is really important because the map is also built around it.

Another important aspect is the safety and reliability. From that perspective - one information source should not be fully trusted because it may malfunction or completely break. Autonomous vehicles are considered fault-tolerant systems and fault-tolerant systems are systems in which if one fault occurs they can still operate without causing damage to themselves or the surrounding environment. It implies applying fault-tolerant techniques to avoid the presence of the fault or fail safe if a fault occurs.

For solving this problem a commonly used technique in both industry and the DARPA challenges is sensor fusion. There are several techniques for positioning using Global Positioning System (GPS), Inertial Measurement Unit (IMU), Cameras, and Local Positioning System (LPS). GPS systems could be enhanced with Real Time Kinematic (RTK) to provide cm accuracy, which will suffice the requirements. There are several companies working on filtering IMU signals to be able to provide the accurate position.Unfortunately, those devices are pretty sensitive to magnetic fields and vibrations and could be difficult to use them on a compactor machine.

Cameras could also be used for localization. For one camera, it is very hard to calculate distances accurately. So to provide a sufficient accuracy a system of two cameras might be required. This configuration could be very expensive and also may need very powerful hardware to be able to process that much amount of information [17]. Another point is, to detect objects at longer distances; the resolution of the camera needs to be high, which might require even more data processing. Instead, more appropriate is to complement the GPS data with mono camera data and use that fusion to reduce the cost and achieve very high precision on the positioning [18]. Local Positioning Systems are also an option, but these systems might be a problem for the business model of the compactor. In order to use them, the customer should already have them, which could be a problem. When it comes to GPS systems, they are already established and everyone can use them.

The last but not least in importance problem is to localize the newly laid pavement mat and put it on the map. It is required because based on that the machine could build its trajectory. In the DARPA Challenge, the sensors used for localization of the road in the winning vehicle Stanley [6] were very expensive Lidar sensors. They could locate the banks of the road in the desert, and in that way find the borders of it. However, for the compactor this problem is much easier. Opposite to the cars, where the requirements are to drive autonomously on any surface that could be considered as route, the compactor needs to drive only on a hot newly laid asphalt. The usual temperature of the asphalt is between 80 – 120 degrees Celsius, which means that it is almost impossible to have any other object in the camera scene that has the same temperature as asphalt mat. That allows usage of heat sensors such as thermal cameras to locate the pavement. Another option is to use color cameras and detect the asphalt, according to a predefined color. For this, the sensor needs to be tuned to the desired color upfront.

3. Related Work

A preliminary research was carried out over these research community websites IEEE Xplore, Science Direct, Springer, and Google Scholar. First “Autonomous Compactor” were used as keywords. Unfortunately, there were no relevant results in the area of asphalt compaction. The few found papers were related to waste landfill compactors. To explore more the related work in the field, a search was conducted using the phrase “Intelligent Asphalt Compaction” in IEEE Xplore and “Intelligent Compaction” in Google Scholar and Science Direct. It found the papers related to the IACA, geo analysis of the density of the asphalt layers and other papers not related to computer science. That assures the authors that the proposed concept is unique in the research area of Intelligent Compaction and worth exploring. The study of the related work is focused on the foundation papers in the related areas of research.

There two main research areas that are related to the presented work in this report – intelligent road compaction and autonomous vehicles. As a base for the thesis are used papers from both areas. The knowledge is combined together with an additional contribution forming the concept of an autonomous compactor.

In the recent years, the topic of intelligent road compaction received interest both from the academia and industry [3] [14] [19] [20] [21] [22]. However, the work is limited to the compaction process itself and does not address the autonomous operation of the compactor, as this project does. Apart from that, papers - [3], [14] and [20] – have strong relevance to this project. They explain in detail what the current state of the art in Intelligent Compaction Systems is. The Intelligent Compaction Systems are considered part of the autonomous compactor design as described in section 2. They provide the basic requirements needed for enabling full automation of the process. Of particular interest is the IACA device. It allows the possibility of measuring the density real time, which enables the machine to monitor the quality of the compaction work. Based on that the compactor could built a compaction pattern, which is a necessary prerequisite for making it autonomous. And not only that, but also this means that the IACA opens the possibility of building an autonomous machine that could achieve compaction quality comparable to what humans could achieve. All the papers mentioned above are related to the IACA, but the one that summarizes all the research aspects is [3].

In “Intelligent Asphalt Compaction Analyzer” [3], the author present a standalone device as a solution to estimate the density of the compacted area real time. It also could continuously monitor it for the whole length of pavement and not just for several points as in the traditional process. This system is only tested on vibratory compactors and it helps to prevent under and over compaction of the asphalt mat during the compaction process, which is considered vital to the quality of the asphalt. The system contains several different sensors that could be used for different purposes but since the thesis only needs to get data related to the density of the asphalt mat we are not interested in all of them. In the paper, the author describes how the system works and how to mount the system on the compactor. On Figure 3 a) is presented the way the author proposes to install the IACA and all needed sensors. On Figure 3 b) is presented the software functional block diagram that briefly explains the algorithm for measuring the density. The author also describes how to calibrate different part of the system since the system needs to be calibrated before each use. The information about the density of the compacted area will be used by autonomous compactor to track the quality of the compaction. The data provided in the paper shows that the accuracy of the device is promising and comparable to laboratory measurements. That makes us believe that IACA could be used as a part of an autonomous compactor design and it enables the possibilities to design compaction patterns that are comparable and even better than the existing ones.

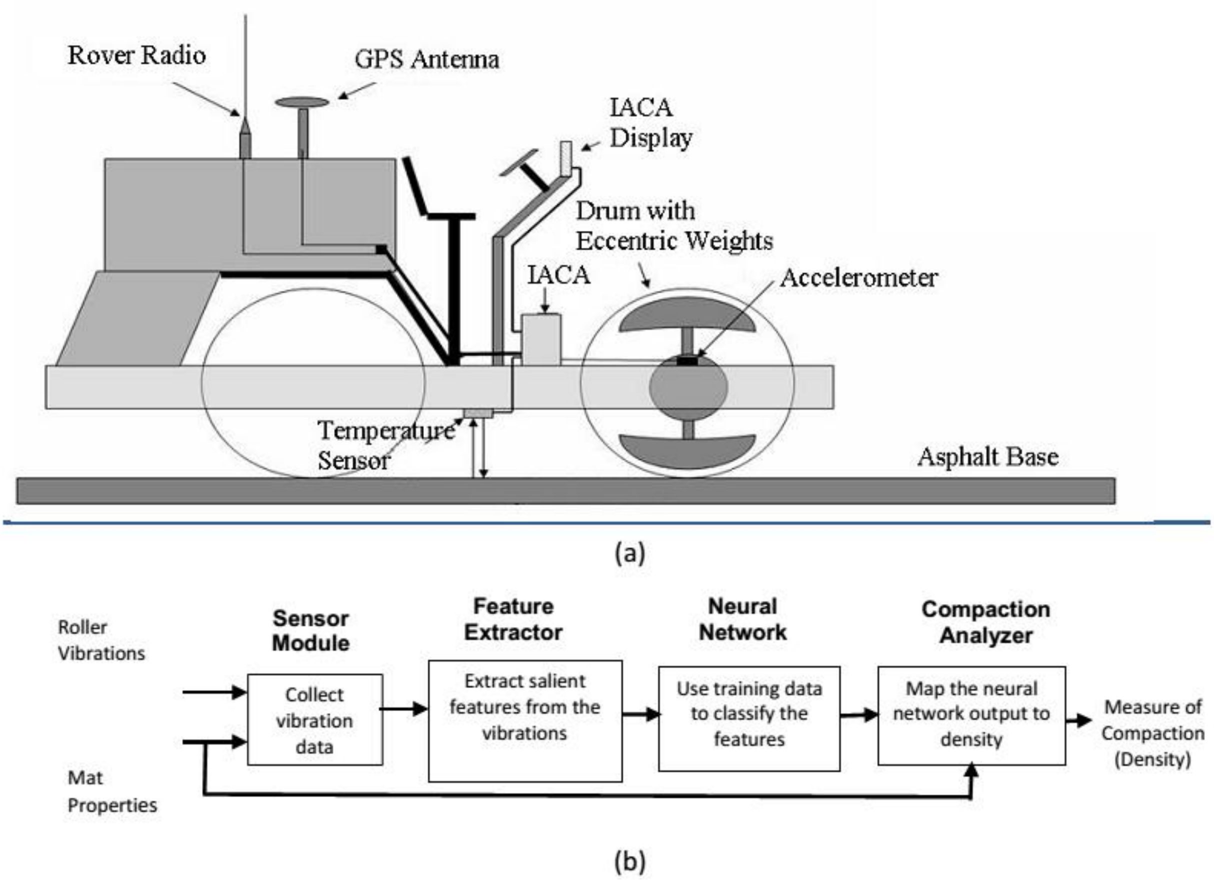


Figure 3. Experimental Setup (a) Instrumentation of the compactor; (b) Functional block diagram of the IACA (Image credit: Sesh Commuri [3])

Besides the intelligent compaction area, another focus of the thesis is on autonomous driving. As a base for this research, we started with the DARPA Grand Challenge [6], a competition held in USA for driverless cars. It is considered the foundation for the autonomous vehicles area. Since the compactor is operating in a rugged environment with much dust, high temperatures, and high vibrations, research work is studied that presents autonomous vehicles operating in those conditions. The second DARPA Challenge [6] was held in the desert which we consider a rugged environment that is similar to what is needed for an autonomous compactor. Another area where autonomous vehicles are studied in a rugged environment is the agriculture. Of particular interest is [23] which presents operating an agriculture machine with high accuracy similar to the one required for the autonomous compactor.

In [6], the authors present the DARPA Challenge competition and 'Stanley' the car that won the challenge. The authors consider the problem for a robot navigating autonomously on a track mainly as a software challenge. The paper presents system design and the implementation of this design on the competing vehicle. Of a particular interest to the authors is also the hardware and software concept as well as the sensor fusion of Stanley.

The shown design covers most of the necessary requirements for autonomy needed for the compactor. It is considered as more suitable for a base for the autonomous compactor because it is simpler compared to the designs from the DARPA Urban Challenge [15]. And it also covers safety consideration, sensing, mapping, road finding, path planning and user interface. However, it needs to be adapted to cover all the requirements for the compactor case. Also, an important difference from the design presented in this paper and the Stanley design is that the autonomous compactor system needs to be made modular. In this way it could cover different sensing technologies and allow different implementation and more flexibility when it comes to prices and precision.

The hardware setup and particularly the sensing technology is very interesting. The presented setup includes various sensor types. The authors show techniques for sensor fusion of vision sensors in term of cameras and distance sensors in terms of laser scanners and radars. They introduce the concept of mapping the environment and use small local maps to make the navigation as simple as possible. The current report uses their proposition but adds to it other sensor types and studies the difference between different sensors and the trade-off between price and precision.

Another interesting section of the paper is the path planning. The proposed simplifications for steering and velocity control and the fact that they are proven to work well in the competition motivate the authors to use them when developing the prototype implementation of the autonomous compactor. However, the control strategies used in this report are changed based on the authors' previous experience in the field of autonomous vehicles.

Since the technology has advanced from the second to the third challenge [15], an investigation over the advancements has been carried out. There are interesting propositions in [15] and [24]. Although studied, those papers did not contribute much to the concept presented in this report.

In [23], the author starts with an introduction to GNSS systems and explains how the navigation system works. After that, he/she explains different use-cases of localization based systems in the agricultural environment. The author used GPS antenna along with RTK antenna for mapping the position of the plant with high precision. Since the localization is a key point in this thesis for finding the position of the compactor and the deviation from the desired position, it is necessary to have a high precision localization system. The author claims that the RTK-GPS based expected seed location versus actual plant position is in the range of 3 to 3.8 cm. That particular study shows that the precision of this system is high enough to be used for an autonomous compactor. The author also presents a method that is used for measuring the accuracy of the system. It is called RMS [25] accuracy. The results from RMS shows that the accuracy of this system is 2.67 cm which means that the system has an error of at most 2.67 cm in 68 percent of the time. The thesis uses a same technique inherited from RMS method called 2DRMS which will be described later in detail. These results are used as a base for the feasibility study on the design and the prototype implementation presented in this thesis.

Other areas that are not directly related to the intelligent compaction and autonomous driving but are related to the current report are communication technologies and image processing techniques. A study of different communication protocols is presented later as part of the system design considerations. For related work we use only the standards as a reference [26], [27] and [28] in order to build an objective comparison between those protocols. That is why we are not going to explain them in detail in this chapter. When it comes to the prototype implementation presented in this thesis for verification of the design, there are image processing algorithms related to the road recognition that are used. Those techniques are found useful by previous experience of the authors. They have been presented in detail in the following papers – "A Computational Approach to Edge Detection" [29] and "Minimum-Area Rectangle Containing a Convex Polygon" [30]. But since the focus of this thesis is on the design of the autonomous compactor and the prototype implementation is only one possible perspective of implementing this design, we would not go into more details about this related work either.

All the described papers above are used as base papers for this report. They are related to the proposed design, prototype implementation and verification techniques. Although very relevant, they are all solving slightly different problem than the one presented in this thesis. So the authors use their findings and enrich them and adapt them to the case of autonomous compactor. None of the presented techniques in these papers are actually used out of the box in this report.

4. Design

In this section, we will cover a concept definition of an autonomous compactor. It will be presented as a functional model. The functional model will include the set of required responsibilities for the compactor in order to be considered as autonomous compactor. Together with that we will propose a base for a full system design of the hardware-software solution required to operate the machine. It will be presented by assigning a system module to each function from the functional model. The system module will comprise of necessary hardware or software or both. Each of the system modules will be described in details together with their functional and non-functional requirements. This section is tightly related to RQ1 and provides the answer that describes all the considerations gathered from the related work, industry and contribution from the authors.

4.1 Functional Model

The functional model represents the set of functions that needs to be available for a given concept in order to be viable. Figure 3 shows the functional model for an autonomous compactor according to our understanding of the problem. The main function is the decision-making that decides which direction should the compactor go and with what speed. In order to do that it should be able to sense the environment (detect static and dynamic obstacles). It should be able to localize itself and the paver to be able to follow the compaction process properly. Also, to achieve quality requirements for compaction [20] it should sense the mat temperature and density.

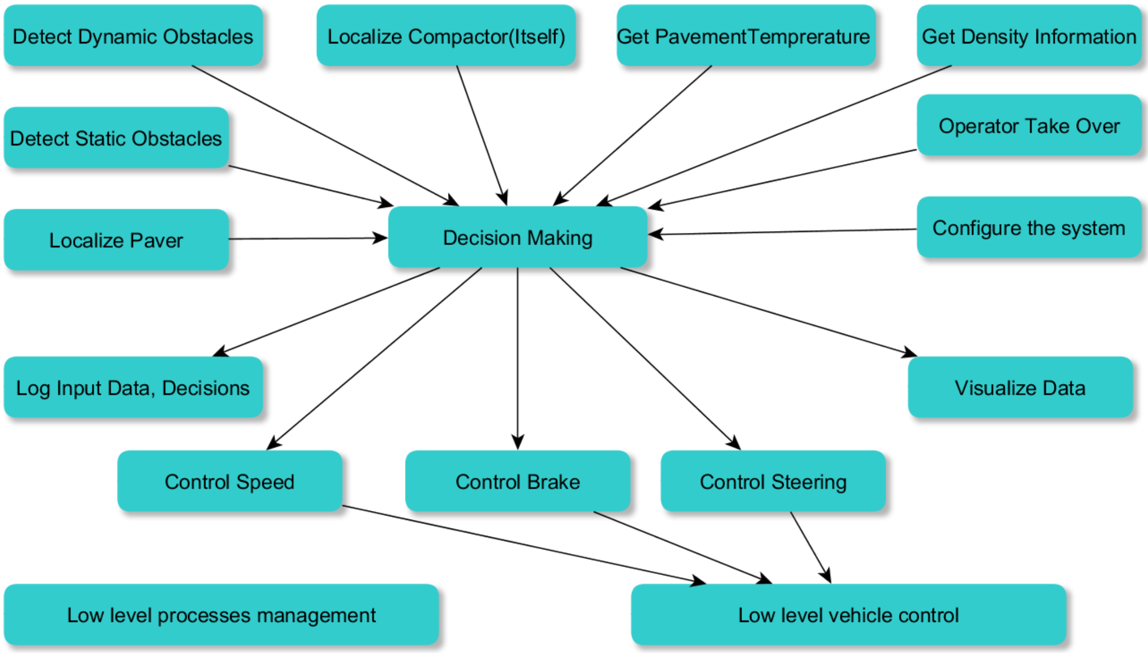


Figure 4. Functional model for autonomous compactor

Another important set of input information should be entered by the operator such as configuration of important system parameters and taking over the machine control in case of emergency. As an output of the decision-making, the implementation should be able to provide commands for controlling the vehicle steering, speed, and brake. It should log all critical decisions for further analysis of the system operation. The system should be able to show all received data to an operator mainly for monitoring the compaction process. The commands output from the decision system for vehicle control needs to be translated into low-level commands. Those commands should be implemented on the machine itself – like steering by wire commands and actuator movements. That is why we define a low-level vehicle control function. Finally, the last function that is related to all the others is the low-level processes management.

Safety is a key factor in autonomous vehicles, and it is required by current laws for the system to detect on its own if a fault has occurred. That implies a need to design the system with self-healing mechanisms in mind. Monitoring of every computer process implementing some of the functions discussed above is required to achieve a self-healing system. And not only that, but we also need to check if the processes are stuck and take appropriate measures if something is suspicious or not working. That is what is encapsulated in the low-level processes management function.

4.2 System Design

The General system design model is presented in Figure 4. As discussed before, since the amount of literature covering the topic of autonomous compaction is very limited, an analogy is made to the automotive industry in order to build this model. The presented model is based on the model used for the car – Stanley [6]. The model used for Stanley was changed and adapted to the requirements and the application of the autonomous compactor. It was chosen because the compactor job is very similar in terms of complexity to the one achieved by Stanley during the DARPA challenge. The requirements for a rolling vehicle are much more relaxed in terms of speed (required speed for compacting is up to 12km/h). It allows a reduction in sensors and processing power. The team that was behind the Stanley concept tackled the problem of autonomous driving fully as a software challenge. In the case of the autonomous compactor, the software will take a big part, but the hardware is also important. Creating a solution according to this design model that has a reasonable price is critical. This criticality originates from the industry because it is hard to justify and integrate a system that increases the price of the machines significantly.

The functions in Figure 4 are taken from the previously discussed functional model. The arrows connecting different modules with the functions represent implementing coverage of those modules for the corresponding functions from the functional model. The arrows that have data related to them represent the data exchanged between modules. The functions needed for operating an autonomous vehicle are executed by four different systems consisting of a variety of modules.

- The first one is the “Sensors and External Systems” (SES). It consists of modules that are handling the sensors, the Intelligent Asphalt Compaction Analyzer (IACA) and the operator itself, who here is modeled as an external system.
- The second one is the “Vehicle system” (VS) it consists of the module that directly access the actuators and modules for handling the feedback sensors inside the vehicle.
- Next one is the “Operating System” (OS). It should be considered as the operating system of the whole vehicle. If the architecture is distributed, this system is distributed. The idea of this system is to encapsulate operation regarding process handling, health monitoring and storing logged data. OS is supporting the operation of all the other systems and applying all required fault-tolerant techniques for the reliable operation of the system.

- The last one, but most complex one is the “Decision System” (DS). As it could be seen from the figure, this system is the main module of the autonomous compactor. It gets all data from the SES as inputs, takes the decisions, and passes the output to the VS and OS.

Each system will be described in more details in the next subsections.

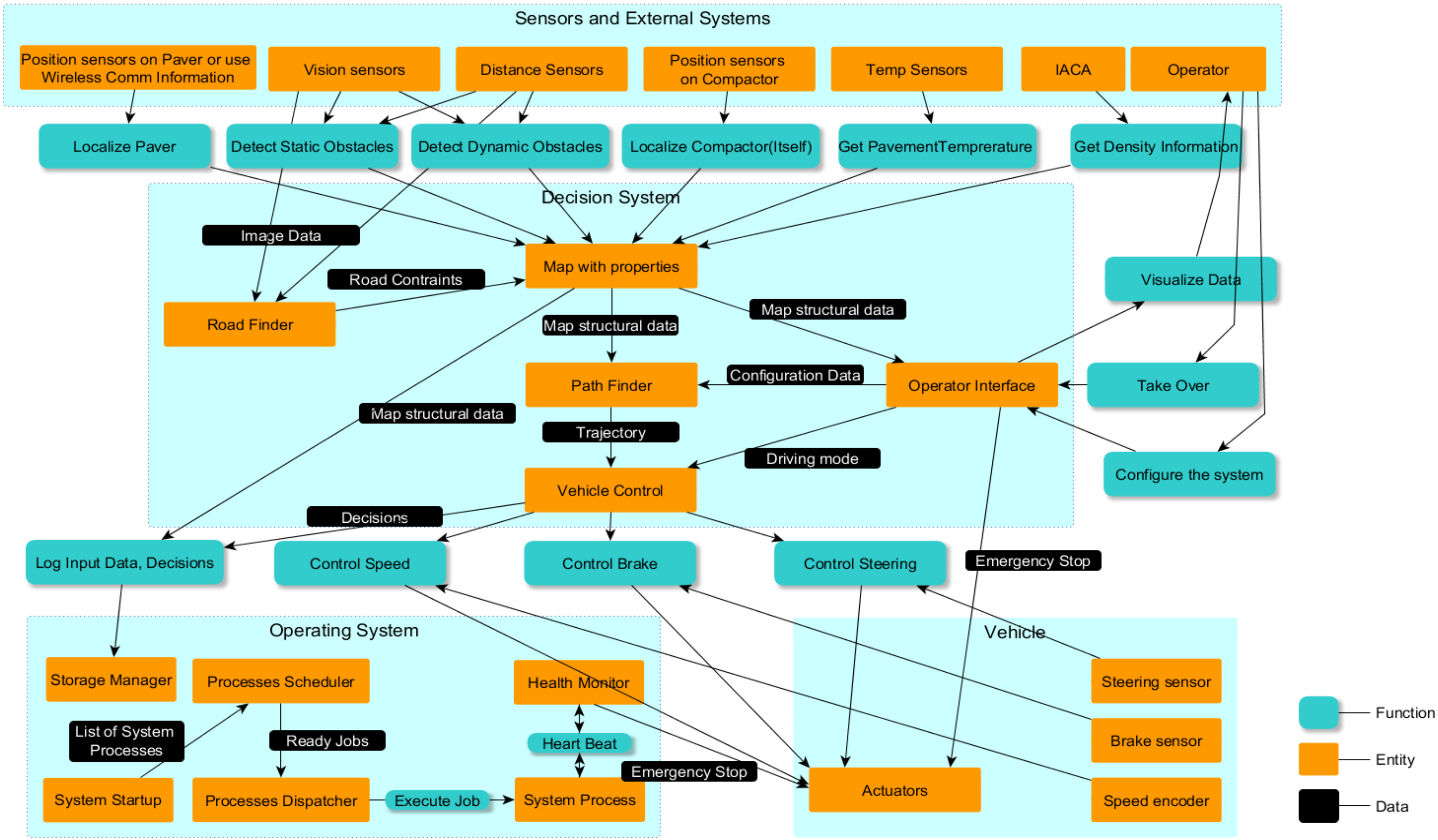


Figure 5. System architecture. It consists of four subsystems – Vehicle, Operating System, Sensors and External Systems, and Decision System represented by the light blue rectangles.

4.2.1 Sensors and External Systems (SES)

This part contains several different entities that give us raw data for different purposes.

Position sensors on paver are used to detect the location of the paver. This data can be used by localize paver function to find the distance between compactor and paver. This data is usable for both paver and compactor to adjust the distance to get the best quality of compaction.

Vision Sensors could contain different type of sensors. The main idea is to detect the road and obstacles on the road (static, dynamic) with visionary sensors like cameras. Detecting the road helps to find the asphalt pavement and make decisions about compaction. It also helps to detect obstacles on the way of the compactor, and it can be used as a redundant system along with distance sensors for obstacle avoidance.

The distance detection sensors are used for acquiring information about the objects around the compactor. In autonomous vehicles, safety is the most important part that should be taken care. In that sense, the distance detection sensors are somehow the most important sensors on autonomous vehicles because the data provided by them is used to preserve the safety of the equipment and the crew.

The position sensor on the compactor helps to find the location of the compactor on the pavement. This data will be used in DS to make a map from the previous locations of compactor and decide about new trajectory.

The temperature sensors are used for detecting the temperature of the pavement surface. This data is useful to adjust the suitable distance between the compactor and the paver. Also, the ability of the asphalt to be compacted will vary in relation to temperature. When the asphalt is too cold, the compactor is not able to compact it.

The IACA is a standalone device and gives information about the density of the pavement. This data will be used in DS to decide about the path planning.

The operator is needed to enter configuration data to the system and also to track the compaction of the pavement and stop the compactor in case of emergency.

4.2.2 Vehicle System (VS)

Vehicle System consists mainly of the vehicle actuators that will act directly on the throttle, brake, and steering. However, it also includes the feedback sensors that give feedback for what has been actuated. The idea is to have a closed loop operation for better precision. This means that for example when a steering command has been sent to an actuator, the sensor will continuously being pulled to check whether the command was executed successfully, and if not this needs to be communicated throughout the system.

The functions that will interact with the VS are controlling throttle, brake, and steering. The VS is also interacting with the Health Monitor. If there is any problem with system health, an emergency stop command is sent to control the actuators and stop the vehicle. Another way of emergency stopping the system is through the operator interface.

4.2.3 Operating System (OS)

The Operating System is the system that provides global services to all other systems. Its name is OS because it is very tightly coupled to the operating system on the device. A responsibility of this system is to provide a start-up/shutdown point to the system. It should also schedule all processes from the other modules in a pre-configured way and monitor their execution and overall system health. It also has to manage data storage. OS is not directly interfacing with most of the other systems, but it is acting as a necessary environment for them to work properly. However, there are some direct interactions such as managing the data storage and also handling emergency situations. In the case of emergency, when critical processes are down or restart of a critical process does not succeed, the OS sends a stop command directly to the low-level actuators interface of the VS.

4.2.4 Decision Systems (DS)

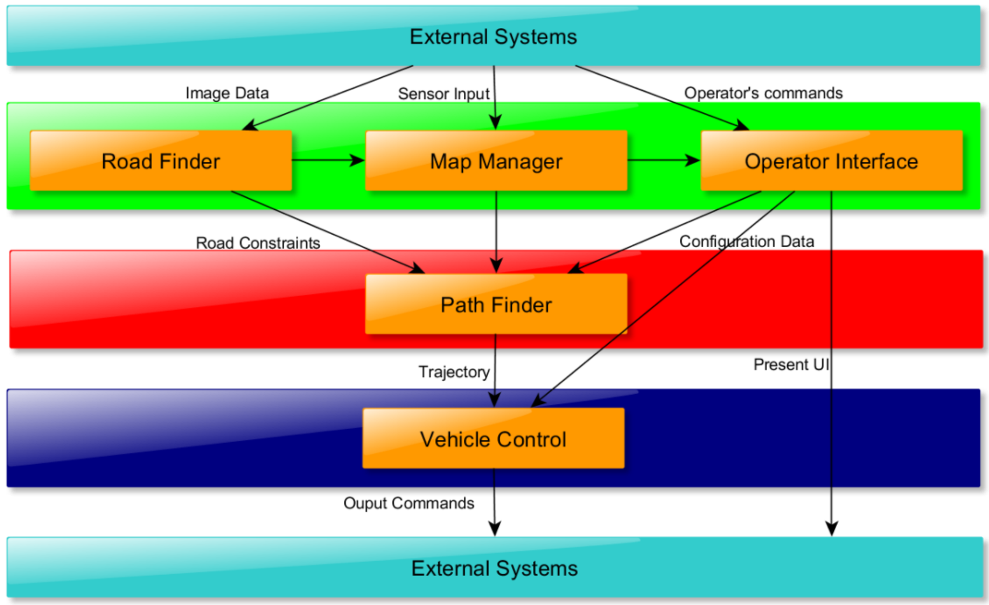


Figure 6. DS overview. Components design as three layer architecture – input layer(green), decision layer(red) and action layer(dark blue).

The Decision System could be considered as the main system of the Autonomous Vehicles. It has all critical responsibilities for operating the machine in autonomous mode. The DS consists of five modules or entities that are responsible for taking the decisions for autonomous compacting. As shown in Figure 5, they could be divided into three layers. The green layer could be described as the input layer. It contains the modules that should structure the input data from the external systems and send it to the next levels for further processing. A special module is the Operator Interface since it also has the responsibility to show the structured data directly to the operator. Here are the three modules in more detail:

1. Map with properties (Map Manager)
   This entity is responsible for gathering the data from the sensors and structuring it as a Map. It should also allow putting certain properties to each point like asphalt density, the asphalt temperature, and if the point is part of an obstacle or not. Essentially this entity could be organized as an object database that will allow querying for certain regions and certain properties. The Map should be able to incorporate all data from the sensors – vision data and distance data and translate it into global points and corresponding properties.
2. Road Finder
   The Road Finder is responsible for finding the boundaries of the road pavement region, so the compactor does not leave it. The compactor has its goal set as coordinates, and it also has position sensors, but in order to anticipate cases when the localization functions output erroneous data, the Road Finder module is needed.

3. Operator Interface
   This entity is responsible to decide what to present to the operator. It also gets the input from the operator and provides it to the other decision taking entities. Operator Interface should use common UI devices such as touch screens to present data to the user like the Map structured data and command interface.

The red layer is the decision layer that forms the goals that the compactor should follow to achieve proper compaction. The goals are specified by a path trajectory. The trajectory is sent to the last layer. The only entity in this layer is the Path Finder. It is one of the most important entities since it has to decide the compactor trajectory based on the map structured data. It should consider all properties of the map like density, temperature, occupied zones by obstacles, the current goal, and the current position. In some emergency situations, it could output no path trajectory available, which should trigger a stop command from next layer.

The last dark blue layer is the action layer. Its function is to decide based on the goals and current situation what action should the vehicle do. The only module in this layer is the Vehicle Control. It is mainly responsible for interacting with the control functions by providing them with desired speed and desired steering. The Vehicle Control should contain the vehicle model and its dynamics, restrictions and constraints to free mass movement. Depending on the input trajectory, it should calculate at what speed the vehicle should be driving and what should be the steering angle. The corresponding control functions should provide algorithms for following certain speed and maintaining steering, they also get input from the VS and its corresponding feedback sensors.

The fault-tolerant aspects of DS have been thoroughly discussed with the experts in the partner company. The DS is a critical part of the operation of the autonomous compactor that is why it requires a special attention. A strategy to ensure proper operation and minimize the risk of malfunctioning could be to make the system distributed. In some cases, it is even mandatory. Some examples are presented below. They cover minimizing the risk of not enough processing power or other resources and cases of not having operator inside the vehicle cab and the underlying physical machine fails.

- Addressing the risk of not enough processing power.
  Processing an input from vision sensors is a heavy operation and may reduce the processing availability to other critical processes like Vehicle Control that is why Road Finder module should be separated from the Vehicle Control. Same could apply to the Map module that manages the map. It will rely on heavy reading and writing operations that may reduce the availability of the processor and other resources, so in this case maybe even separated machine could be considered.
- For the case when no driver is in the cab, an example could be when an operator is sitting in the Paver machine and monitoring the compactor from a distance. Then the operator interface needs to be installed on the Paver, which essentially make the DS distributed.

A similar approach to those problems has been adapted by the vehicles participating in the DARPA challenges [5] [6] [15]. However, more study needs to be done to ensure all fault-tolerant cases are covered.

4.3 Sensing Technology

The sensing technology could be varying in terms of cost, work conditions, and safety.

4.3.1 Position Sensors on Paver

As it is mentioned before this data can be used to find the distance between compactor and paver. The Global Navigation Satellite System (GNSS) is a good option to find the outdoor position of the paver because the paver position accuracy is not that sensitive (around a meter is enough). Then the paver sends this data directly to the compactor via wireless communication, and the compactor is the one that finds the distance. The problem is now with indoor areas when GNSS antenna does not work properly due to lack of the satellite signal. For indoors (like tunnel) there are some different techniques that are not relying on satellites. One of them is short-range communications that use wireless technology Time of Arrival (ToA) to find the distance between paver and compactor. The advantage of using this technique is it is not relying on satellites, and it works in places like tunnels. The problem is this system works at short distances, so to use this technique the paver and compactor should not be too far from each other. Another option is to make a virtual GPS system by having several (at least 3) fixed stations as references and then try to find the distance. The position accuracy of this system is high. Sometimes close to sub-centimeter but again this system works at short distances, so to use this technique we should either move the anchor points time to time manually or find a way to do it automatically. More investigation is needed to find the best solution for this technique. Both techniques are necessary to cover all different conditions.

4.3.2 Vision Sensors

Vision sensors could contain different type of sensors. Cameras could be used in normal conditions to detect the road and obstacles on the road. The biggest advantage is the availability of low-cost components on the market. Unfortunately, these types of sensors are not useable at night and bad weather conditions. Another option to detect road at night is IR camera that is more sensitive to light. It has the same result in bad weather conditions. The good thing is in bad weather condition it is prohibited to do compaction on the road especially the asphalt pavement. So it is a good choice to select an IR camera in this case.

4.3.3 Distance Sensors

There are different types of distance detection sensors that could be used in this project. They vary in terms of cost, technology and speed. They are usually used to give information about the distance from the sensor to objects around the sensor. The data will be used to detect static and dynamic obstacles and avoid collisions. Some of the commonly used sensors are described below [15] [6].

3DLIDAR

3DLIDAR (3 Dimensional Light Detection And Ranging) is one of the sensors that could be used to get distances from different objects and also able to determine the shape of the objects. It uses a wavelength that is not contained in the sunlight, so it does not rely on lighting conditions, and it works at night just as well as in daylight. Because this technique uses light to detect objects it is faster in comparison with the ones that use sound. It helps to detect more objects within less time interval and make a high-resolution map of the environment [31]. This type of sensors usually contains an array of laser beams which gives a 3D image of the environment by distances in real time. Some type rotates 360 degrees and some not. There are different companies that make 3DLIDAR such as Opal (OPAL-360 series), SICK (JEF3xx 3D laser scanner) and Velodyne (HDL-64E). They use different technology to detect objects but all of them are using a laser beam to get distance. Unfortunately, not all of the sensors can give proper information in the rugged environment. Some are sensitive to dust and bad weather condition, but the most important drawback is the price. They are usually expensive, but the cost effect is also valid for mechanical parts. Usually having a single robust and reliable sensor helps to have less complexity compare to having several sensors that do the same job (for example some LIDAR instead of one 3DLIDAR).

LIDAR

LIDAR (Light Detection And Ranging) use the same technology as 3DLIDAR, but it has only one laser beam, and it scans the environment in 2D.There are many companies which produce LIDAR. It is cheaper than 3DLIDAR, and it can be used to detect the exact distance to objects in a certain height (It depends where it is mounted on the vehicle). It is reliable and good to find the distance from objects that are far from the vehicle. It is faster than Radar, but it could not detect objects like glass because the laser beams pass through the glass.

Camera

There are two different types of cameras which can be used to detect distances. First TOF Cameras which works based on time-of-flight technology. It is a camera system that finds the distance based on the speed of light. It measures the time of flight of a light signal between the camera and the object for each point of the image. The entire scene is captured with each laser or a light pulse. It is usually not high resolution, but it is fast. It is not commonly used in the automotive industry, and the operating range is not that high (around 10 meters). The Second option is the 3D camera that provides depth data. This data can be used to calculate distances of different objects in the picture. The camera resolution must provide sufficient depth resolution even for larger ranges. In this case, it is possible to get useful information even at long ranges. For example with 2-megapixel-class cameras and a large stereo baseline of 1.1 m (distance between two cameras) the system could deliver useful distance data even at ranges >100 m. [31]. The 3D cameras need high processing power to process data and find objects related distances. It is complex in comparison with 3DLIDAR and need more investigation in term of complexity, reliability, and safety.

Radar

RADAR (Radio Detection and Ranging) uses echoes of electromagnetic waves of the radio spectrum to detect objects. Because the radio waves do not spread straight, and the shape of the echoes is like a cone, it is not possible to detect accurate positioning of objects. It can define as disadvantage, but it is also an advantage. Because the system can find out that some object is located at a certain distance from the vehicle, and it is not necessary to pointing to the object like what the LIDAR does. It means it has a better coverage in comparison with LIDAR if the exact position of the object is not important. It is also cheaper than LIDAR. Usually, a combination of both RADAR and LIDAR is used to get advantages from both sides. RADAR’s usually vary in terms of detection range. Short-range RADAR seems to be a good choice for this project because the maximum speed of the compactor is not that high (12 Km/h). In the automotive industry, RADARs are commonly used for different purposes like automatic cruise control and lane change assistance.

4.3.4 Position Sensors on Compactor

The estimation of the position of compactor should be accurate. Unfortunately, the GNSS data in real time is not accurate enough (sub-meter) to drive the compactor autonomously by only trusting and using its data. It needs more sensors to fill this gap. The inertial measurement unit (IMU) along with GNSS helps to have a more accurate estimation of the position of the compactor. Of course using more sensors to get more precision increases the complexity and cost but accuracy about the position of the compactor is highly important in this project. IMUs are usually suffering from accumulated error, so it is important to have reliable IMU data to avoid drifting from correct data. It is hard to say which IMU from which company is the best. The price varies from a couple of dollars to couple thousands of dollars. It is not usually the price that shows the precision and quality of the devices, so the best way is to test and check the results. Next sensor that could help to improve the accuracy is encoder on wheels. It gives information about the distance that the compactor moves. All of these data should be filtered in the right way to give good information about the location of the compactor.

Short-range communication is also helpful. Another option that can be used instead of GNSS is Differential Global Positioning System (DGPS). DGPS has some fixed reference stations that broadcast the difference between the positions indicated by the satellite systems and the known fixed positions. These stations usually calculate differential corrections for their location and time of all satellites that they see. Then they broadcast correction signal locally over transmitters to moving receivers. It helps a lot to have a more accurate data about the position of the receiver (a couple of centimeters) but the problem is they are not working for indoor positioning. There is another technique that can be used to find the position indoor like short range GPS system. The good thing is the position accuracy is a couple of millimeter but still the only problem is this system works at short distances. In order to use it, we should either move the anchor points time to time manually or find a way to do it automatically. More investigation is needed to find the best solution from this technique.

4.3.5 Temperature Sensor

Infrared temperature sensor (non-contact temperature sensor) is a good option for this project.

An Infrared temperature sensor already exists on the compactor that is used by IACA to map the temperature of the location of the compactor.

4.3.6 IACA

There is only one option available as IACA. It provides data about the density of the pavement to DS in relation to the location of the compactor.

4.4 Data Exchange

The data exchange could be divided into two different perspectives – data exchange between the system and external systems, and data exchange between modules within the system.

4.4.1 Communication with External Systems

The communication with external systems needs to happen using wireless communication. It will ensure proper operation of the compactor and allow monitoring and control from a remote location.

One possible location could be the paver. The paver operator could monitor the process of paving and provide configuration data directly to the compactor. Since the paver is the main operation machine, it could also be equipped with a wireless device for direct internet connection. This device could get position information from all machines that the paver is in contact with wirelessly. If they are part of the compaction process, then it will update the database with their locations. That will allow synchronization of asphalt delivery, paving process and compaction. Moreover, the speed of the paver and compactors could be controlled based on this information. This synchronization might be difficult to handle by the operator and much easier for a computer. That is why a computer should be installed for performing scheduling optimizations and deciding on the appropriate speed. The calculated speed will be shown to the operator and sent to the other machines in the process.

Since the paving process includes several compactors and several trucks in some road layups, then it might be difficult for the paver operator to monitor all machines. In this case, a separate operator equipped with a remote control device like a tablet or in-house built device could monitor and control the operation. Important parameters for such a device are having a color screen with good a resolution and a wireless interface configured for operation with the roller.

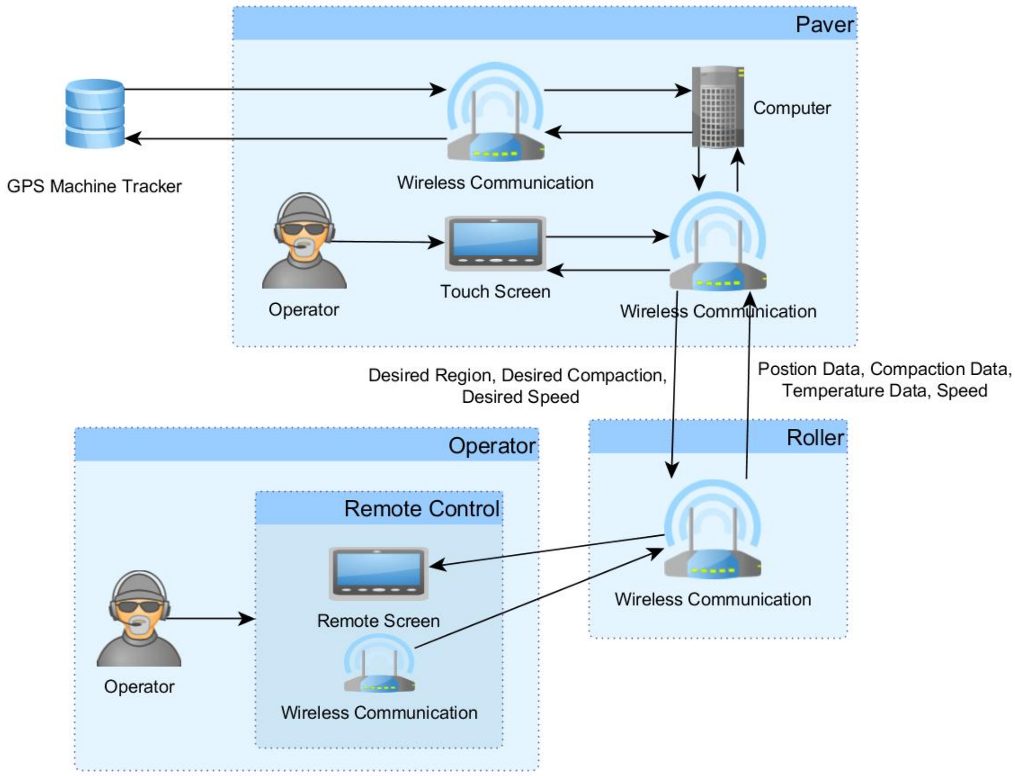


Figure 7. Communication with external systems overview.

Figure 6 shows the flow of information in those two cases. It should be mentioned here that the two cases are not exclusive. There could be two or more operators monitoring the system, and they could use other software to communicate with each other and synchronize their inputs to the Autonomous Compactor System.

In terms of technologies for wireless communication, there are several ways of implementation. One could be conventional Wi-Fi, which will allow the use of off-the-shelf devices. Other ones are Bluetooth or ZigBee. All of these could require additional devices and a further investigation of the ranges and reliability. A thorough study of the choice of wireless technology would not be provided in this report, but a survey of the mentioned technologies has been done within the partner company. The selected criteria for the survey are ‘range of operation’ and ‘price’ – selected by the company, ‘reliability’ and ‘network stability’ – part of the fault tolerance requirements and ‘speed’ – necessary requirement for the systems to operate. Table 4 shows a comparison between the three mentioned technologies according to these criteria. The stars, in Table 4, represent to what level the given technology is fulfilling the corresponding requirements for the concrete criteria. In this case, one star means almost fulfilled requirements but further investigation needed, two stars fulfilled requirements and three stars fulfilled requirements with possibility for development of optional features.

As it can be seen from the table, Wi-Fi has an advantage over the two other technologies in both ranges and speed. The Necessary range for monitoring compaction process could vary depending where the operator is situated, but the considered case is when the operator is in the paver. According to the company, the distance between the compactor and the paver is between 100 – 1000m. The Bluetooth [26] and the ZigBee [27] have capabilities of covering that distance in outdoor. However, if the requirements are changed for example to a static station for monitoring the process, then more devices will be needed to form a network. On the other hand, the Wi-Fi technology with proper antennas and amplifiers could reach several kilometers [28]. When it comes to speed, the Wi-Fi has capabilities up to 600MB/s and using the 802.11n standard, where the standard Bluetooth can up to 24MB/s and ZigBee 250kb/s. In order for the operator to be able to react in emergency situations, all the data should presented in real-time. That data includes map data and sensor data which should be updated at a rate of 50Hz. A prediction of the data size is needed but from the prototype application it seems that ZigBee is not an option.

When it comes to prices, the Wi-Fi devices are the most expensive. Considering their range and speed, they also consume more energy. However, the difference in price is negligible compared to the price of the sensors or the machine.

On the safety aspects, a problem with a ZigBee protocol is that it is a low power protocol. It means that the devices go to sleep from time to time which is considered a risk for malfunctioning or not waking up. Also, since the devices are sleeping, they might more easily lose connectivity in between during their sleep time and thus, need to form a network again which reduces their network stability index. The Wi-Fi and Bluetooth are similar. In fact, the Bluetooth High-Speed protocol is made mostly on Wi-Fi. The reason that Bluetooth is preferred is because of its master-slave behavior and no need for configuration. That allows adding more machines to the network without changing any configuration and using only the master device as presenter to the operator.

Table 3. Comparison between wireless technologies.

	Range	Reliability	Network Stability	Speed	Price
Wi-Fi	***	***	**	***	*
Bluetooth	**	***	***	**	**
Zig-Bee	**	**	*	**	***

There are also other technologies that could be considered for vehicle-to-operator communication, but mainly because they are not well known, they are considered not reliable enough for adaption in the industry. As a result of the survey, we suggest the usage of Wi-Fi or Bluetooth for this type of communication.

4.4.2 Internal Communication within the Autonomous Compactor System

Internal Communication within the system consists of communication between the sensors and the DS, the DS and VS, interprocess communication techniques between processes in OS and communication within modules inside each system.

For communication between sensors very popular solution in the automotive industry is the CAN bus communication. It allows reliable communication and ensures that the high priority messages will always arrive. A problem though could be that the payload of a message is too small and the baud rate rather too small as well for some sensor application. The vision sensors for example or distance sensors such as Lidar could produce a large amount of data for a short amount of time, and that might be very difficult to communicate with CAN bus. For other sensors such as infrared, temperature, accelerometer, and ultrasound the CAN bus is suitable because of its high availability in a rugged environment. Another option that is more suitable for the vision sensors is either USB or Ethernet connection. The USB has made a big progress in the recent years. It allows speeds of up to 3.2 Gbit/sec for USB 3.0 and 500Mbit/sec for USB 2.0. The problem with USB 3.0 is that it is causing interference with devices in 2.4GHz band like Wi-Fi and Bluetooth which might be incompatible with the external systems communication. The Ethernet is also an option. It allows 10/100/1000 Mbit/sec. Some of the sensors like the advanced Lidar sensors used in Stanley [6] are equipped with 1Gbit/sec interfaces. Important factors when choosing the right communication protocol are also the price and the available higher level protocols. Those factors together with the availability and the fault-tolerant mechanisms will lead to the right decision.

For communication between DS and VS, a very reliable network protocol should be used. Erroneous messages could result in wrong low-level commands and eventually in catastrophe. That is why like in the automotive industry, protocols such as CAN should be used. It ensures that the messages with the highest priority always arrive. Its mechanism to check the consistency of the package in combination with time-triggered architecture could ensure decision checking every cycle. It is very important because it enables self-healing opportunities and easier implementation for the low-level processes management module. Ethernet is not suitable because it cannot guarantee the certainty of transmission time or the real-time performance during the data transmission process. It is mainly because of its CSMA\CD mechanism [32] for handling network congestion. No real-time delivery of messages may result in delayed command and lower reliability of the control algorithms. The same could be considered for USB. For example when the collision detection mechanism resends undelivered messages and forces the other messages to wait in elastic buffers until that message is received or when a timeout occurs [33]. There are other automotive protocols, but they have similar properties to the CAN and will not be considered as an option in this document.

The communication between the modules within the DS should be organized in a way that different modules could be distributed to different machines for scalability purposes. It means that higher level communication protocol should be used. The whole system should be real time and the time constraints are very important. As discussed in section 2 the decisions should be taken in less than 60ms. It means that the communication should not rely on protocols that ensure delivery of the message for the price of an undetermined amount of time. Instead, if the message is not delivered at a certain time, it should be discarded, and the next one should be used. Out-dated commands may not be appropriate for the constantly changing situation around the vehicle. The amount of data transfer between the modules of

DS is more than what CAN bus can handle. That is why CAN is not suitable. A consideration for USB or Ethernet needs to be evaluated. Ethernet is more popular and better tested, and there are available high-level protocols that suit our application. One suitable protocol could be UDP. It does not put unnecessary data on the network, like TCP, sends the message as fast as possible and does not check if it is received. Since the communication in all cases is one way, that will guarantee the robustness of the communication. The same arguments are valid for using UDP in the communication between sensors and DS in case of Ethernet.

Finally, a closer look at the communication between all processes in the OS should be done. A centralized system that manages the processes will introduce a single point of failure and is considered not a good practice in safety critical applications. In order to avoid this, OS should be considered distributed and asynchronous. The method used in Stanley [6] is publish/subscribe. It is simple from the implementation point of view which makes it very robust. Further investigation is needed but publish/subscribe could be tested as a viable concept for the Autonomous Compactor since it was already put into practice in the DARPA Desert Challenge.

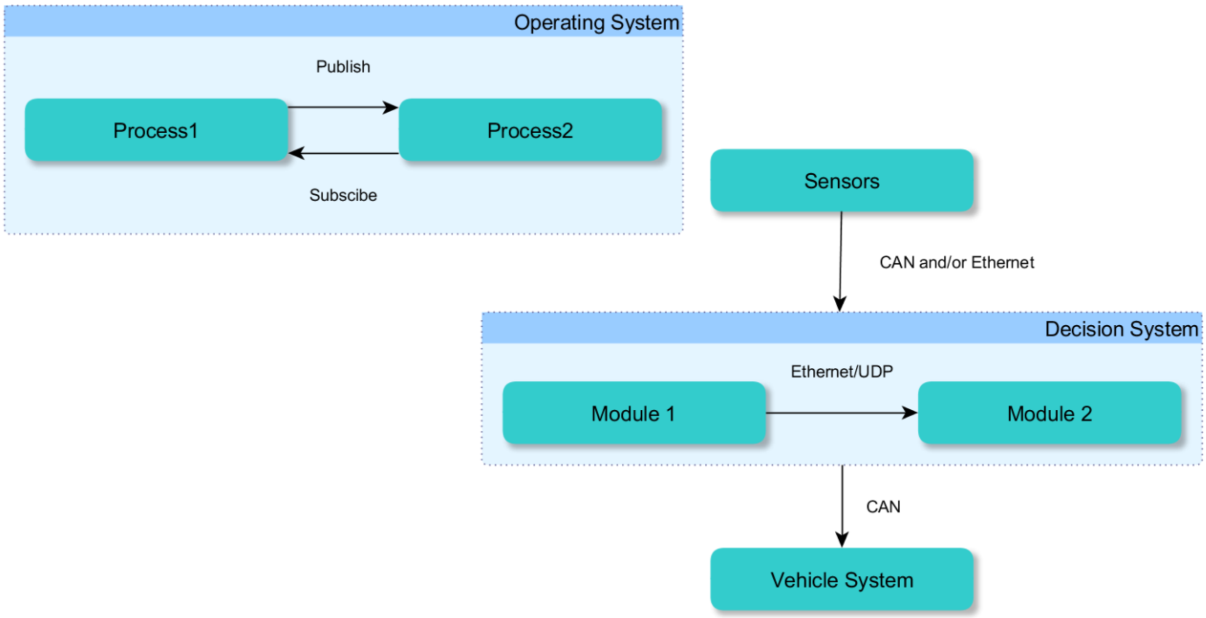


Figure 8. Internal communication overview

The internal communication model is summarized in Figure 7. These communication links need to be analyzed later for critical properties and their behavior in the rugged environment.

4.5 Possible Level of Autonomy

4.5.1 Monitoring System

In this level of autonomy, the goal is to display a map to the user/machine operator together with the proposed trajectory. No real actuation on the machine will be done. Instead, the calculations will be used for a proposition to the operator. In this case, the driver could decide whether to follow the trajectory or not.

It relaxes a lot the responsibilities of the system. It has only supervising role, and the responsibilities for quality and safety are shared between the driver and the system. Since the safety is not that critical, in this case, a sophisticated OS module is not needed. All the scheduling could be done using ad-hoc methods and without spending time on doing a deep down research. The scheduling also could be corrected during operation. The VS is not also needed since the driver will do all the actuation. To allow the driver to stay focused on driving and still look on the map an augmented view might be a good idea, so that he/she can use the screen with the information for him/her judgment.

In Figure 8 the overall functional model is presented. It is very similar to the general functional model for an autonomous compactor presented in Figure 4, but with the simplifications mentioned above.

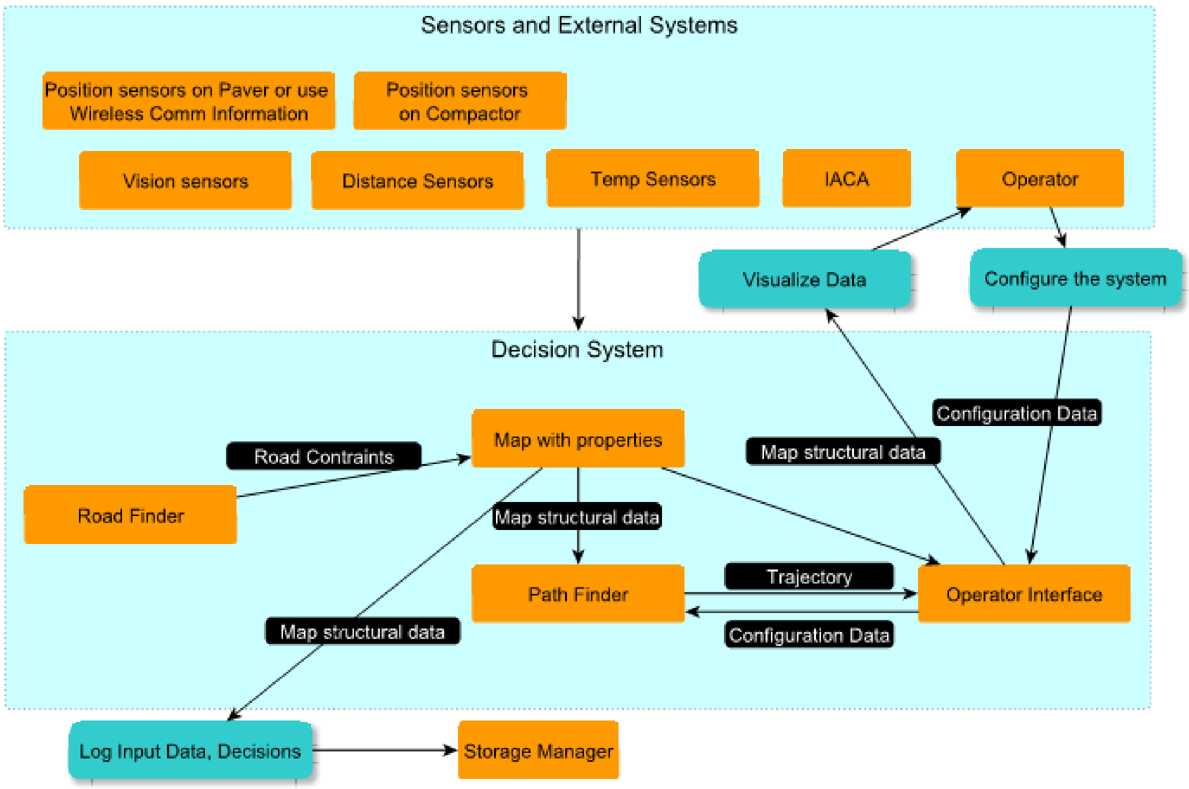


Figure 9. Design simplification for a Monitoring System.

The monitoring system could also be used as an introduction of this concept to the industry since it is a very good tool for winning the trust of the companies that are going to use it. A major drawback though could be carrying that many expensive sensors and sophisticated systems without using their potential benefits on a full scale. So this level of autonomy could be used as a temporary bridge to another more autonomous concept, but not in a full solution because its revenue will be highly doubted.

4.5.2 Supervised Driving

The next level of autonomy after the Monitoring System, which is a no actuation system, is the Supervised Driving. It means that the driver will have to interact with the system, otherwise it is not going to operate. On the other hand, the system will have the freedom to control one or more actuators. All features from the Monitoring System are present here, plus some extra features depending on the particular case.

This type of systems could be used to analyze and verify the risks of making a fully autonomous compactor more thoroughly and gain trust within the industry. It is much more viable in terms of money because the system is partially responsible for the quality of service and safety, so there is a great opportunity for improvement of those properties. In comparison to the Monitoring System, the system will do some part of the work and get some more visible revenue for its price.

Within this level of autonomy three different use cases are identified – System controls only steering, System controls only speed and System controls all actuators.

System controls only steering

In this case, the driver will have to control the throttle and the brake, and he/she will be in charge for the speed of the compactor. On the other hand, the system will control the steering in order to follow the estimated trajectory. The driver also will be able at any time to gain control over the steering by inputting a signal to the system.

In this situation, the responsibility for the quality is more or less on the system, but the safety is still more on the driver as in the Monitoring system. Again advanced scheduling is not necessary but the VS system need to be present with steering actuator and steering feedback sensor.

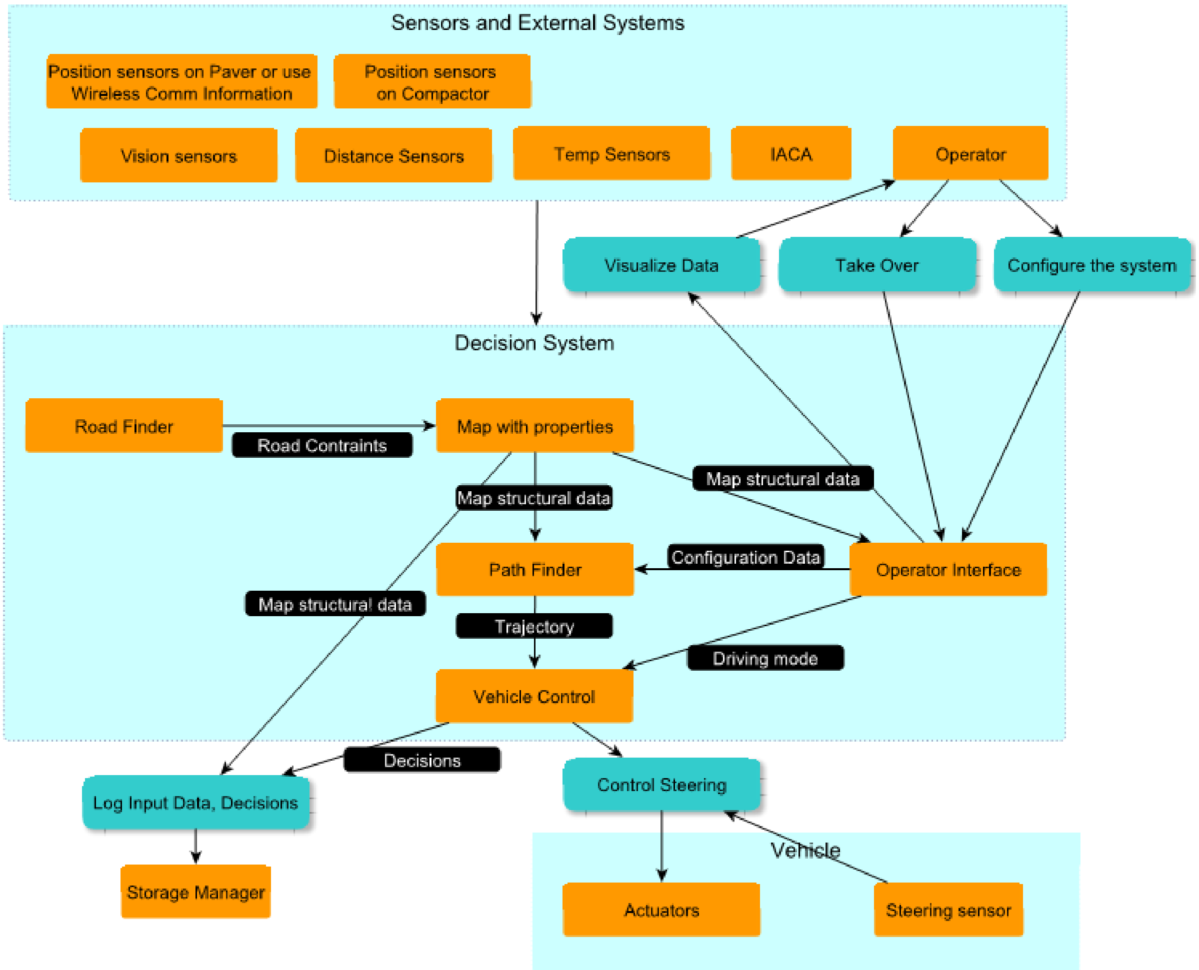


Figure 10. Design simplification for a System that controls only steering

On Figure 9 the overall system design model is presented. It is very similar to the design model for the Monitoring System in Figure 8, but with a few changes. As discussed the VS is present. Vehicle Control is needed in the DS to control the steering. A new operator function is added - Take Over, which will allow the driver to take over the steering at any time.

System controls only speed

In this case, the driver will have to control the steering and also controlling when the compactor should move and when to stop. On the other hand, the system will control the speed at which the compactor should move and follow the calculated speed propositions assuring optimal compaction. The driver also will be able at any time to gain control over the speed by inputting a signal to the system. This mode could be implemented as considering the throttle pedal as an on/off switch. When the driver pushes the pedal, the compactor will start running, and when the driver lifts the pedal the compactor will stop. However, the input from the pedal would not be used for any other purposes then on/off switch. If the driver inputs a takeover command, then the pedal will work as normal. It is just a suggestion and any other on/off switch could be used as well.

In this situation, the responsibility for the quality is shared between the system and the driver, but the safety is still more or less on the driver, as in the previous levels of autonomy. For the same reasons, we can discard advanced operating system tasks. The difference is that VS system will be needed for control of the throttle and break together with the speed feedback sensor. Also in the Vehicle Control a function is needed for controlling the speed and the brake. The overall system design model shows in Figure 10.

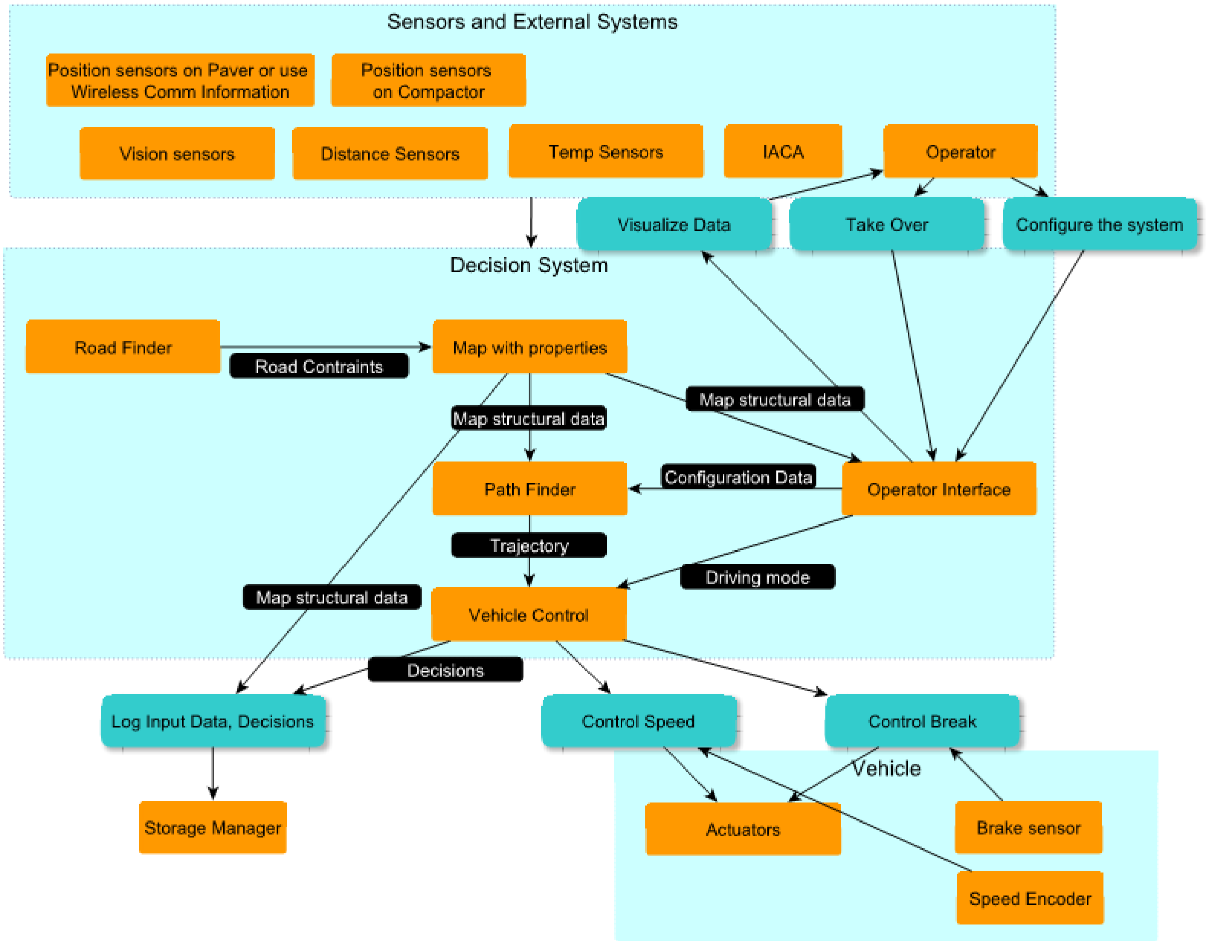


Figure 11. Design simplification for a System that controls only speed

System controls all actuators

In the last case, the system will be able to control all actuators and follow the trajectory fully autonomously, but the driver will control when the system should run and when it should stop. The driver needs to press and hold an on/off switch for the system to run. One example of how this could be done conveniently is explained in the above paragraph – "System controls only speed" – the case is using the gas pedal as on/off switch. This measure is needed to relax the safety responsibility of the system. However, in order to relax them, the system should be sure that the driver is present in the vehicle. That is the role of the on/off switch to ensure that the driver is in the vehicle at any time the system is operating.

In this case, the system will be fully responsible for the quality, but the safety will still be shared with the driver. Since we are not completely relying on the system for safety, the advanced scheduling is still not needed. The quality is important, so any process malfunction could lead to emergency stop and jeopardizing the quality of that particular spot. So, in this case, the system needs to have a self-monitoring mechanism to heal itself if something happens to a process. It means that the OS system will be present, but only in the sense of health monitor that will take care of process malfunctions, and even will back up the driver in case of emergency situations.

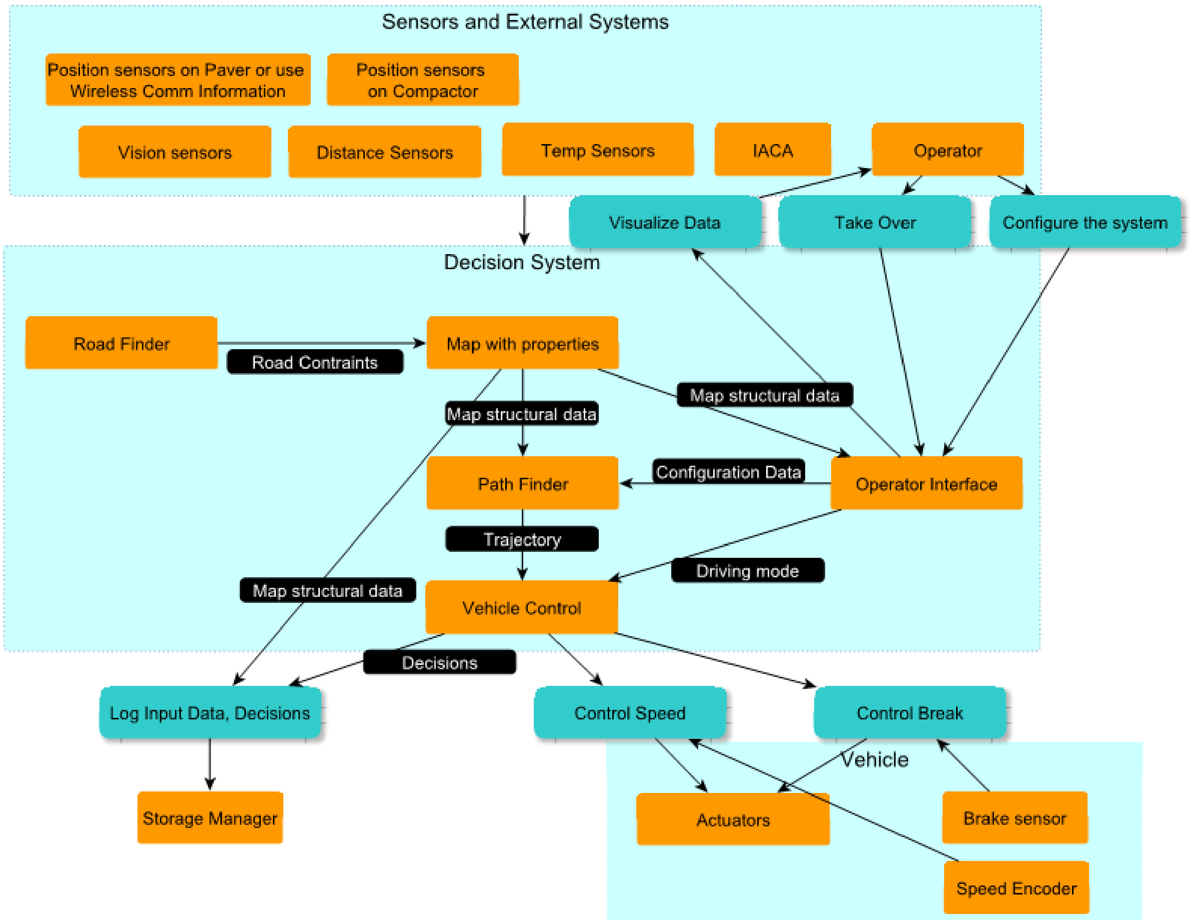


Figure 12. Design simplification for a System that controls all actuators under driver supervision

In Figure 11 the design model overview is presented for this particular case. The VS is the same as for a fully autonomous compactor, so the only difference is the advanced scheduling.

4.5.3 Autonomous Driving

The last level of autonomy defined here is the fully autonomous compactor. In this case, after once entered the autonomous mode, all responsibilities are up to the system that controls the compactor. The quality and safety are no longer shared. Of course, the system provides a takeover function as well as several ways for emergency stopping the vehicle, but it should be able to operate even without supervision.

This system will include all components described in Figure 4. In terms of implementation, it could be considered as an upgrade from one of the previous steps or fully separated development and totally different approach up to the development team.

5. Implementation

In this section, will be presented an implementation of a subset of the design functionalities. This subset is considered enough to proof to the industry that the concept of autonomous compactor is possible to be realized within certain cost constraints. The presented solution is a test-bed that allows performing experiments to proof that such system could cover the requirements for pavement process. However, it could not be directly used for autonomous compactor because it does not have the needed industrial quality. The main goals are to be able to conduct tests on a real machine and to find answers to the scientific questions about the movement accuracy of the vehicle, performance of the system, and cost effectiveness of the solution. The implementation is needed to answer RQ2 and prove that critical requirements could be met by following the proposed design. More on the methodology for performing tests and evaluating results are presented in section 6.

5.1 Scope

The implementation provided here will cover the system design for “System controls only steering” level of autonomy. This level is chosen because it is covering most of the systems for the overall design, and it is a good trade-off between complexity and functional coverage. The Monitoring System does not do any actuation, which means that the test with the real machine will be hard to conduct. Thus, this case is not appropriate to proof of concept for the current topic. Certain limitations on the available test machine do not allow the team to control the speed of the vehicle, which cuts-off all other levels of autonomy. Finally, as discussed earlier in the chosen level of autonomy, the responsibility for the quality is more or less on the system. That is considered more valuable to the partner company than just having a monitoring system that could be built in a lab using a simulation environment.

5.2 Platform

Since we are aiming for cost effective solution and the IACA is running on a low-cost computer such as tablet, we decided to build the autonomous compactor software (ACS) in an Android environment and if possible install IACA and ACS on the same device. The hardware platform for the ACS comprise of Samsung Galaxy Tab 3, AXIS Q1931–E Thermal Network Camera, AXIS M1014 Network Camera, GNSS, RTK stationary antenna, and CPAC module for communication with the machine. Table 5 shows the important parameters of the tablet. The Intel processor allows execution of 4 threads in parallel at one time instant. These characteristics are important for giving a perspective on the performance of the presented implementation solution. All performance metrics will be measured and evaluated on this platform.

Table 4. Samsung Galaxy Tab 3 specification

CPU	1.6GHz Dual Core; Intel® Atom™ Processor Z2560; Number of Threads – 4.
Memory	1 GB RAM
OS	Android 4.2.2 Jelly Bean
Display Size	10.1”

The AXIS cameras provide image data for localization of the pavement on the map. The thermal camera specification could be found in Table 6. Important for the evaluation procedure are the frame rate, sensitivity, and resolution. The video compression is important for the solution since it is a vital part of integrating the camera into the software. Moreover, the operating conditions mark the bounds for operation with this hardware; they are presented to show that this type of camera could be used for performing asphalt compaction. The measurable temperature is 300 °C. The Axis Company could also provide different housings for cooling the camera sensor if the surrounding temperatures are more than 60 °C.

Table 5. AXIS Q1931-E specification

Sensitivity	< 70mK
Video Compression	Motion JPEG
Resolution	388 x 288
Frame Rate	Up to 30 fps
Operating Conditions	-40 °C to 60 °C Humidity 10 – 100%

GNSS together with the RTK provides the position information to the compactor. This system provides data within centimeter accuracy. Finally, the CPAC module for communication with the machine provides functionality for getting all the data from the machine CAN buses and streams it over Wi-Fi to the tablet.

The operating system is Android 4.2.2, and the implementation language is Java.

5.3 Machine setup

Tests were performed on a wheel loader machine instead of a compactor for several reasons. The main reason is that the compactor could not be driven on a regular road because it can ruin the mat. There are only specific test facilities where tests with compactor machines could be performed, and the current project does not have access to one of those. Since the partner company is producing the steering-by-wire systems for both machines, they assure us that the way both machines are steering could be considered the same. So tests of the system that is controlling only steering could be done on that machine. More on relating the results from the real machine tests to compactors could be found in section 6.

The wheel loader (WLO – Figure 12) has similar dimensions as the compactor, the same steering mechanics, and its big advantage is that it has wheels instead of drums. On a later stage, the system on a compactor should also be tested to verify the assumptions of similarities and check the dynamics of the machine. Calibration of the control algorithms will be required to achieve the expected movement accuracy. The calibration procedure is explained in section 5.5.

Figure 13. Wheel Loader used for testing

5.4 Overview

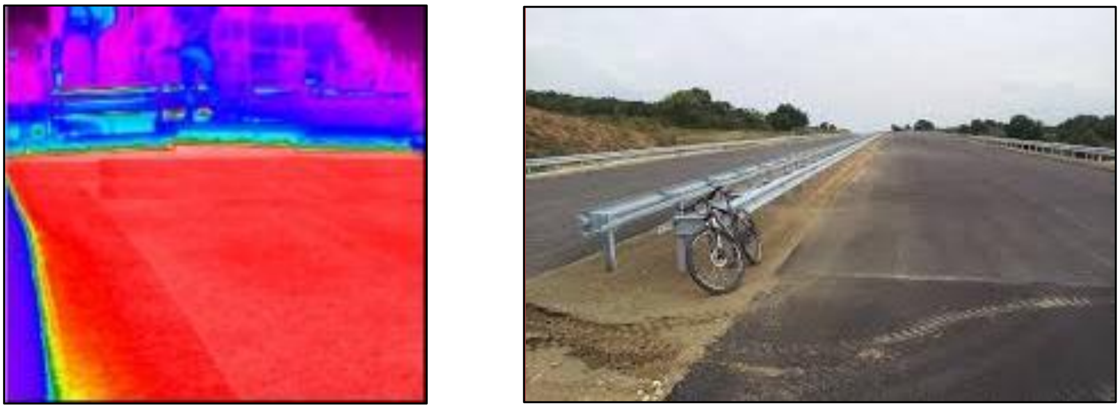
In section 4.5.2 an overall design of the system is presented. The ACS application developed for testing the design and answering the research questions is following the design for **“System controls only steering”**.

For the current implementation, the Vehicle System is considered as an external system. It is a steering by wire system developed in CPAC Systems AB, and it also provides feedback sensing for precision control.

The Storage Manager is an SD card inside the tablet, and all the logging is done using Android’s file operations.

The sensors system comprises of the two cameras for visual sensing and GNSS system for positioning the compactor. For the current implementation, IACA is not used, and the interaction with the Operator is only for visualization of the software decisions, map, and inputting configuration data.

The reason for choosing a thermal camera for localizing the pavement on the mat is that the mat for compaction has a very high temperature compared to the environment around it. That makes it very easy to distinguish the mat from the other objects in a picture provided by a thermal camera. A particularly hard case for a normal camera is when there is a newly laid mat next to an already compacted or old mat region. In Figure 13 a) is shown a thermal camera pointed at the hot mat, the mat is the red region of the picture, the blue-purple region on the left is an old asphalt mat. In Figure 13 b) is shown a newly laid mat, which ends next to the bicycle and an already compacted mat after that. It is showing how hard the problem could be if not using a thermal camera. The heat camera could be selected with a low price when short distance detection is needed as in the case of the compactor (up to 50m) and when the driving speed is not very high – around 3m/s,.



a) Thermal Camera Image b) Normal Camera Image

Figure 14. Camera images. On a) there is an image from a thermal camera and on b) is another image from a normal camera. It shows how difficult could be detection of road with normal camera and how easy with thermal

One very efficient image-processing algorithm that fits perfectly into that solution is to use edge detection algorithm such as Canny [29] to find the edges of the mat. Then fit them into the smallest possible rectangle (Min Area Rectangular Fitting [30]), which will give the area where the hot asphalt is. After that, the area is localized with respect to the camera position and the compactor position and positioned on the map. This simple two-step algorithm provides the necessary accuracy for pavement localization as well as an efficient algorithm that could be run on a low-cost platform.

The ACS software covers the decision system and includes communication mechanism to get data from all external systems, and interaction with the operating system and tablet user interface.

5.5 ACS – Decision System

The implementation of the decision system is organized as follows.

The starting point of the application is the Operator’s Interface. It means that the operator needs to start the application manually. The application is installed as a normal Android application on the tablet and from the programming perspective the starting point is the main Activity of the application (for more details see [34]). This activity contains the implementation of the interaction between the application and the user. When the application is started, it runs all other components in the background and starts outputting commands to the vehicle itself.

On the screen, the user can see the position of the compactor, the desired road to be followed, the camera data, GPS data, and CAN communication data. Besides that the user could also interact with the application by manually setting desired steering for testing the application, and starting or stopping of logging mechanisms are also possible.

The UI design is presented in Figure 14. On the top left corner, the user gets information about the current GPS data received. On the bottom left corner are presented the frames received by the two cameras and in the middle are situated the buttons for starting/stopping the logging and manually interacting with the steering. The operator can start and stop the logging of the data or can send a command to the steering with inputting desired steering angle. The last button is for saving the visual log presented on the top of it. That visual log shows all the commands send by the ACS to the steer-by-wire system on the vehicle. Finally, on the right part of the screen the user could watch the movement of the compactor, can monitor the gates and the goal lines calculated by the Path Finder. It allows the operator to monitor the work of the ACS in real time.

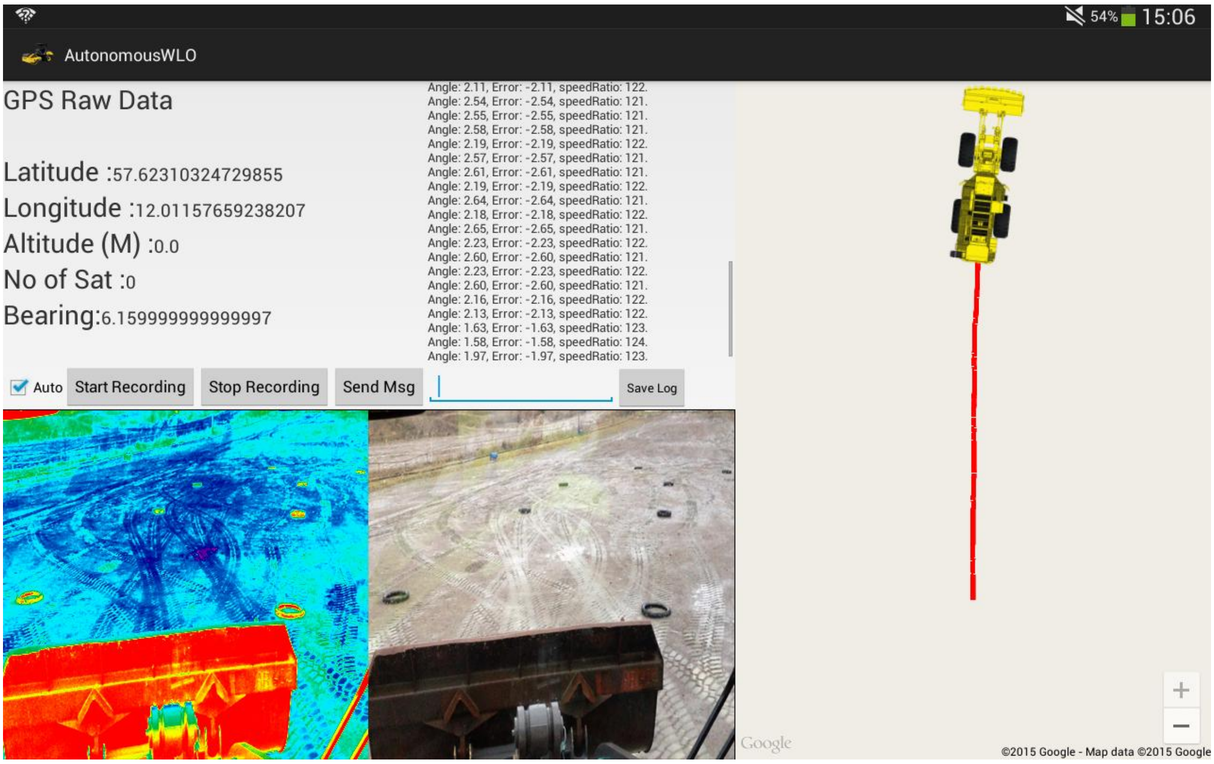


Figure 15. Screenshot of the UI of ACS

The Road Finder is implemented to recognize the road profile and use it as a correction to the GPS positioning. To locate the road position and complement the pavement position information is entered manually into the software as gates.

The gates are points on the border of the mat region and are recorded into a file prior to application use via helper application – Position Recorder (PR), which will be discussed later in section 6.3. It is also used for validating the movement accuracy. The gate is represented by two points each of it representing a GPS coordinate. Those points are the border of the gate, and the compactor is supposed to go through the gate following its middle line. After that, the gate information is read from the Path Finder to position the road on the map. The information from the cameras is used to locate the road on the frames, match them between the two, and then provide the results to the Path Finder. The Path Finder uses this information to relate the position of the compactor to the position of the two points of the gate and possibly correct its output based on that. For efficiency, the road finding functions are executed on the arrival of new frames. They are designed to do checking if the two frames from the two cameras arrive within certain predefined time. If they do not the Path Finder does not output any information. It relies only on the statically defined data and the GNSS output.

When processing the images, the Road Finder converts the image to black and white by using a thresholding and after that applies the algorithms discussed in Section 5.4. First it uses the Canny algorithm [29] for edge detection and contour finding. Then the result contours are fit into Minimum possible rectangle [30]. The biggest rectangle in the picture within certain dimensions constraints and with a certain ratio between the long and short side is picked. If a rectangle is not found, the frame is dropped. The reason for that is that the frames are arriving 5-6 every second and the decision should be taken in 20ms, which means that the algorithms that are used have to be very efficient. If a rectangle is found then, the Road Finder uses the lowest middle point of the image as a reference to the compactor. Then it computes the ratio between the distance from the compactor to the left border of the road and the right border of the road. This ratio is used by the Path Finder to correct the compactor position on the map if needed.

The input to the Path Finder comprises of the current compactor position in terms of GPS coordinates, compactor position on the road in left/right border ratio, and road profile in gates represent as a pair of GPS coordinates. As discussed above the ratio is acquired from the Road Finder and the gates are statically defined in a file and read by the Path Finder on system boot up. The current position is received from the GPS antenna installed on the machine. The Path Finder takes this information and produces a goal trajectory as an output that the compactor is supposed to follow. For simplicity, the trajectory is selected as a perpendicular to the gate line passing the gate in its middle point (see Figure 15). The yellow points on the map in Figure 15 represent the goal line, the green – the gates and the red – our current position. The control error is the distance between the current position and the goal line. Also, the Path Finder is responsible for finding the edge of the compaction area and informing the Vehicle Control when it needs to stop the vehicle.

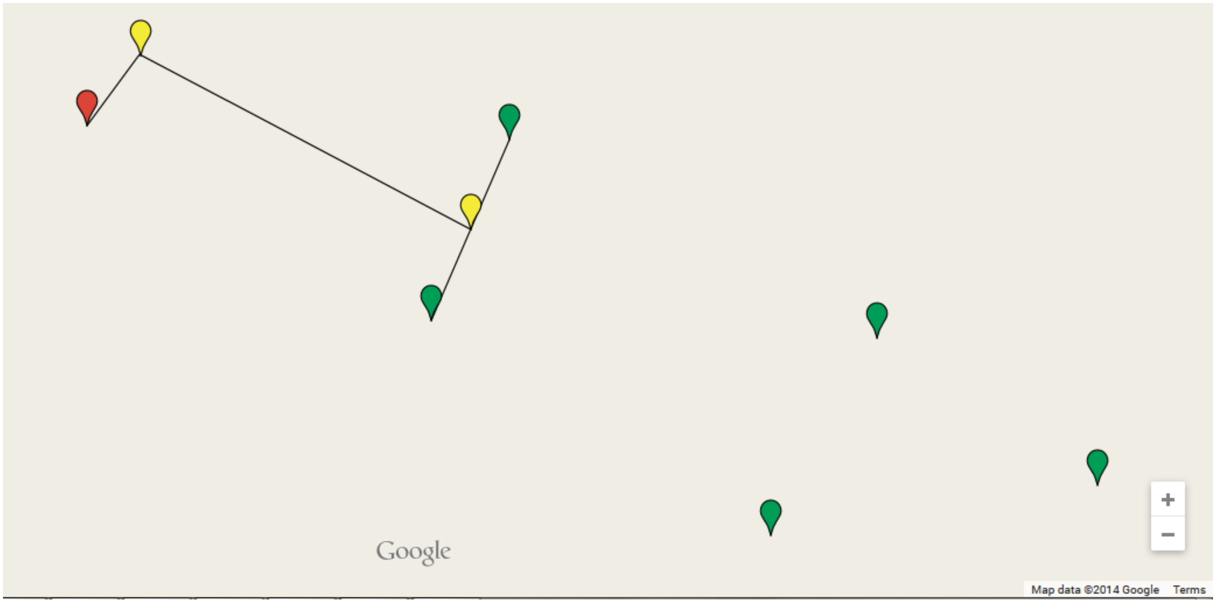


Figure 16. Gates and current goal line
(screenshot with own overlay data; image credit: Google, Inc.)

The Vehicle Control is using a PID control algorithm to follow the goal trajectory output by the Path Finder. The PID parameters are tuned during testing, and certain measures are taken to minimize the erroneous behavior. For example, the integral error is limited in the range of plus-minus two times the lateral error. The range of steering angles that are allowed could be also configured. For the current machine that range is between -32 and 32 degrees.

The Map as a data structure exchanged between different components is represented by a set of GPS coordinates. In the terms of visualization, the Google Maps API is used for plotting those coordinates in real-time and showing them to the user.

5.6 ACS – Communication

The communication between the systems is designed according to Section 4.4 and follows the organization shown in Figure 16. The cameras are IP cameras that are powered by Power-over-Ethernet technology, so they are delivering the images by streaming them over Ethernet. The CPAC communication box contains Power-over-Ethernet switch to power the devices and receives the data, and a Wi-Fi module to send it to the tablet. It also contains a CAN module to receive the data from the sensors on the machine (steering angle sensor and vehicle speed) and from the GNSS and stream it to the tablet.

The Wi-Fi communication allows several tablets to be connected to the system, and if they have ACS installed, several operators can look at what is happening on the machine. On the other hand, if there are concerns about bandwidth or security, a 1GB direct Ethernet connection is available. Unfortunately, of-the-shelf tablets do not allow direct Ethernet connection. In this case, an adapter is needed to translate the data to a USB port.

When the data is received on the tablet, the ACS is attaching a timestamp to each data object. The data is used in the algorithms if it has arrived within a predefined time window. If a critical data is not received in the current time window, no command is output to the machine, so it keeps the previous command. When switching to fully autonomous mode, the software should enter an emergency procedure for failing safe and should notify the operators for a sensor or communication failure.

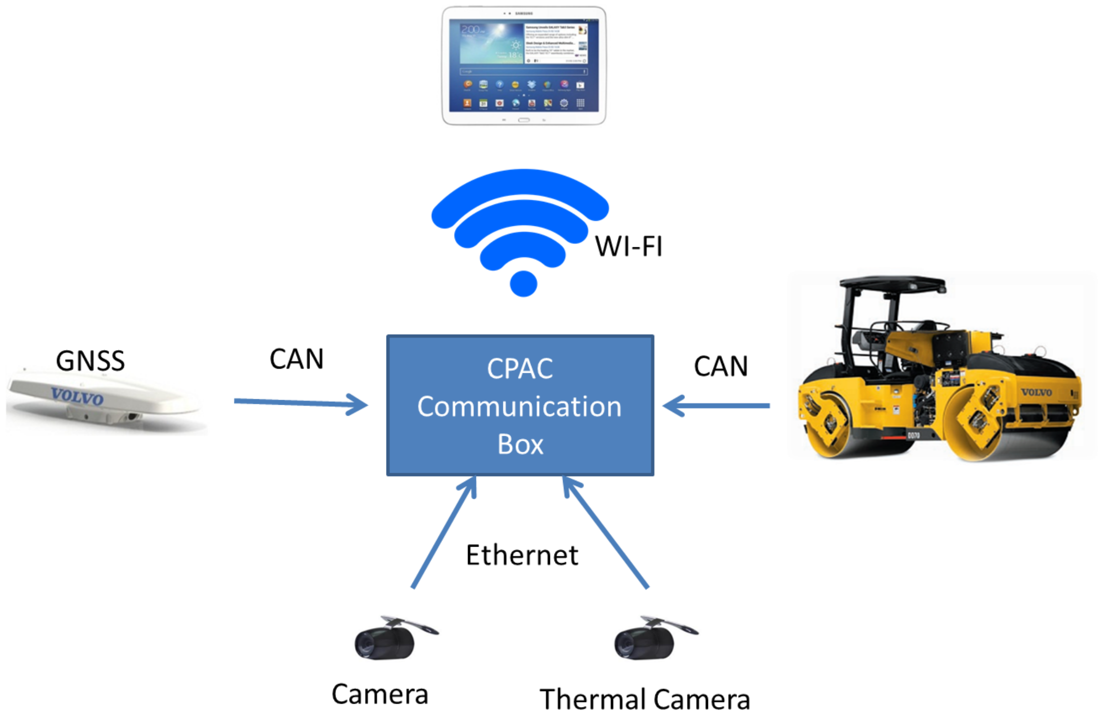


Figure 17. Overview of system communication. It includes communication with sensors, the tablet and machine itself.

6. Evaluation

After presenting the design and prototype implementation in previous sections, this section presents the evaluation of this design and how the provided implementation could help in that process. In the first subsection, a set of specific goals will be set. They are in close relation to the already defined research questions in the introduction section, but with increased granularity and well-defined outcome. After that, the methodology for evaluating the design of those goals will be formulated, and all methods and tools for achieving the answers will be shown. Later on, results from all the carried out tests will be presented. In the final subsection, a detailed analysis of the results will be conducted, and the section will be concluded with a discussion on the limitations of the methodology and the presented tests.

6.1 Goals

The evaluation of the design for an autonomous compactor will be focused on proving that the critical compaction requirements could be met (RQ2).

In order to do that, answers to the rising questions from the process requirements that are explained in section 2 should be found.

- G1. Could a system, designed according to the design in section 4, follow a movement accuracy of 50cm? (inexperienced driver [2])
- G2. Could a system, designed according to the design in section 4, make a decision within 60ms?

Finally, there are additional questions from the industry concerning the cost-efficiency and safety of the system:

- G3. Could a system, designed according to the design in section 4, occupy less than 80% of processing power and memory resources during its operation?

This final restriction allows the proper operation of the underlying operating system and possible additional software that might be required for facilitating the operation of the system.

In order to prove that the design answers RQ1, we should provide evidence that the critical modules in the design are feasible.

- G4. Are Road Finder, Map Manager, Operator Interface, Path Finder, and Vehicle Control feasible for implementation?

To make future work easier later:

- G5. The evaluation should also provide a base understanding of where the weak spots of the presented technology are, and propose improvement measures for future work.

6.2 Methodology

In order to achieve the defined goals, several techniques need to be used to prove that a system designed according to the design can perform as specified in those goals. For that purpose, the prototype implementation described in the previous section was developed. It helps to quantify the answers to the goal questions. For each goal questions, an evaluation will be conducted on the prototype implementation including tests on real platform (described in section 5.2), simulation tests, and validation tests over the gather data against external software system with better precision.

6.2.1 G1 – movement accuracy

For G1, movement accuracy tests are conducted. The system is evaluated on a compaction test scenarios with a simulator and one test scenario with the wheel loader machine in the real world. The tests on the simulator are mainly used for finding appropriate parameters for the high-level control algorithm and also for identifying the complex scenario that could be used as a real world scenario. However, as evaluation results only the results from the real world scenario are considered.

The simulator is described in more detail in section 6.3. The simulation of machine movement is verified with real data from the wheel loader. Although the results from the simulator could not be directly matched with the real world, they show trends and relations between different configurations and scenarios.

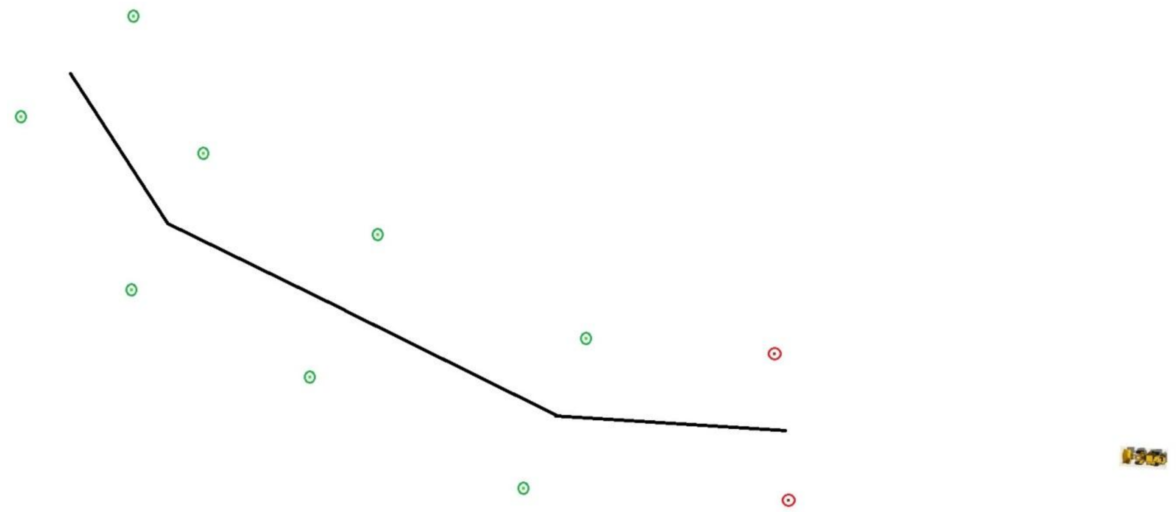


Figure 18. Road profile used for the tests. The dots represent the gate markings. The red ones show the next gate and green – not passed gate.

The road profile over which the machine need to do compaction is input to the system as a set of gates as described in section 5.5. A representation of the chosen road profile that is used during the real world tests could be seen in Figure 17. The corresponding profile is chosen because it represents maximum curvature (30m) on a highway according to the American Association of State Highway and Transportation [35]. Another reason to take a curve is because it is considered more complicated than following a pattern on a straight line. The turn could be made smoother by interpolation and essentially adding more gates, but it is deliberately left with sharp turns to allow investigation of the limitations of the machine and the current algorithm. Those sharp turns will not be part of a normal compaction work. They simulate situations when the compactor is supposed to change its steering angle rapidly in order to compensate an error, avoid an obstacle or follow irregular patterns based on the density data. The input from the simulator is taken into account when designing the test scenario and also the limitations of the testing area. The test scenario includes both driving forward and backward as well as shifting goals with the width of the vehicle. A desired overlap of 50cm is tested as required by the compaction process specification [2].

Figure 18 shows a run of the test scenario performed in the simulator. The machine starts at the lower right corner; then it performs one run in the middle of the gates and reaches the green checkpoint at the top left corner (first compaction round). After that, it drives backward until it reaches the other green checkpoint on the other side of the road. At that point, it switches its position to follow a trajectory parallel to the previous one but with the size of the compactor – 50cm skewed to the left of it.

The movement accuracy is measured as a lateral error between the traveled path and the expected traveling path. In order to suffice G1, the maximum error during the run should be below 50cm. To verify the actually traveled path, the precision of the GPS system and its error – external in-house developed software is used called Position Recorder. It uses

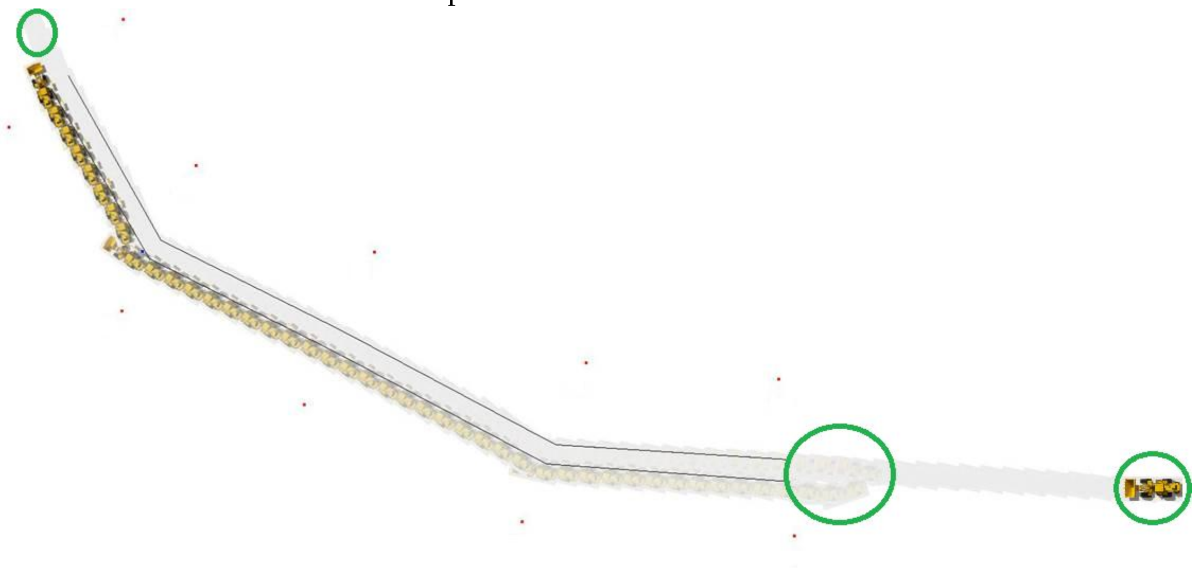


Figure 19. The test scenario implemented in the simulator. The machine passes the road once forward, then backward, and finally switches a lane to the left and passes it again forward.

statistical methods to measure current location with high precision. It is described in more details in Section 6.3. So after the test is performed, random measurements are taken on the traveled path to verify the precision of the GPS data received by the system. It is important because the maximum deviation from the desired road is measured with the GPS system, and we need to know its precision to be able to ensure that the results are within some boundaries in real world.

6.2.2 G2 and G3 – performance measurements

For G2 and G3, an application is used to monitor all processes on the platform and report CPU and memory usage. Based on the output from this application, the response time analysis is conducted to show systems' response time. The measurements for the performance are taken during the execution of the real world scenario for the movement accuracy test because that ensures the system behavior in the production environment. One measurement represents a 1-minute monitoring of the system's process with 60 times probing the operating system on CPU usage and memory usage. That gives a statistics on the response time and CPU usage for 1-second. Higher probing rate increases the CPU load above the 20% allowed for external processes and may not leave enough processing power for the ACS. An additional counter is added in the implementation of the prototype software to count number of task executions for one second (tasks are time triggered, executions could between 9 – 11 per second in the normal case). For calculating the response time of one task execution, an average value is found by dividing the probing measurement by the number of executions for one second. A deviation is calculated by taking into account the minimum execution time of a task that is measured with the same software. This time it is scheduled to execute every second and it is monitored for 10 min – 600 executions.

6.2.3 G4 – feasibility

The evaluation relies on the smooth performance of the movement accuracy tests to achieve G4. For the components that are implemented and fully functional in the real world test scenario, no further motivation is needed. Those components are Map Manager, Path Finder, Vehicle Control, and Operator Interface. They comprise the whole system that is running the tests, and the system cannot operate without them being functional. It ensures their feasibility. The only component missing is the Road Finder. Its integration into the system is not needed, but in order to show that it is feasible, it is needed to run it during the test runs and show that it performs its job. So the Road Finder was also running during some of the tests processing image data from the cameras and recognizing the road based on them. That ensures that the measurement for G2 and G3 is also accurate.

6.2.4 G5 – Error analysis and quality tests

For G5, a thorough analysis over the successful runs is made to find out what are the main reasons for movement accuracy error. The reason to use only the successful runs is because on the other runs misconfiguration of the high-level control was responsible for the error and do not allow fine-grained analysis. Also, one possible reason for reducing the quality of localization are the weather condition and the number of visible satellites, that is why a recording of this data is made before running each test.

Besides that, the following methodology is used to configure the system. So the tests are performed on a quality system. The simulation environment is used to find relatively good parameters for the Path Finder and Vehicle Control. The low-level steering control is tested directly on the vehicle to save time and to get accurate results. Some of the tests runs over the real world scenario are used for tuning the configuration, especially the ones that do not suffice the critical requirements for the compaction process.

6.3 Tools and complementary software

To be able to measure the outcome of the system behavior and trust the data and results, external tools and software are needed. The tools used are two in-house built applications – Position Recorder and AC Simulator, and two external Android applications – System Tuner Pro and Usemon. Position Recorder is designed to measure the current position with high precision and also to evaluate the precision of the GPS system. It is needed because ACS process only uses one measurement, and it is important to know how accurate that measurement is. AC Simulator is used for simulating test scenarios, offline tests of the system, and tuning. System Tuner Pro and Usemon are used for the monitoring process, system performance, and response time. System Tuner Pro is more advance application. It uses low-level functions to access processor information. It can use processor timers if available to measure how much time each process is using the processor. The second one is used only for verification. It uses high-level kernel functions to monitor performance characteristics. A decision is made to use two independent applications to show that the results are consistent and accurate. The latter of this section will present those external tools and software in more details.

6.3.1 Position Recorder

This application is used to find the gateway points with high precision and save them to use them later as an input to the Map Manager. The procedure for recording is as follows.

First the GPS receiver is placed at a desired point and recording is turned on. Then the received data is recorded for one minute and finally a calculation of the mean value is done to get the best possible point from those recorded points.

Besides that, it is also used to calculate the precision of the GPS system on the machine. Moreover, a validation for this precision is done on the field during the real life scenario. The validation points are the ones where the compactor crosses the gate. So the Position Recorder is run on those points after a test run. The logged data from the machine is compared with the one from the Position Recorder. Then it is checked if the value from the logged data is within the precision range.

The software has two main functions – record data and analyze data.

- **Record data**

After starting the application, the person should wait until the application shows the position. After that by pressing the start button it starts recording data. Since the user is interested only in the current position, the GPS should be standing still. The application records the timestamps and coordinates (Latitude, longitude) of each point. Then it converts them from degree (geographical coordinates) to meter (UTM coordinates) at the same time and save both in a temporary file. The recording is stopped by pressing the Stop button.

- **Analyze the data**

After pressing the stop button, the application stops recording the data and starts calculation of the mean value (μ) for Latitude which is defined as X and longitude which defined as Y in meters. These values are converted to geographical coordinates and saved in different file to use as gateway point and comparison to other data in the future.

The application also calculates the accuracy of the data with the help of Distance Root Mean Squared (DRMS) [25]. DRMS is a value that shows the 2D accuracy. This value represents the radius of a circle centered on (X, Y) that contains 68 percent of the recorded points. The smaller the radius means the higher is the precision. The application UI is presented in Figure 19.

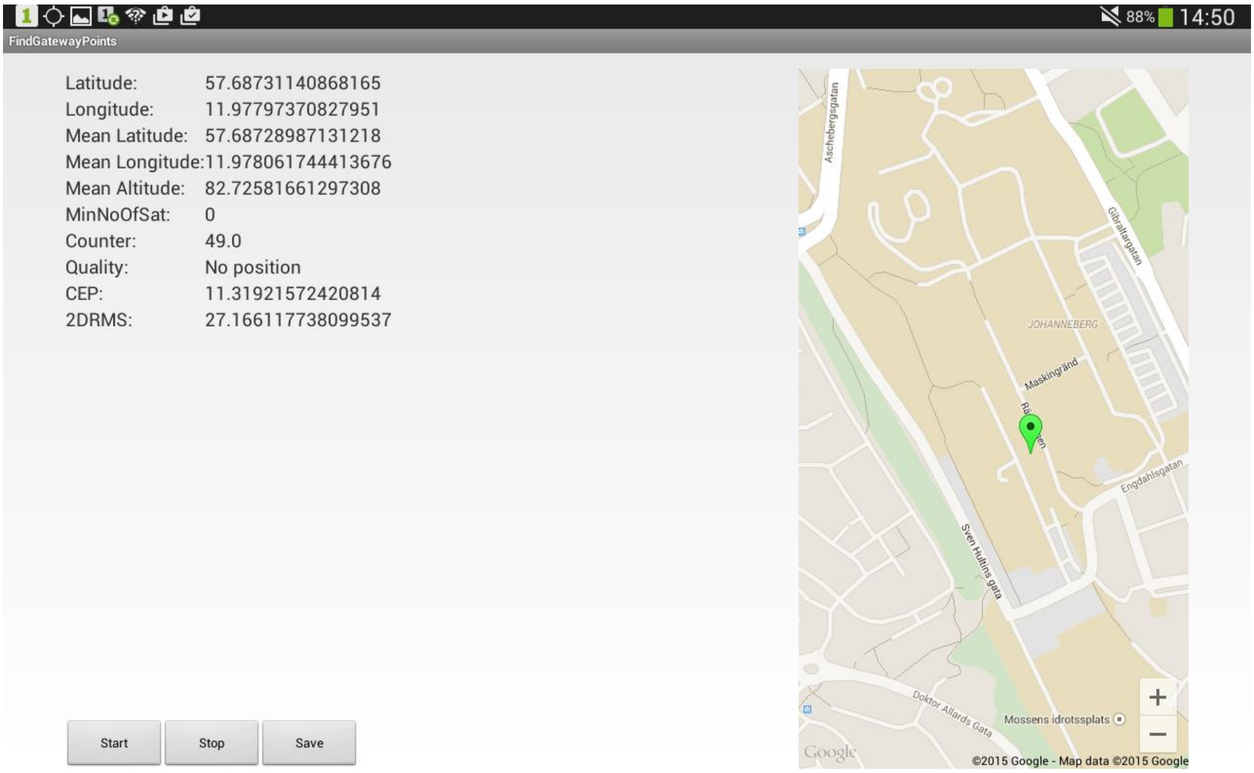


Figure 20. Screenshot from the Position Recorder software.

To calculate DRMS, X and Y are needed (available from the GPS). After that, the standard deviation of them is calculated. The standard deviation is the average distance to the mean value. Below is the formula used for the calculation of the standard deviation. N is the number of points gathered during the recording:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

The calculation of the average distance to the mean value is calculated for both X and Y and results in the pair(σ_x, σ_y). To find the circle radius around (X, Y) that contains 68% of the points, the following formula is used.

$$DRMS = \sqrt{\sigma_x^2 + \sigma_y^2}$$

According to the empirical rule, in Figure 20, if we multiply this number by two the result is the radius of the circle that contains 95% of points [25].

$$2DRMS = 2\sqrt{\sigma_x^2 + \sigma_y^2}$$

The application also calculates the Circular Error Probability (CEP). CEP contains 50% of points, and it calculated as follow [25].

$$CEP = 0.83 * DRMS$$

Approximation could be done one from another by following the relation:

1 meter CEP = 1.2 meters DRMS = 2.4 meters 2DRMS

After the calculation, the application shows the (X, Y) point on the map and by clicking save it save all data in a file and clean temporary files.

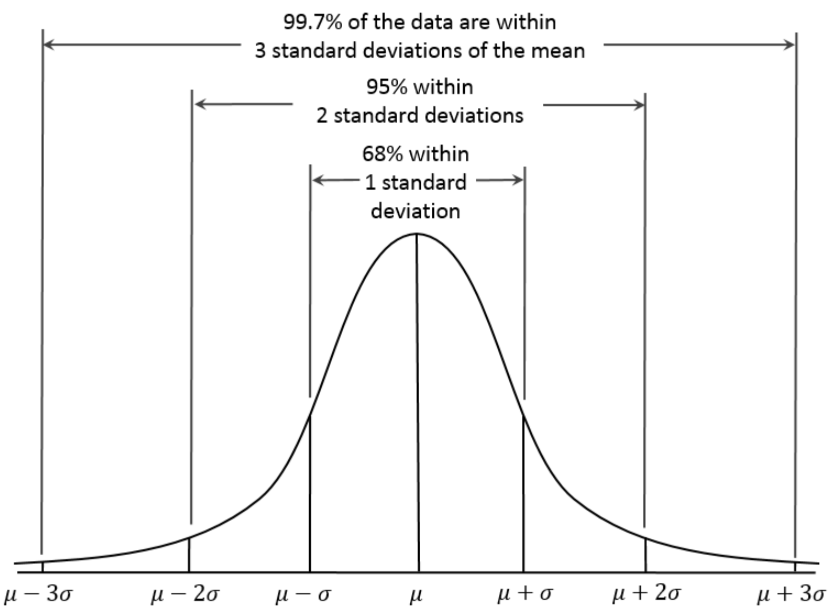


Figure 21. Comparison of DRMS, 2DRMS, and 3DRMS [36]

6.3.2 AC Simulator

The Autonomous Compaction Simulator is software that simulates the movements of the machine based on speed and steering angle. In each moment of time, it takes the current speed, vehicle parameters, and current steering angle and outputs the new position as GPS coordinates where the machine is expected to be. It also models and simulates the steering actuation as an articulated-point steering, and it incorporates the delay for steering as in the actual machine.

The simulator has a graphical interface that allows plotting of logged data and plotting of an on-going simulation. The input to the simulator that is specific to the machine is the width and length of the machine. The length of the machine is divided into two parts, front-to-articulated-point, and articulated-point-to-back. Also, the steering actuation delay as ms per degree has to be specified. For convenience the system allows time limit parameter to be specified, which defines when the simulation should stop if the scenario is not finished. The AC Simulator is important because changing the parameters allow finding relations between the prototype machine and another machine where the software will be implemented. In our case the results from the wheel loader machine could be transferred to a compactor machine and that will allow smoother transition of the knowledge to a real compactor.

Another important aspect of the simulator is to provide an environment for tuning the PID control algorithm for the vehicle. Simulation is done over several scenarios to find an appropriate scenario for the real world test. Also, PID is sensitive to speeds, so over those scenarios simulate runs are made in all possible compaction speeds (0.8 m/s to 3.4m/s) in order to determine optimal parameters. In Figure 21, a comparison between different parameters sets is made after simulating the real world scenario over all possible compaction speeds. The result from this is the parameter set 4 is used during the real tests.

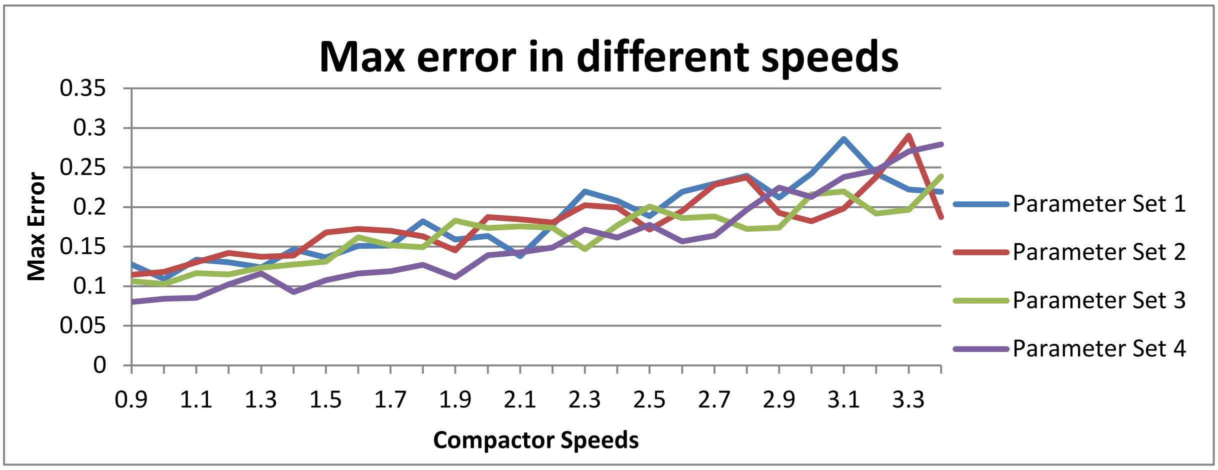


Figure 22. Comparison of different parameter sets during tuning.

The simulator can also be used to replay recorded data and calculate statistics based on that. It allows calculating mean and max error over the run, traveled distance, and localizing the max error point on the map.

6.3.3 Performance Tools

Two external programs – System Tuner Pro and Usemon – are used to measure the performance characteristics of the system. Both of them allow monitoring the processor load in percentage and memory usage in MB. Usemon is monitoring from a global perspective, and it does not distinguish the demands of each process, but it is mainly used to complement and verify that the results from System Tuner Pro are correct. System Tuner Pro allows monitoring per process and calculation of response time because it records how long each process has occupied the processor. Figures below show snapshots of the system load during a real world test scenario on the field with the wheel loader machine.

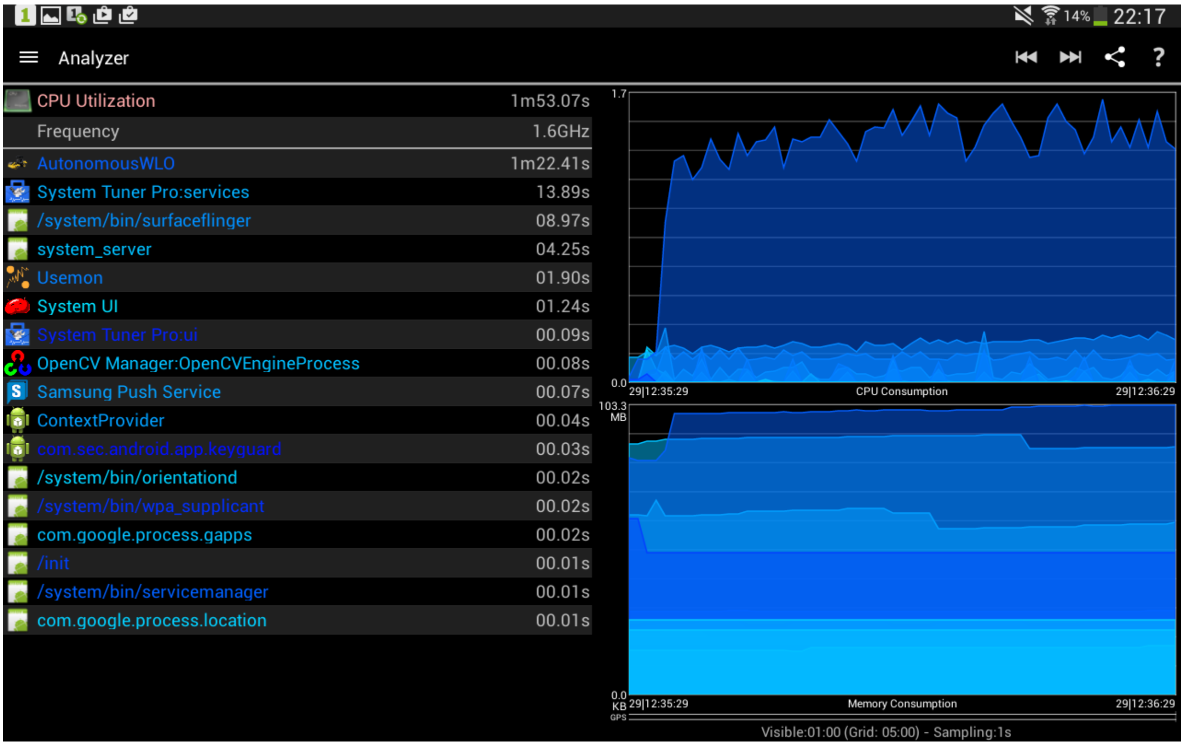


Figure 23. Monitoring of individual processes with System Tuner Pro.

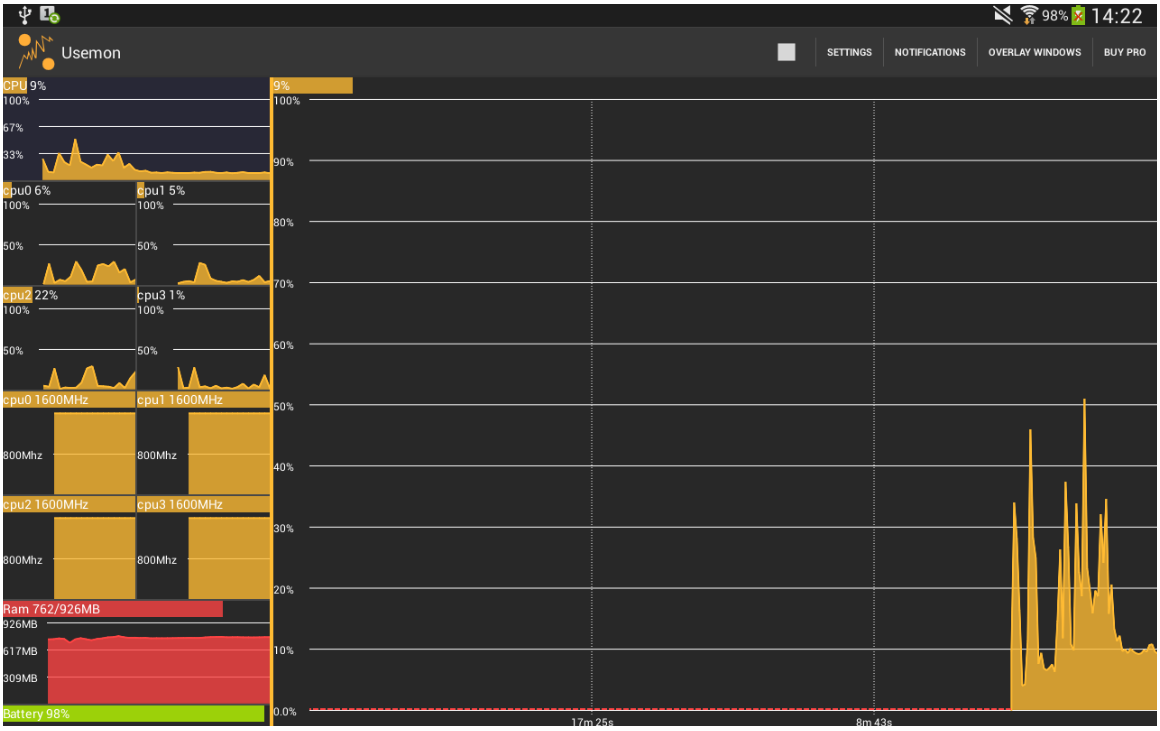


Figure 24. Monitoring of system load with Usemon.

6.4 Results

In order to fulfill the goals, the authors made ten testing sessions with the test platform described in Section 5. Those tests sessions started with integrating the software system with the machine. After that configuration and tuning of the Path Finder and Vehicle Control were done. Then finally the test sessions ended with performing the real world scenario described in Figure 18. For the real world scenario, 17 test runs are conducted over three days.

6.4.1 G1 – movement accuracy

Fourteen out the seventeen test runs are used to make the system stable. The last three test runs are a full simulation of a compaction scenario without changing the system configuration. Results from the mean and max error measurements could be found in Figure 24. The red line is representing the goal for movement accuracy.

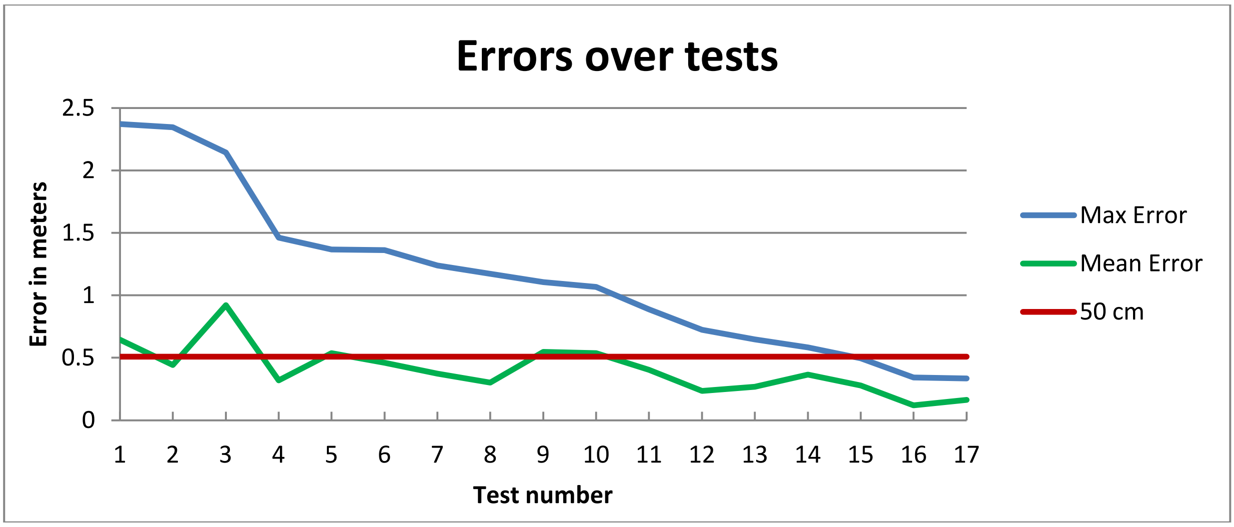


Figure 25. Errors statistics over test runs.

6.4.2 G2 and G3 – performance measurements

Besides the movement accuracy of the system, performance analysis on the prototype is done. Ten tests are performed with System Tuner Pro. Each test contains data for 1-minute containing 60 samples for each second, which measures processor occupation by the autonomous vehicle software processes. In addition, OS monitoring is done with Usemon to show that the whole system is not overloaded during the performed tests. Those ten tests are conducted during the first minute of each movement accuracy tests – from test number 8 to 17 on Figure 24. Figure 25 shows the maximum resources taken during the runs. The blue line represents the resources taken by the ACS prototype software, and the red line shows the

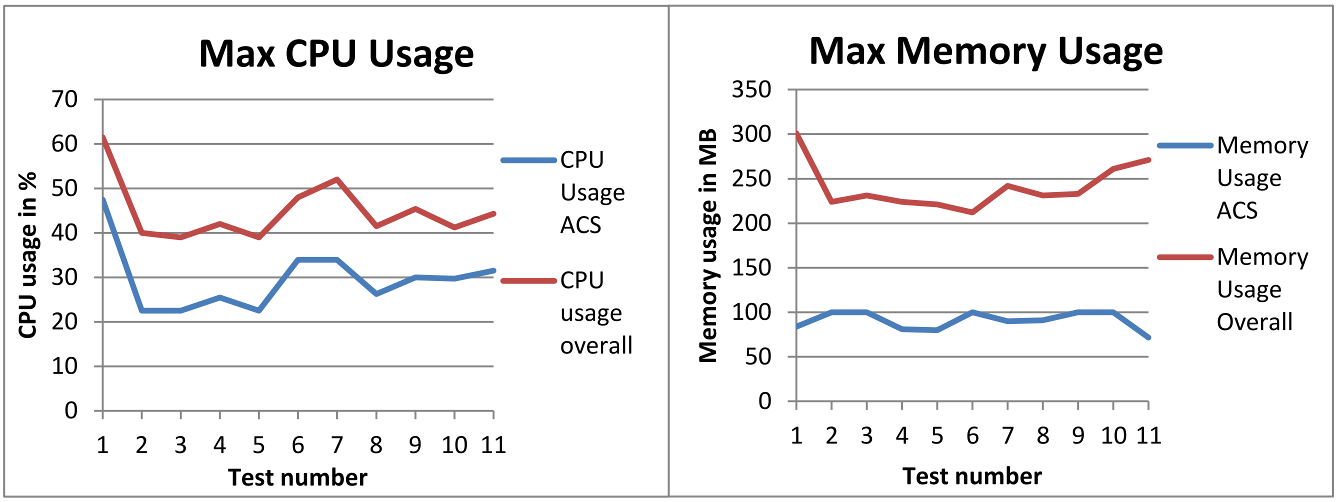


Figure 26. Max resources usage over the runs.

amount of processor load and memory usage by all the processes on the device. Finally, due to the capability of System Tuner Pro to record processor usage by each process, a response time calculation for each scheduled execution was made. The software recorded the response time of a process per second and ACS has 20 executions per second since it is time-based and

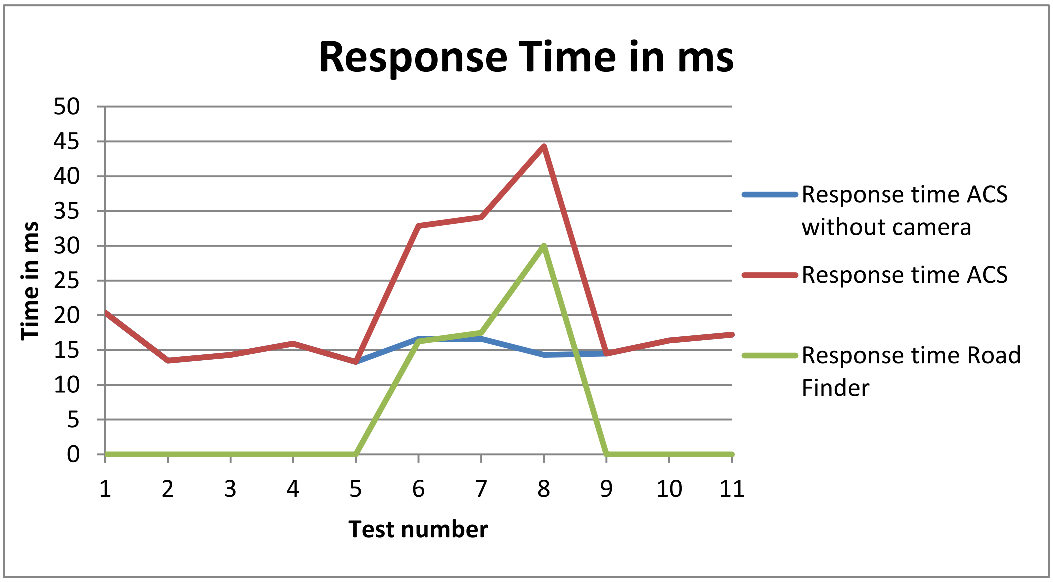


Figure 27. Average response time over the runs.

executes every 50ms. So in order to calculate the average response time per execution, a division by 20 is needed. Finally, we use the results for all the 60 probes to get the average response time per test. Figure 26 shows the average response time over the runs calculated in this way. Since the Road Finder was not used during the movement accuracy, there was a need to turn it on for some of the runs in order to be able to make performance measures over the whole system. As it could be seen on the graph, it was turned on for tests 6, 7, and 8 to show the system load altogether.

6.4.3 G4 – feasibility

Since most of the components are tested for feasibility with the other tests that are targeting G1, G2, and G3, here the focus is on the Road Finder. The Road Finder processes images from a thermal camera and tries to locate the road by assuming that it is hotter than anything else on the image. To verify that after tuning the system, we recorded a video for 30

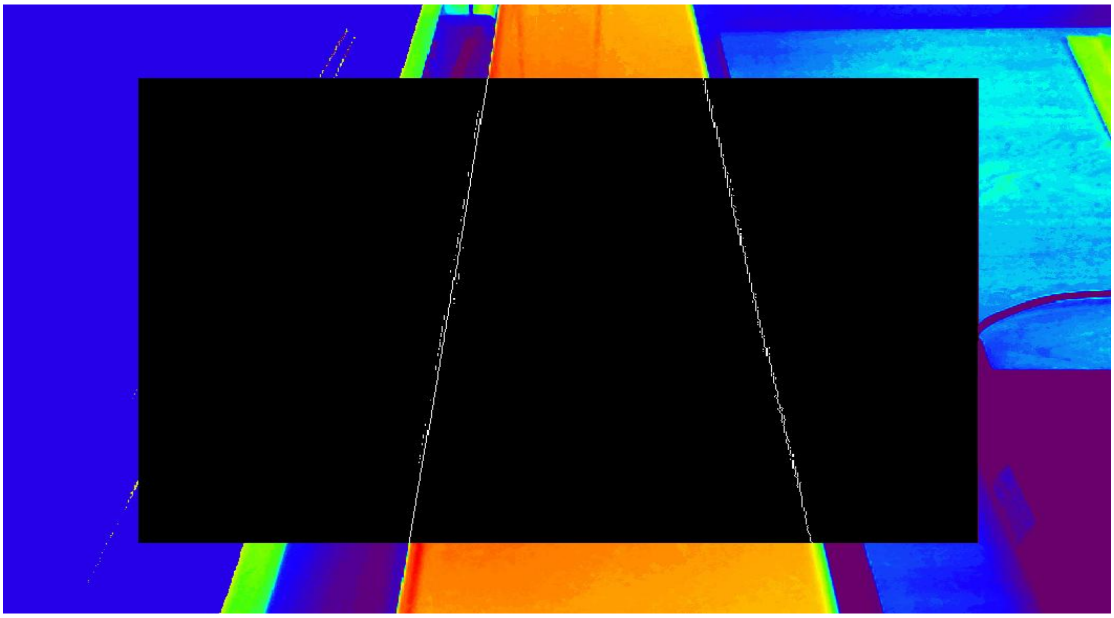


Figure 28. Road Finder operation. It shows recognition of the road within the small black rectangle.

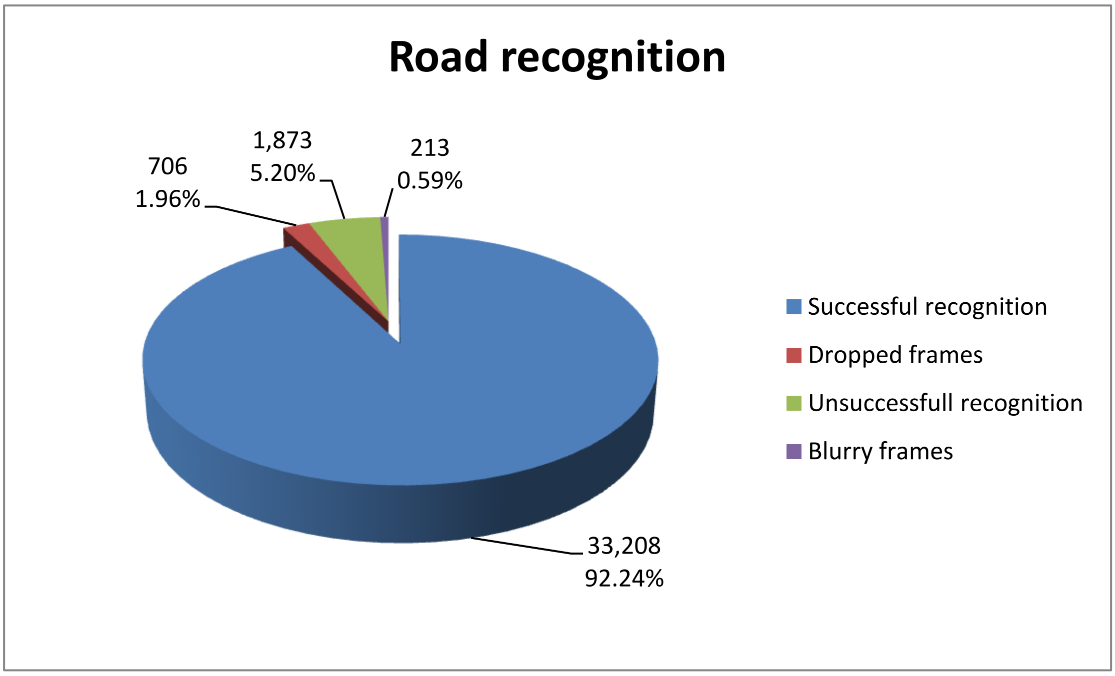


Figure 29. Road recognition verification.

minutes processing 20 frames per second, which resulted in 36000 frames processed. The software operated only on part of the image frame as shown in Figure 27. The rest was left untouched to allow human to verify the work of the component easily. The black rectangle is representing the processed frame by the Road Finder. Results of the verification are presented in Figure 28. Successful recognition means that the Road Finder finds the hottest area in the image, which is supposed to represent a hot asphalt road. It should be recognized and enclosed in convex contour, and nothing else should be shown in the final result – example in Figure 27. Blurred images are those where the hottest are is recognized but is shifted from the real position because of bad image quality. Dropped frames are those that are generated by the camera but not processed by the Road Finder. All the other cases are considered unsuccessful.

Besides that, a cost analysis of the prototype system has been done to show its relation to the machine cost. The analysis is based on the DD110 compactor machine that is used for highway compaction, and the results could be seen in Table 7. The formula for calculating the total positioning cost is special because the RTK antenna could be used for several compactor machines. After a discussion with our company partner, a decision was taken to consider one RTK antenna for five machines. A distribution of the cost is shown in Figure 29.

Table 6. Overall Cost Analysis.

Product Category	Description	Cost in SEK
Machine	Volvo Compactor DD110	1,040,000
	Total	**1,040,000**
Positioning	(1)Hemisphere V320 GNSS Antenna	80,000
	(2)Hemisphere S320 RTK Antenna	87,900
	Total [(1) + (2)/5]	**97,580**
Cameras	AXIS Q1931–E Thermal Network Camera	46,900
	AXIS M1014 Network Camera	2,100
	Total	**49,000**
Communication	IAR Kick start Kit(CAN interface)	2,500
	DOVADO TINY Mobile Broadband WLAN Router	850
	Korenix JetNet 3810G PoE Boost Switch	5,150
	Total	**8,450**
Computers	Samsung Galaxy Tab 3	2,000
	Total	**2,000**

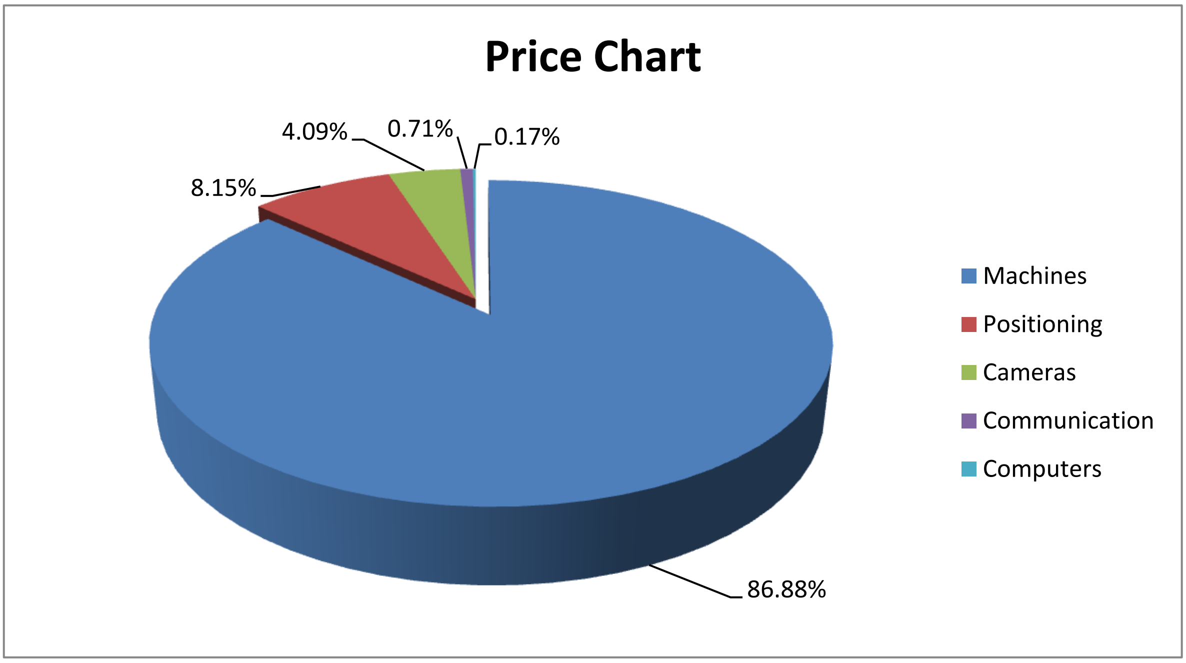


Figure 30. Cost Distribution.

6.4.4 G5 – error analysis and quality tests

There were different weather conditions on those days as shown in Table 8. The precision of the GPS system is measured before every test run, and a metric is derived showing the precision and the number of satellites during the run.

Table 7. Weather conditions on the test days

	25/11/2015	28/01/2015	29/01/2015
Condition	light rain	heavy rain	sunny
Wind	windy 16m/s	light wind 8m/s	no wind
Temperature	10	4	2
Humidity	93	97-100	50-61
Number of Satellites	11	7	14

The intention is to investigate the impact of the weather conditions over the system as described in Section 6.2.4. On the first test date, only one test run was made out of 8 planned,

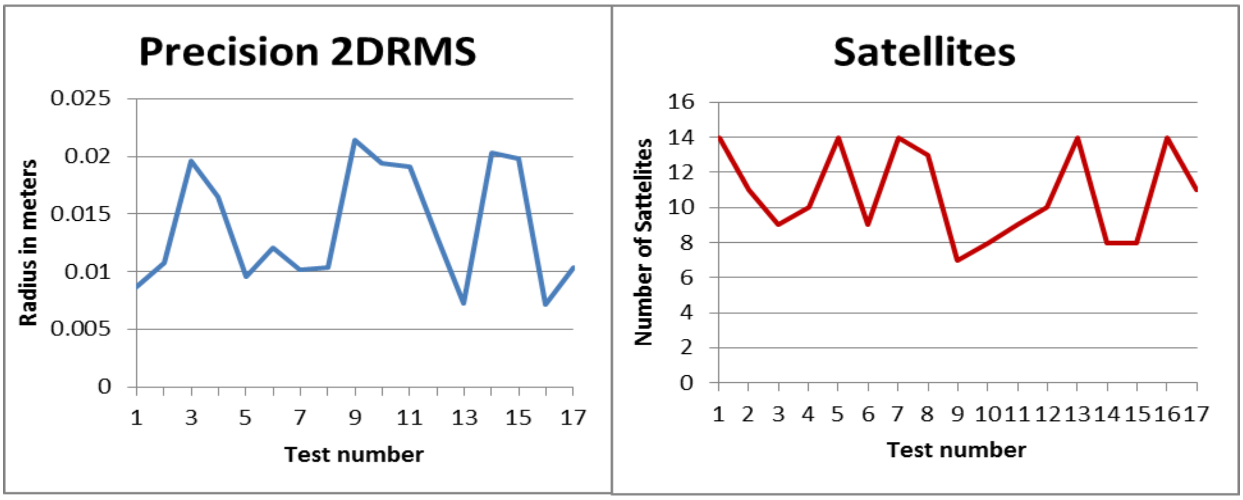


Figure 31. Calculated precision and found satellites during the tests.

because of integration problems and on the other two dates full eight runs were conducted. Graphs of all 17 test runs for the number of available satellites, as well as the calculated precision of the 2DRMS method described in Section 6.3.1, are presented in Figure 30.

Over the tests, different properties of the platform and the system were investigated. First tests were focused mainly on the platform, and understanding of the steering actuation and its mechanics and moreover how much time it takes for the steering actuator to turn the machine wheels to the desired angle. It also incorporates the low-level steering control, which is responsible for stopping the actuation when the desired angle is reached. Figure 31 shows the results of low-level steering tests. The graph shows what the error is in degrees from the desired angle and in respect to time. The right side shows the corresponding commands that are sent to the actuators.

Another information that is not visible on the graph, but is important for analyzing the response time of the system is the average time needed for the actuators to perform a change of one-degree angle. This response time may vary depending on the issued command. This information is presented in Table 9.

Table 8. Average actuation time per degree in ms.

Actuation command	5	10	15	20	25	30	40
Average actuation time per degree	60ms	60ms	53ms	40ms	36ms	32ms	25ms

Few test sessions were conducted to tune the high-level PID control and enable the machine to follow a line and a curve successfully. In those tests, measures of the mean and max error of a run have been taken, and also the relation between speed and those errors were investigated for its relevance to the tuning process.

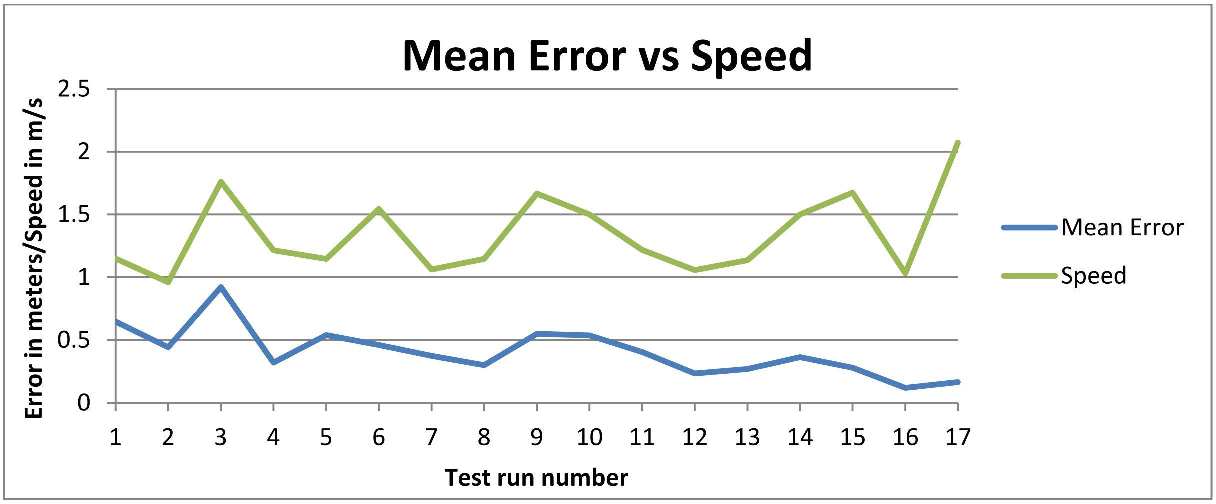


Figure 32. Mean error over tests and its relation to different speeds.

Figure 32 shows a graph of the mean error over tests in meters and the speed used during the corresponding test. As it could be seen from the figure, there is a correlation between speed and mean error. It led to using a simulation to simulate the tests over the track using all possible speeds to ensure that the chosen parameter set is usable. Results from the simulation tests are shown in Figure 21 – max error over several parameter sets and Figure 33 – mean error over several parameter sets. The results from the simulation are tested in reality and compared to the real world scenario in Table 10.

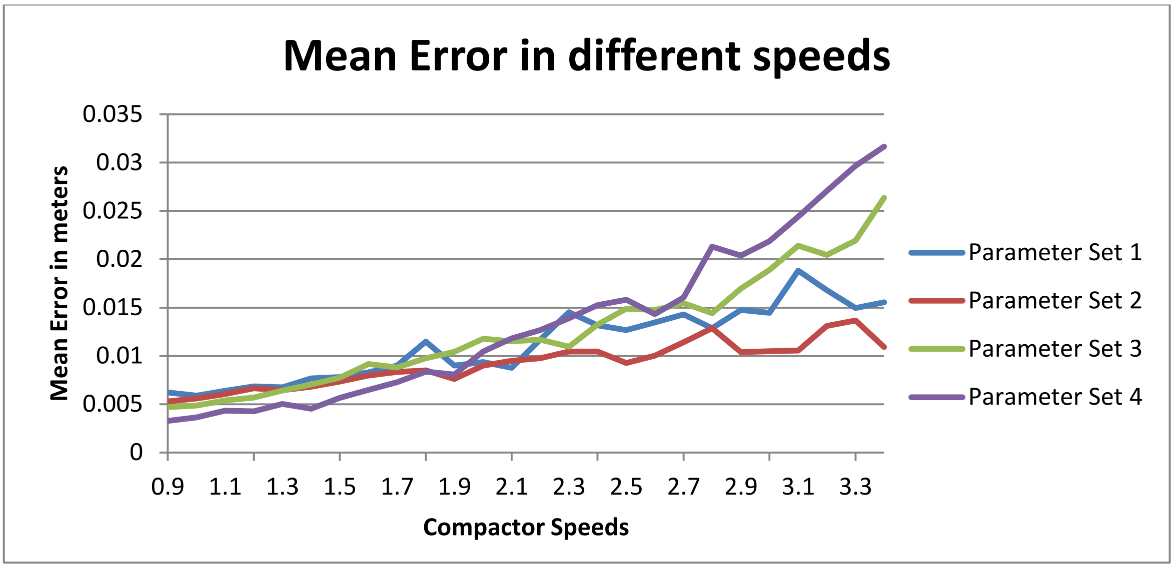


Figure 33. Mean error over different speeds in simulation.

Table 9. Simulation vs. Real world results in meters.

	Max Error	Mean Error	Simulated Max Error	Simulated Mean Error	Speed
Parameter set 1	0.58	0.36	0.15	0.009	1.7
Parameter set 2	0.50	0.28	0.14	0.007	1.4
Parameter set 3	0.34	0.12	0.10	0.003	1
Parameter set 4	0.33	0.16	0.11	0.004	2

6.5 Analysis and Discussion

In this section, an analysis of the results presented in the previous section will be made. The analysis will be tightly coupled with the goals, and its purpose is to evaluate the results and conclude whether the goals specified in section 6.1 are met or not, and what is the reasoning behind that.

6.5.1 G1 – movement accuracy

Movement accuracy of 50cm essentially means that the machine should follow a line with maximum lateral error less than the specified amount of centimeters. Figure 24 shows the results of the movement accuracy measurements taken during all 17 runs performed as the test scenario described in Section 6.2.1. As stated earlier, the first 14 runs are mainly for configuring the system and achieving a good system quality, and the real movement accuracy tests are the last three. In the figure, it could be seen that there was constant improvement of the movement accuracy over the tests. As it is presented in the detailed results in Table 11, the last three selected tests are below the goal of 50 cm. The tests were performed at different speeds as shown in Figure 32. Moreover, from that figure, it could be derived that the speed affects the mean error but not necessarily affect the max error. The covered speeds cover all types of compaction and all types of compactors as per requirements described in Table 1 in Section 2. The GPS system precision during the runs is also measured and presented in Figure 30. These facts allow us to conclude that test runs 16 and 17 are without a doubt a success.

The result from test 15 is very close to the bound of 50 cm and the GPS accuracy that day is 2 cm, which may result in actual 51 cm max error.

Table 10. Detailed results movement accuracy.

Test Session	Mean Error	Max Error	Speed
15	27cm	49 cm	1 m/s
16	12 cm	34 cm	1.6 m/s
17	16 cm	34 cm	2 m/s

Further investigation on that run is needed. The result is fed to the simulation, and it shows that only one point is resulting in 49 cm error and all other points are below 48 cm. That particular place is found on the real track and measured again with the Position Recorder to verify the error of 49.35 cm. These three tests cover the required speed and the allowed movement accuracy of an inexperienced driver. The results show that a system designed according to the presented system design can drive a compactor during a compaction process as good as an inexperienced driver.

6.5.2 G2 and G3 – system performance

The system should be able to make decisions within 50ms in order to satisfy G2. It includes only the computation of the decision and does not include the actuation and the response time of the actuator. Figure 26 shows the average response times for the performed tests. The reason for having higher response time on the first test is because the tablet was configured in balanced mode. It means that the CPU frequency is lowered when not needed, which creates certain delay for making it maximum again. In the other tests the configuration was switched to performance mode, which means static frequency set to maximum possible. The results show stable response time without the Road Finder at around 15ms in performance mode and 20ms in balanced mode. The execution of the components is done on time-based schedule with the frequency of 20Hz. With the current response time, it leaves more than half of a cycle-free, which guarantees that the decision will be made every time on a fresh input data. When adding the Road Finder in tests 6, 7, and 8, the system did not show a stable result for the response time. This is mainly, because the image processing could demand more time when there are more features on the image that needs to be filtered out than other times when there are less features. Test 8 was performed on a sunny day, and there are more reflections which made the computation heavier. However, besides that the results are still below the set goal limit – with the Road Finder the response time varies between 32 and 45ms still allowing the machine to make a decision before the next cycle.

Another performance-related goal is G3, which concerns the usage of system resources such as CPU and memory. The results in Figure 25 show the resources used by the system over the tests. As explained earlier, during the first test the system was in balanced power mode which is the reason for higher CPU usage. Later on the system shows consistent results between 22 and 30% usage without the Road Finder and between 27 and 34% with the Road Finder. It is much less than the set goal of 80% and allows improvement of the algorithms and adding more functionality to the same platform. The figure also shows the total CPU usage of the machine including the operating system and other applications running on the tablet. These results show that the rest of the system is consuming between 13 and 18% of the CPU. This confirms the assumption that a safety margin of at least 20% is needed when choosing a platform for the system.

The results for memory consumption are even better. The used platform presented in section 5.2 have 1 GB of RAM memory. The results show memory usage between 72 and 98 MB without the Road Finder and 92 and 102 with the Road Finder, which is at maximum

10% of the capacity of the platform. The reason for that is that the prototype implementation does not keep any data in the memory and makes decisions only based on the current data. After that the decision is taken this data is cleaned from the RAM. If later on, a different algorithm is used that incorporates predictive techniques, the memory usage needs to be monitored. Another conclusion is that an algorithm needs to be eight times more memory demanding in order to overshoot the safety goal of 80% memory usage, which is much memory left for experiments. The margin between the ACS and the rest of the applications running on the platform, when it comes to memory, is between 117 and 223MB. This is below 17% in all cases except the first test where the result is 22%. This result happened when the system is in balance mode, and it seems that the memory usage is increased when the CPU power is lowered. This points out that in order to use the same system configuration in performance mode, it is needed to make sure that the memory margin of 20% is sufficient. Maybe for safety reasons is better to design the system with a lower margin – 70%. Switching to performance mode will reduce battery life but still gives full 8 hours of working which is one working day. However, those concerns are not related to the prototype application since it uses much less than 70% of the memory.

6.5.3 G4 – design feasibility

To assure the feasibility of the design all components part of the decision-making need to be implemented and analyzed. Those components are presented in Figure 5. Map Manager, Operator Interface, Path Finder and Vehicle Control are part of the prototype system run during the movement accuracy test. During the real world scenario runs, those components proof their correct operation. It is not possible to achieve the levels of movement accuracy presented in Figure 24 without proper operation of all those components.

The component left is the Road Finder. This component was tested separately as shown in Figure 28. During the test run over the 30 minutes, 1.96% of the frames were dropped. The reason for that is not fully clear. A suspected reason is the scheduling of the processes that are publishing and requesting image data. Some of the frames are blurry – 0.59% mainly because of reflections and movement at the same time. Finally, the successful recognition is 92.24% of the recorded frames. The Road Finder will run at the frequency of 20Hz. It means that out of each 20 frames per second – 18.4 will successfully identify the area of the hot asphalt, where the operation should be carried out. If one frame is not properly recognized, the machine has the chance to correct it with the next frame resulting in no proper information for maximum 50ms. Transferring this to lateral error it may result in 5cm error, which is not vital to the operation of the machine. And as the results show it could happen with a chance of 8%. The chance of two consecutive errors is 0.64% that is considered improbable, but could result in 10cm more error in the movement accuracy of the machine.

The presented arguments lead to the conclusion that presented prototype implementation proofs that all components – Road Finder, Map Manager, Operator Interface, Path Finder and Vehicle Control could be implemented and fulfil the function required from them.

Another aspect of the feasibility study is the cost analysis. In order this system to be able to be implemented in the industry it should not add significant cost to the existing machine cost. In collaboration with the company, a cost margin of 20% of the machine cost was selected as a goal for the ACS hardware. As shown in Figure 29 the prototype system hardware costs less than 14% of the machine cost. Those prices are prices for consumers, not companies. Moreover, it is expected that the prices for companies will drop with 10 – 20% because of the fact that companies producing autonomous compactors will have to buy large amount of those devices. It results in 11.2 – 12.6% of the machine price more expenses for hardware. When it comes to the steering of the machine after a talk with the partners was figured out that the steer-by-wire will not make the machine more expensive than it is now.

The software price estimation is much more complicated, that is why it is not included in the cost. It is hard to estimate on how many machines the cost has to be distributed, and how many man hours are needed for industrial quality software. However, our partner expectations are that the software cost would not cross the margin of 5% of the machine cost. As a result, the final cost is considered between 16.2 – 17.6% of the machine cost, which is fully fulfilling the goal of 20% set before. Further investigation on cheaper positioning systems and cameras with similar properties could lower the cost even more. Those technologies exist but exploring them is left for future work.

6.5.4 G5 – system quality and error analysis

Several test runs were conducted just for improvement of the prototype software quality because it is not possible to conduct tests to verify the design without having a good quality implementation. As quality measures for the system are used the metrics from the previous goals such as movement accuracy and response time. As it could be seen in Figure 24, there was constant improvement in the movement accuracy during the tests. In order to achieve that quality, extensive tests were analyzed with different parameter sets for the high-level control. The first four tests show that the speed should be considered when choosing the parameter sets. Figure 32 shows the correlation between the speed and the mean error. Unfortunately testing each parameter set over all possible compaction speeds is not possible in real world scenario, because it will take much time and resources. Instead, to reduce the time, those parameter sets are tested in the simulation.

After several simulations, the top four parameter sets are selected for further investigation, and the results are presented in Figure 21 and Figure 33 – they represent the mean and max error analysis over different speeds. Next step was to verify that the results from the simulation are useful for the system running on the machine. Four tests are executed with those parameter tests, and the results could be seen in Table 10. The values are not very close, but the trend is the same. The results are sorted in descending order of the quality metrics – max and mean error. Moreover, they show that the parameter sets 3 and 4 are suitable for the final tests.

An important part of the implementation is the GPS system, and its quality is important. During the tests, information about its precision is gathered and shown in Figure 30. Before starting the tests, weather conditions and number of satellites are considered factors that have an impact on the precision of the system. The weather conditions are documented in Table 7. The weather conditions do not seem to have any impact on the GPS system – first nine tests are conducted during rain and the other during sunny day and the graph in Figure 30 shows similar maximum and minimum precision in both conditions. The second factor though shows a strong impact on the result, as it could be seen, when the number of satellites increases the radius in which all points are gathered drops.

Another important aspect of G5 is to develop analysis of the current maximum error and to investigate which part of the system has an impact on the error and how much. The analysis of the error distribution is done over the last three test runs. The GPS error is calculated with the precision metric displayed in Figure 30. The Map Manager error is because of the spherical transformation of the coordinates and it is verified with the Position Recorder. Moreover, a comparison is done between all gateway points after the transformation and with the points recorded by the Position Recorder. The other components are dynamic and are variable with speed and steering commands.

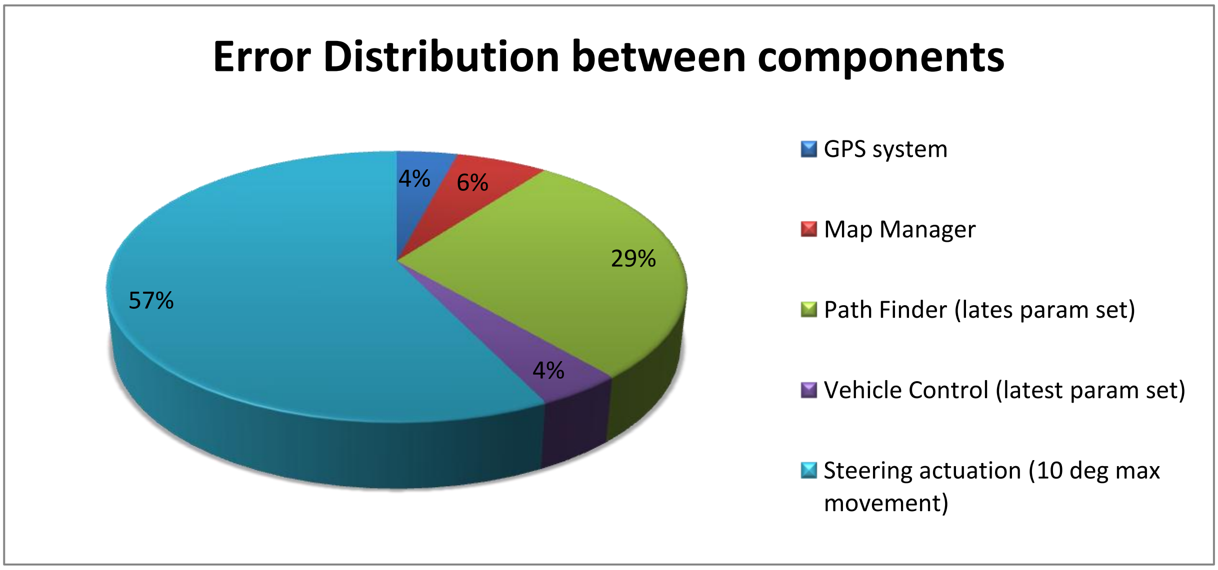


Figure 34. Error distribution between components.

The point with highest error during the run is chosen in order to analyze those components. The results from the steering actuation behavior tests are used (Figure 31) for analysis of the steering actuation error. The delay from the recorded data is used and is multiplied by the speed and cosign of the current angle to calculate the impact of this delay on the error. On the same point, a calculation of the impact of the low-level vehicle control is used. From the data from steering actuation analysis, it is visible that the low-level control needs 20-40ms to stabilize the final command. This delay is input into the same formula as the one used for the steering actuation itself. Since the response time analysis presented in Figure 26 shows that the decision is taken before the next command then, the operating system and the scheduling are not generating any error. The calculation of the impact of the Path Finder or its high-level control over the error is very hard. But considering the level of improvement when changing the configuration of the algorithm during the tests shown in Figure 24, we can conclude that the rest of the error could be appointed to that component. If there are other factors that should be considered, their impact could be considered negligible in comparison with the ones presented.

The error distribution is shown on Figure 34. These results are average from the three tests at the point of movement where the highest error is registered. As it could be seen, the greatest impact is on the steering actuation and the Path Finder.

When it comes to steering actuation, it should be pointed out that in the current test scenario, the max steering actuation is chosen to be 10 degrees. If there are no sharp turns then the max actuation could be reduced as well as the impact on the error by the steering actuation. With the current algorithm, the error reduction could be from 28cm to 18cm, based on the described formula above. There are algorithms that can use prediction techniques and even further reduce the impact of the steering actuation, but it will still have a strong impact because of the compaction requirements for minimum speed. If the system was allowed to lower the speed and wait for the actuation, this error could be reduced significantly to error close to 2–3 cm. Unfortunatelly in the compaction process, there is a requirement for minimum speed of 0.8m/s [2], so absolute minimum using a prediction technique and a plan that allow maximum of 1 degree actuation is 12 cm error. However, in this case, the impact of the algorithm on the whole system should be analyzed separately. For further improvement, faster steering actuation is needed. On the other hand, if more max steering actuation is needed in case of avoiding obstacles or more complicated compaction pattern based on the density, the impact of the steering actuation will be bigger. It has to be taken into account when designing the system for following density patterns.

For the Path Finder and its PID control, it is important to note that the parameter set is not fully optimized, and it has a potential for reducing the error as well. The problem is that finding the optimal parameters is not an easy task. In fact, it is NP-hard [37]. The technique used could not find a global minimum in the error space because this will take years, but could search in a range of values and find a local minimum in a reasonable time. Furthermore, the parameter sets should be tested over all compaction speeds, which make the search for optimal parameters even harder. If a change of the algorithm is made, its efficiency could be compared to the one that is currently presented. It has an impact of 14 cm lateral error on average during the three test runs.

The other three components have very low impact on the specified goals and are not considered threat. However, if the system is made to drive as good as an experienced professional driver and has to achieve 15 cm accuracy, then they could take bigger part and should be analyzed further.

6.5.5 Discussion

The design presented in Section 4 was evaluated in this section, and as the results for the set goals in Section 6.1 show, it is successfully covering all of them. The prototype implementation for implementing a supervised driving system that controls only steering actuator is proven to be a good start for industrial implementation. The system that follows the design could drive as good as an inexperienced driver. It could match the safety requirements for performance on the presented platform and also pass the criteria for feasibility including cost of the system. It was analyzed for error distribution and reasons for that so it could be improved further based on this analysis.

Several tests were performed on a simulation environment and real platform including a selected prototype machine with as close behavior to compactor as possible. The designed simulator has the purpose not only to be used as tuning platform for the prototype ACS, but also to be used for investigating relations and trends when switching the machine from wheel loader to the compactor. When the parameters of the compactor machine on which this software will be installed are known, they could be easilyl input in the simulator. Then the difference between the two platforms could be further investigated and put into practice while installing the system. Although the system was tested on a wheel loader, the simplicity of the used algorithms allows easy transfer of the system to a compactor machine after re-tuning with the simulator.

The requirements for the high-quality system are difficult to be met with the limited amount of real world tests since the convergence of the results is questionable. However, since the last tests proof to be successful in meeting the goals, the system could be considered as a good quality system.

Finally, in the last subsection, analysis of the threats to validity of the conducted tests is presented. It has the purpose to inform the reader of test limitations and further analysis that needs to be done to ensure high-quality results for a complete industrial product.

6.5.6 Threats to validity

There are many situations, where the validity of data can be compromised. The results in this thesis are based on data collected from different test sessions and can vary due to change in the situations. There are several threats to the validity of our results and could be characterized in different groups that are mentioned below:

- **Weather Conditions:**
All tests are conducted in temperature above zero degrees centigrade and below ten degrees, which means that the system have not been tested in freezing temperatures and high-temperature situations. In fact, freezing temperatures are not very probable to happen during compaction [2], but temperatures above ten degrees are more probable and should be investigated further. There are no suspected reasons that high temperatures will have a negative impact on the shown results, but it is a valid case that needs attention.

- **GNSS Satellite communication:**
The communication between satellites and GNSS antenna needs a direct visibility that is why the GNSS does not work indoor. All our tests are conducted in an open area with a good visibility to satellites even in bad weather conditions. As it is clear from Table 8, in the worst case the system was connected to 7 satellites. It might be different when the system works in some area with less satellite visibility like forests or different part of the world. As discussed before, during the analysis of the precision data from Figure 30, fewer satellites could cause loss of accuracy and precision of the data. Since the impact of the GPS data on the current algorithm is not that high (as shown in Figure 34) this was not investigated in more detail. However, it will be important if a higher movement accuracy is needed, for example, 15 cm for experienced compactor driver.

- **Test Scenario:**
As it is mentioned before, all tests are conducted in only one test scenario. The machine always starts from the right side of the test track and follow the road as shown in Figure 17. No tests are conducted in other scenarios with different test track shape like a curve to the left or a road with different sizes. One assumption that has to be validated in real world scenario is that system will behave similarly in right and left curves, which is also based on the steering actuation behavior presented in Figure 31.

- **Testing time for the platform:**
The Galaxy Tab 3 is a normal tablet that is not produced for industry usage. This platform shows that it can tolerate the load of our prototype application. However, the platform is only tested for a short amount of time during each test. It is necessary to run the application for a longer amount of time to find all possible corner cases and limitations in order to verify such a platform. Due to the limited access to the machine, not enough tests are done to make the system converge to stable values for movement accuracy that would have proven a high-quality behavior. Also running the system for the extensive amount of time could exploit limitations of the system that might not be visible for a short period. Possible examples could be proper use of resources or processor behavior when the battery is running low.

- **Technique:**
The simplicity of techniques that are used in the prototype ACS ensures low resource usage and reaches the desired performance. However, there are other popular techniques for autonomous vehicles, which are more complex and use more resources. In other words, the performance results need to be reevaluated for any other technique that is used to achieve the same goals set in this thesis. However, the purpose of the prototype application is to show that the design is feasible and that such

implementation is possible, not to present the optimal implementation or to compare several algorithms.

- **Platform itself:**
  Due to the specifics of the compactor, a wheel loader is used as a test-bed in the current project. The wheel loader has similarities to the compactor as described in section 5.3. There are though some small differences in the dimensions, and the fact that the compactor is using drums and the wheel loader tires needs to be further investigated. Those differences will affect the high-level control and changes in the PID parameters will be needed. To address this threat, the authors developed a simulator that could be used for the compactor dimensions and trends could be analyzed and compared between the two machines to find the optimal parameters easier.

7. Conclusion and Future Work

The research in this thesis report presents a design and evaluates a concept of the fully automated compactor by combining off-the-shelf sensors with state-of-the-art algorithms.

The study extends the current knowledge of intelligent compaction with this concept for the autonomous compactor to achieve high quality of road layup. On the other hand, it also extends the practical areas of autonomous vehicles, navigation, and path-finding in complex environments.

The concept itself covers several different scenarios for autonomous and semi-autonomous modes of operation and also introduces several types of sensors that could be used for facilitating positioning and maintaining movement accuracy to satisfy paving process requirements. It also led to the implementation of cost-efficient, fault-tolerance semi-autonomous compactor system that could work in the rugged environment.

The requirements for the autonomous compactor are presented, a functional model is built on top of them and finally a design is proposed that satisfies this functional model. The design is inspired by a known autonomous vehicle design and is adapted to the problem domain and functional needs.

For evaluation of this design, a test-bed is prepared, and prototype software implemented. As a test-bed for the evaluation, a wheel loader is used. It is equipped with several different types of sensors such as GNSS and RTK antennas for localization and cameras for localizing the road that the machine is supposed to follow. The software makes the machine follow a trajectory with respect to data gathered from those sensors. The data itself is also evaluated in terms of accuracy and precision. Third party tools are used for evaluation of the performance of the system and verify the cost-efficiency.

The results from this report show that the scientific questions presented as thesis goals are covered together with the industry requirements. The system such as autonomous compactor could be implemented with the current technology in a company without significantly raising the cost of the machines, and usage of the presented design is feasible for implementation.

This report also uncovers many questions and opportunities for autonomous vehicles within the area of industrial machines and intelligent compaction. Some of those topics that are suggested for future work are:

- **Sensor Fusion**
  The current prototype only uses the satellite communication for positioning the machine. If the system loses the connection to the satellite, it is not functional anymore. To improve this part, it is better to use other alternatives such as cameras and short range GPS to localize the position of the compactor. Some of those techniques are presented in section 4.3 but need more investigation. The implementation of the functions for avoiding obstacles is not part of this report, but when a fully autonomous system is developed, the sensor fusion between localization sensors and distance sensors needs to be investigated.

- **Algorithms**
  The algorithm that is used for decision-making could be improved by testing it in different scenarios. As described in section 6.5.6 more tests with different weather conditions, satellite visibility and time span needs to be investigated and considered in the algorithm.

There are also other good algorithms that are popular for localization and positioning like Simultaneous localization and mapping (SLAM) and with adding more sensors this could be tested with the design as well. However, for such an algorithm to be used more data from different sensors, like cameras and range finder sensors is needed. It adds more complexity to the system but also might help to get more accuracy in positioning of the compactor.

Besides the positioning as the analysis in Section 6.5.4 shows, a major part of the error is because of the current Path Finder implementation. Other techniques for control such as Model Predictive Control (MPC) with a good vehicle model could help in reducing this error or even more advanced non-linear control such as Neural Networks could be tested.

- **Safety**

  The current report focuses on parts of the design that does not concern the safety since the supervised driving mode is used for the evaluation. For future work is very important that the safety functions are evaluated and verified. In order to achieve fully autonomous compactor, all safety functions need to be implemented. Special attention needs to be given to the fail-safe modes of the compactor since it has requirements for minimal speed and its stop on the hot asphalt is not recommended except when it is unavoidable.

  Investigation of different approaches for process monitoring needs to be investigated to fulfill the requirements for self-healing system [13].

  Finally, the interface to the operator needs to be improved to allow emergency control and usability quality.

- **Other Scenarios in Intelligent Compaction:**

  The current thesis does not evaluate the integration with existing intelligent compaction systems such as the IACA [3]. The density information input into the control Path Finder should be analyzed, and different compaction patterns need to be investigated for optimal compaction.

  In this thesis, the focus is only on a system for a single compactor. Another useful scenario is to use several compactors at the same time as usually happens during highway compaction [35] and let them collaborate. They can be considered as one distributed system and help each other to compact the asphalt in more efficient way.

There are probably other areas and more questions for investigation on this topic, but the idea is to use the thesis as a base for further development and fusion between the autonomous vehicles and intelligent compaction.

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Figures