

REPORT

Autonomous Object Hunting

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# 1 Introduction

This research project has the objective to design a system that is able to navigate on its own in an unknown environment, search and identify an object<sup>1</sup> and build a map of the navigated route as well as a map of its surroundings. The system as a whole will consist of a mobile device, further named robot, and an auxiliary external computer. As the robot on its own only offers limited computing power, it will outsource computing intensive tasks to the external computer. Hence multiple processes on different platforms will be involved. To be able to operate in any arbitrary location, the system shall be independent of any additional hardware as for example networking devices. Besides it is desirable to design the system in such a manner, that supplementary software, which is not planned now, can be added easily by additional external computers. Figure 1 shows a potential connection between the robot, i.e. the symbol in the middle, and other devices via a wireless LAN<sup>2</sup>.

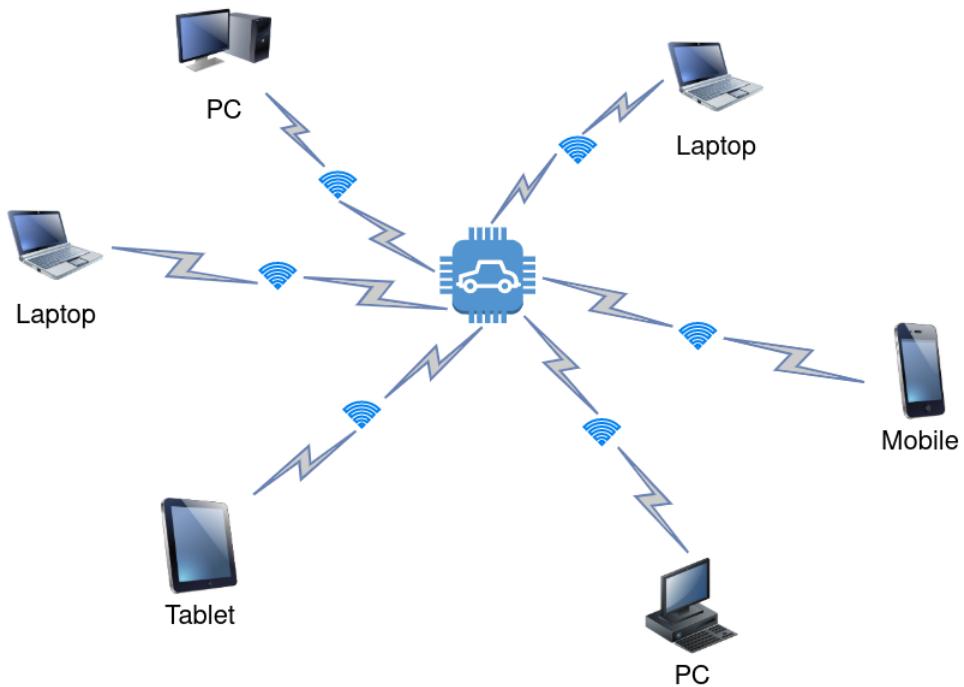


Figure 1: Display of possible connections

The robot will steer by controlling multiple motors, which will be attached to wheels. Furthermore it will be able to capture its surroundings and any obstacle near it by distance measurement sensors. They will be mounted around the robot in order to register surroundings in any direction. Additional sensors will keep track of the orientation in space and movements of the robot. The target object will be identified by processing data of a visual sensor, i.e. a camera attached to the robot.

The aim of the robot is to avoid collisions in any environment and find the target object. When the target object is found it shall stop navigating and indicate the successful identification of the object to the user.

<sup>1</sup>The action of searching and identifying an object will further be referenced as object hunt.

<sup>2</sup>A LAN (local area network) is a computer network that interconnects computers within a limited area.

## 2 Hardware

The hardware of the device can be separated in two subsystems. On the one hand, the robot, which will navigate in the environment, on the other hand the external computer with a static location. This section only focuses on the hardware of the robot. The hardware of the external computer is not further described in this report as any arbitrary recent computer with a working WiFi interface can be used.

Following you will find a short description and the use case of each part used in the robot. All parts mentioned in this section will be combined to one mobile robotic system.

### 2.1 Chassis

The chassis forms the foundation of the robot. It consists out of two identical floors, arranged above each other. Drive motors, wheels, revolution sensors and the power unit are mounted on the first floor. Attached to the second floor are the processing unit, PCB board, ultra sonic sensors, smart movement sensor and the camera unit. Each floor has several holes in order to lay the cables from processing unit and PCB board properly.

### 2.2 Gear Motors

Every movement the robot as a unit can make, is realized through four direct current gear motors, each attached to a wheel. Since the processing unit can not operate the gear motors directly, dedicated motor drivers are needed in order to operate the gear motors properly. The L293DNE quadruple half-h drivers [1] are suited and each can operate two gear motors forwards as well as backwards.

### 2.3 Stepper Motor

The stepper motor is connected to an attachment for the camera module. A stepper motor with 5 V DC operating voltage, 64 steps per revolution and four phases is chosen. The stepper motor can be driven by a single L293DNE motor driver. This allows to turn the camera module theoretically by an arbitrary angle. However, attention should be paid to the cable, which connects the camera module to the processing unit. It is long enough to enable the camera module some free moving space. If it is stressed to much, the equipment can be damaged permanently.

### 2.4 Revolution Sensors

A brake plate is mounted to each gear motor. With this plates the revolution of the respecting motor can be measured. The plates offer a resolution of 20 counts per revolution, which is sufficient precise for this project. A TCST1103 [2] optical sensor attached to each brake plate allows to get notification of the status of the regarding brake plate. A resistor connected in series with the phototransistor output leads to a signal fluctuating between ground and the applied voltage, depending if the light of

the emitter can pass the brake plate or is blocked by it. An auxiliary circuit consisting of an operational amplifier is interposed and outputs a clean edge, if the fluctuating voltage surpasses a threshold value. This edge can be detected by e.g. a microcontroller. In combination with the wheel diameter the revolution measurement is used to calculate the distance traveled as well as the speed of the robot.

## 2.5 Ultra Sonic Sensors

In total four ultra sonic distance sensors are mounted on the robot. The HC-SR04 [3] model is used for all ultra sonic distance sensors. They allow the robot to measure the distance to obstacles in the front, in the back, to the left and to the right. As the HC-SR04 operate on 5 V, most likely a voltage divider has to be interposed between processing unit and each HC-SR04 module. The ultra sonic sensor information is crucial for the robot to navigate, as it is the only information it can receive about its surroundings.

## 2.6 Smart Movement Sensor

The smart movement sensor is used to get information about the orientation of the robot in space. This is needed in order to locate the robot with respect to the starting position of the hunt. Furthermore this sensor can be used to read acceleration data of the robot. The sensor communicates via an I<sup>2</sup>C<sup>3</sup> interface.

## 2.7 Power Unit

For the robot to be mobile a rechargeable power source is needed. A portable power bank with a voltage of 5 V and Li-polymer battery cell is used. It provides a peak output current of 3 A, which is sufficient to allow simultaneous control of all attached motors and electronics. Furthermore it offers a capacity of 20000 mAh, to allow the robot exploration of spacious environments without recharging.

## 2.8 Processing Unit

The processing unit of the robot is one of the most important parts of this project. There are several specifications, which it needs to comply with in order to realize the objectives of this project. The specifications are the following:

1. Low power consumption

As the robot is battery driven, the processing unit should consume as low power as possible to extend battery life.

2. Extensive and accessible GPIO interface

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<sup>3</sup>I<sup>2</sup>C (Inter-Integrated Circuit) is a two wire, synchronous, serial computer bus invented by Phillips Semiconductor in 1982.

The sensors and actuators are connected directly or via auxiliary circuits to the processing unit. Therefore it is important to have sufficient GPIO pins for all planned hardware.

### 3. Ability to create a WiFi hotspot

The robot needs to maintain its own WiFi network in order to operate in any location and be independent of additional hardware.

### 4. Supports TCP/IP<sup>4</sup>

The connection to external computers needs to be bidirectional and reliable. TCP/IP satisfies these specifications and is a state of the art solution.

### 5. Supports I<sup>2</sup>C

I<sup>2</sup>C is needed for communication with the smart movement sensor (see section 2.6).

### 6. Supports multithreading

The robot needs the ability to perform various tasks simultaneously. therefore a CPU<sup>5</sup> with multiple cores is inevitable to archive the objectives of this project.

Taking all specifications into consideration, a Raspberry Pi 4 model B is considered to be used as the processing unit of the robot. It fulfills all mentioned specification, is less expensive than comparable products and offers a big community. Since the Raspberry pi 4 is available in different versions, differentiate in the available RAM, the version with 4 GB RAM is chosen. This enables potential for further additions.

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<sup>4</sup>TCP/IP, or the Transmission Control Protocol/Internet Protocol, is a suite of communication protocols used to inter-connect network devices.

<sup>5</sup>Central Processing Unit

## 2.9 Entire Overview

The resulting hardware, without the power supply, of the robot and its interconnections can be seen in figure 2.

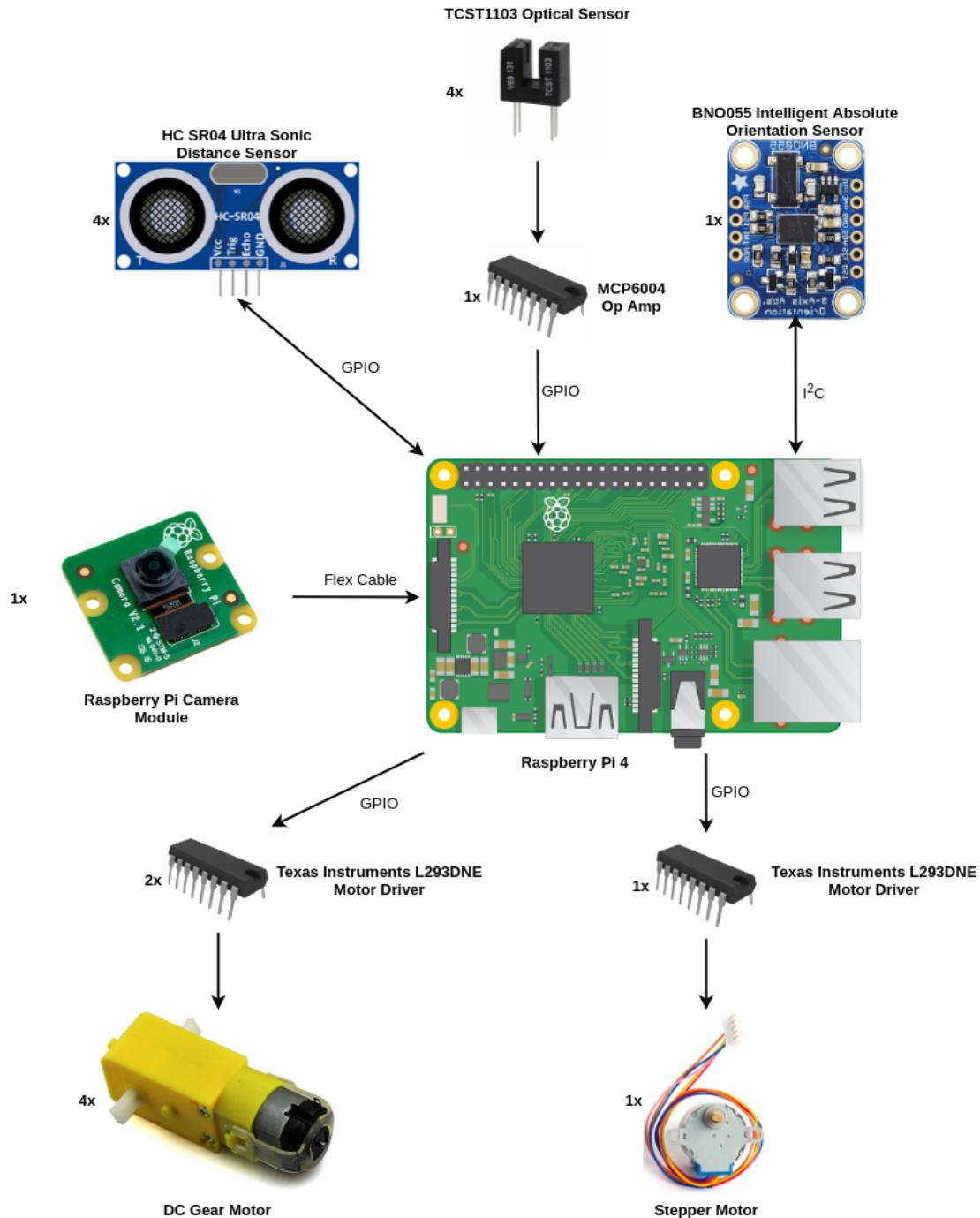


Figure 2: Combined hardware

## 2.10 PCB Board

The wiring of all components is expected to be rather complex. Since breadboard connections are prone to errors and can get unclear, if multiple connections are involved, a PCB board is designed

for the circuit. Furthermore each device will be connected by a dedicated connector in order to allow easy assembly and disassembly of the system as a whole as well as replacements of single devices. At first a test circuit is designed for every part. In this manner the function of each sub circuit can be controlled and potential modifications can be realized easily. When each circuit is working as desired, the single sub circuits are combined in one system wide circuit and transferred to an electronic design automation software. In this project the education version of EAGLE [6] is used.

The circuit can be assigned to a two layer PCB board of the dimension 82 mm x 65 mm. It is designed to be easily plugged in on top of the 40 pin GPIO connector of the Raspberry Pi. The mounting holes have the same dimensions as the ones of the Raspberry Pi. Hence the same screws to install the Raspberry Pi, are used to attach the PCB board. All GPIO contacts are lead through to allow easy measurement of signals while the PCB board is installed on top of the Raspberry Pi. Figure 3 shows the populated PCB board.

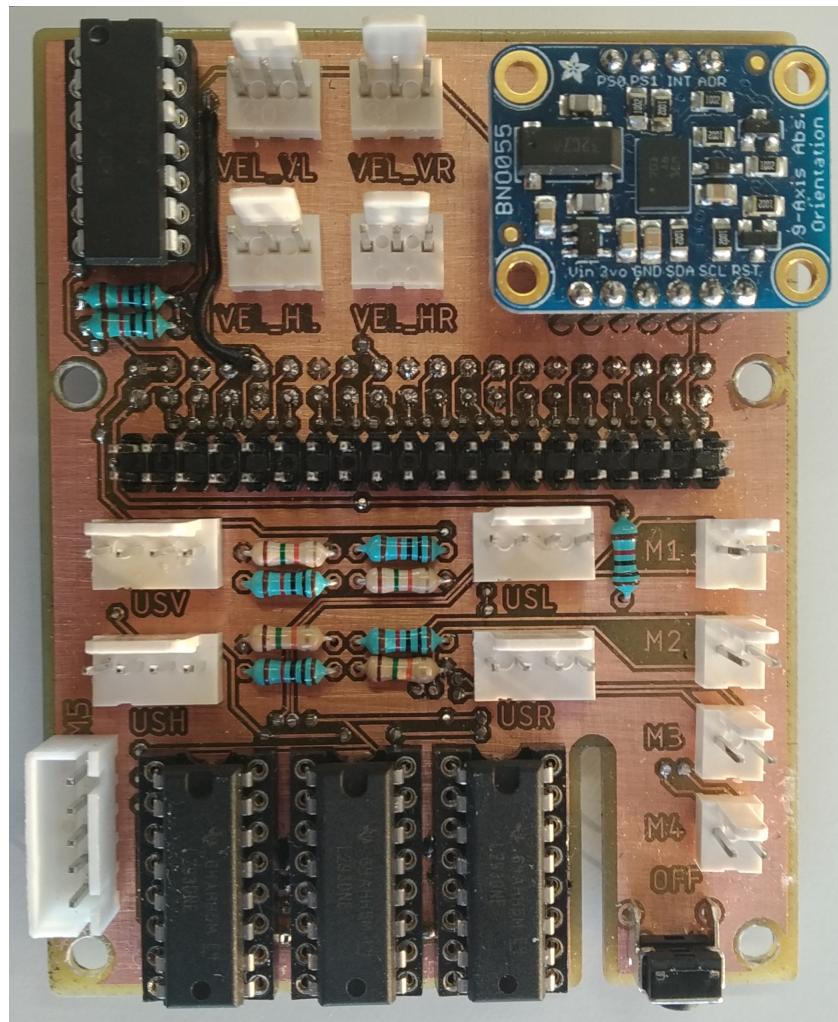


Figure 3: Populated PCB board

### 3 Internal Software

The in this section described processes are internal processes, i.e. running on the robot itself. In total there are three custom processes running on the robot. Figure 4 shows the structure of the developed software. This section focuses on the base and the navigation process. The image streaming process is referenced in section 4.

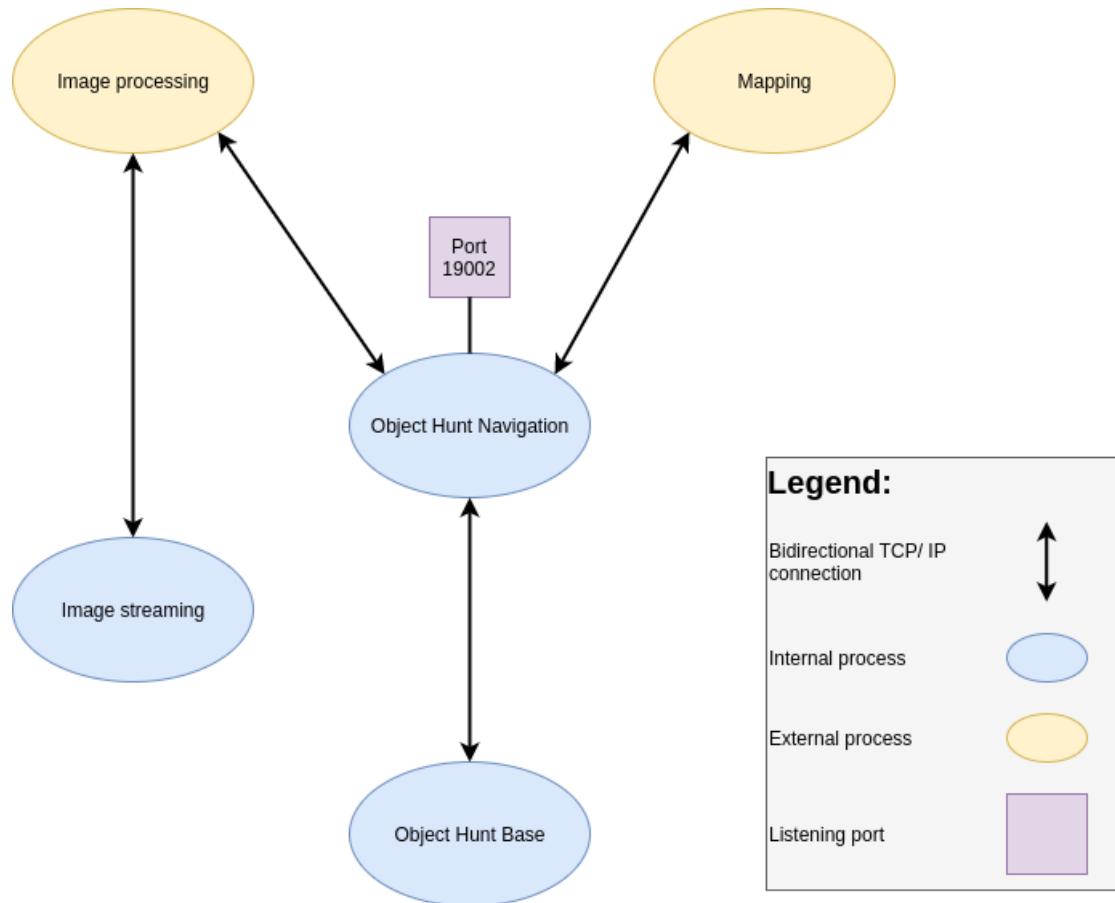


Figure 4: Software structure

#### 3.1 Design Principles

The system in its entirety shall not be bound to any programming language. In that way virtually any language that supports the usage of raw sockets in collaboration with TCP/ IP can be used to develop software for the system. At the time of writing this report Java, Python and C++ are already employed.

Furthermore underlies the internal software particular specifications, which are defined at the beginning of the project. They define, among other things, how the system as a whole will behave and handle dedicated tasks, i.e. inter-process communication. The compliance of these principles ensure that the developed software works in the expected manner and offers the possibility for adding further processes in the future.

The defined principles are listed in the following:

- Communication
  - Via TCP/IP
  - Independent from other devices
  - Beyond system border
- Economical
  - No unnecessary CPU consume
  - Fast reaction times
  - Event driven
- Documentation
  - Complete
  - Easy accessible

### 3.1.1 Communication

All participating processes communicate via TCP/IP. Therefore a purpose-built way of exchanging data is developed. Messages are generally separated in action identifiers, commands, requests and responses. Table 1 declares the usage of each message type.

Action identifiers	This message consists of exactly one byte in all implementations. It is put in front of each other message type and tells the receiving process what data is about to come in.
Commands	Gives a specific order to the base process. Only the base process can handle commands. A command does not implicate any result, so the sending process will get no feedback, if the command succeeded or not.
Requests	Asks for the cars state. That can be in particular a reading of one or several sensors, speed or orientation data. Every request implicates a response with the desired value. Each request contains an identifier field.
Responses	A response message will always follow an earlier request. It can either indicate an invalid request or contain the desired data. Each response contains an identifier field. It will adopt the identifier of the respecting request.

Table 1: Definition of messages

There exist several implementations of each message type. A motor will most likely be controlled by a respecting command message. A sensor measurement on the other hand can be triggered by a correct request. Please refer to the project documentation page [7] for further information about which messages exist and their exact composition.

### **3.1.2 Economical**

### **3.1.3 Documentation**

## **3.2 Base Process**

The base process interacts directly with all controllable hardware parts listed in section 2. Therefore it is a crucial process for the correct function of the robot. If the base process crashes unexpected, any other process concluded in the project will be disconnected or shut down as well.

## **3.3 Navigation Process**

## 4 Image Processing

### 4.0.1 Definition of the object detection task

The deep learning computer vision area consists of different tasks, which serve different purposes. In figure 5 we can see the representation of these different tasks. In our project we will take a closer look on the object detection. Like we can see in the image, object detection means detecting multiple objects. But the task is not only to detect and classify them, it is also the task of the program to locate the objects. This will be evaluated on the bounding box around the object. The desired result can be seen in the following figure.

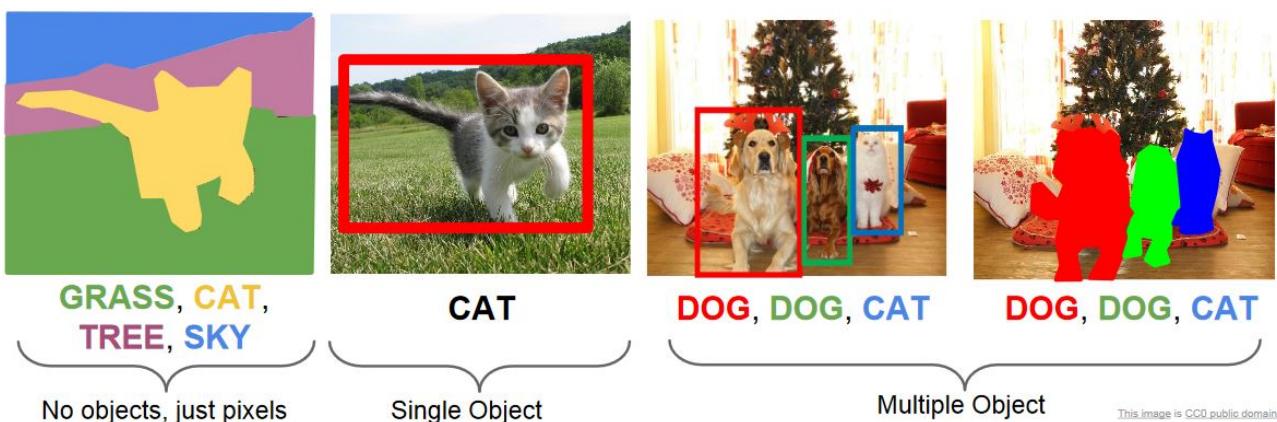


Figure 5: Representation of image processing tasks

### 4.0.2 Requirements on object detection

In our project we only define the object, which we want to detect. It is not defined how many of these objects will be present, but for the expandability of the project, we will use methods capable of detecting multiple objects.

Also, the image processing needs to be real-time capable. The robot navigates autonomously around an unknown area and should detect the objects, when they appear. It is not desirable to have delays in the detection. For this also a sufficient accuracy is needed to detect the object under different lighting and background conditions.

## 4.1 Basic model selection

Regarding these requirements, we need a specialized model to match the real-time capabilities, while having a decent accuracy. In the image recognition area, the drive for increasing accuracy leads the progress. But it comes with the cost of increasing complexity of the models. This leads to increasing computational cost, which decrease the real-time capabilities. Mobile phones and embedded system

are not capable of providing this performance. For this purpose, the MobileNet [9] network was created. It drastically decreases the number of trainable parameters with different techniques. The main difference from conventional networks is the depthwise convolution. In the conventional convolutional network, the convolution determines features by applying kernel filters on the different input channels and combines the features to reach a new representation [9].

This results in a computational cost of:

$$D_K \cdot D_K \cdot M \cdot N \cdot D_F \cdot D_F$$

The MobileNet splits these two steps up and computes them separately [10, 11]. First the depthwise convolution is applied by applying a single filter per input channel. In the second step the pointwise convolution combines the resulting features. Both operations present an own layer and are followed by a batch normalization and a ReLU activation. This separation results in a new computational cost of:

$$D_K \cdot D_K \cdot M \cdot D_F + M \cdot N \cdot D_F \cdot D_F$$

Comparing these two costs, the depthwise convolution reaches a reduction of  $\frac{1}{N} + \frac{1}{D_K^2}$ .

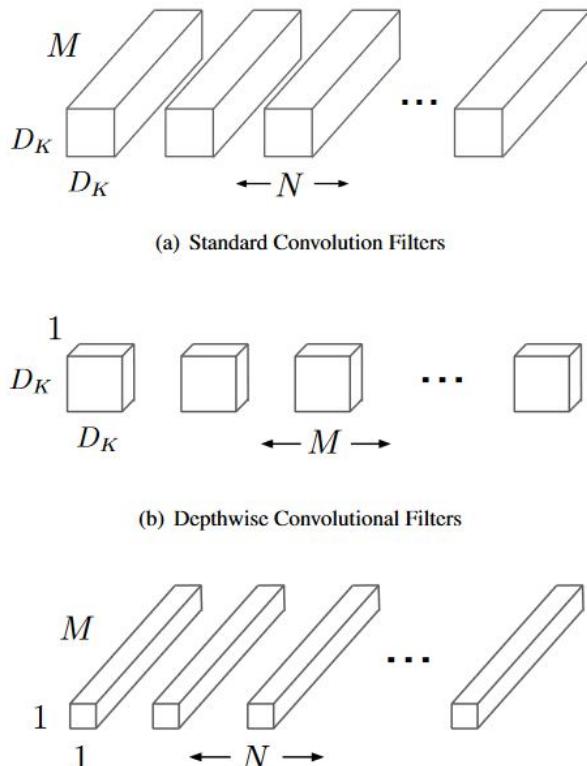


Figure 6: Comparison of standard convolution (a) and Depthwise Convolution [10, 11]

The Mobile network was tested one time with standard convolution and with depthwise separable

convolution. The result was only 1,1 % loss in accuracy, but a reduction of 25,1 million parameters.

Model	ImageNet Accuracy	Million Mult-Adds	Million Parameters
Conv MobileNet	71.7%	4866	29.3
MobileNet	70.6%	569	4.2

Figure 7: Comparison of standard and depthwise separable convolution

## 4.2 Object Detection System

For the object detection there are mainly three different techniques, which are used.

### 4.2.1 Faster R-CNN

One approach is the Faster R-CNN, which is the combination of two modules. First we have a deep convolutional network, which extracts the features. After this the feature map will be shared with a separate network, which predicts the region proposals. In this RPN module the feature map will be fed into two fully-connected layers. One layer computes the box regression and the other one computes the box classification. These predictions will be reshaped through a RoI (Region of Interest) pooling layer and will then be used to classify the found objects within the proposed regions.

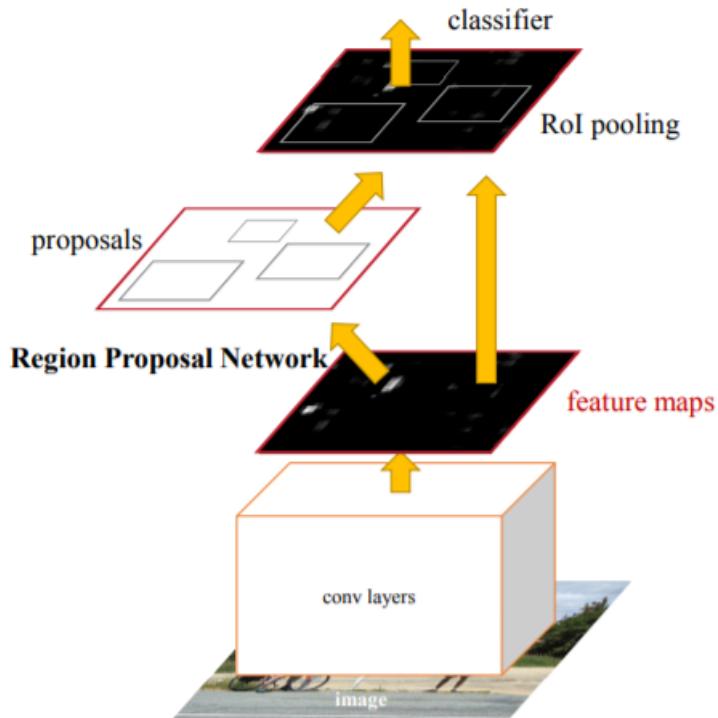


Figure 8: Architecture of Faster R-CNN [10]

#### 4.2.2 You Only Look Once – YOLO

Another approach is to not look at regions with high probability of containing an object, but to split the whole image into a grid and predict first the class probability and secondly the offset for the bounding box for different bounding boxes in this grid. The only probabilities higher than a defined threshold will be taken into consideration. This reduces the architecture to one network and eliminates the bottleneck separate classification and bounding box regression. This approach is called YOLO (You Only Look Once), which is a lot faster than Faster R-CNN, but has the drawback of less accuracy [11].

#### 4.2.3 Single Shot Detection – SSD

The last approach uses the same technique as YOLO, but has some diversifications. Single Shot Detection (SSD) is also a one-stage detection model. It predicts class and bounding box at the same time. Unlike YOLO it will not predict the certainty of the object being an object, its only predicts the class probabilities, but adds a background class. So when the background class has a high probability, it has the same effect as a low confidence score from the YOLO prediction.

Also, the SSD uses different grid layouts, which results in more predictions, but also in more accuracy. Therefore, the YOLO architecture delivers better real-time capabilities, because it is less computational intense.

Method	mAP	FPS	batch size	# Boxes	Input resolution
Faster R-CNN (VGG16)	73.2	7	1	~ 6000	~ 1000 × 600
Fast YOLO	52.7	155	1	98	448 × 448
YOLO (VGG16)	66.4	21	1	98	448 × 448
SSD300	74.3	46	1	8732	300 × 300
SSD512	76.8	19	1	24564	512 × 512
SSD300	74.3	59	8	8732	300 × 300
SSD512	76.8	22	8	24564	512 × 512

Figure 9: Performance comparison of different techniques [13]

### 4.3 Experiments

For our object detection experiments we used the following software components:

- Python 3.7.3
- OpenCV 4.1.2 [14]
- ImageZMQ [15]
- Imutils [16]
- ssd\_mobilenet\_v2\_coco [17]

We used OpenCV, because it is a well-established computer vision library and designed for fast computation also on system with low computational capabilities. It offers the DNN (Deep Neural Network) module, which implements methods to import pretrained models from different frameworks. We decided to take the pretrained MobileNetV2 in combination with SSD trained on the COCO dataset. For reasons shown in Section 4.2. and 4.1., we decided this network will give us enough computation speed to detect object while driving and sufficient accuracy to detect the object in different lighting or environment conditions. The COCO (Common Objects in Context) dataset is a commonly used dataset and offers a lot of classes. We defined the “sports ball” class as the desired object to detect but wanted to have flexibility to change the object if needed. Therefore, the COCO dataset was well-suited for our requirements.

The “ImageZMQ” package is a little library with methods to transport the OpenCV images over the network. It uses the ZeroMQ sockets to enable an easy and fast transport.

The “imutils” package is used to build up the presentation of the images.

#### 4.4 Software

Because The images will be sent over network to an external device, two scripts will be started. One is the client script, which runs on the Raspberry Pi. The server script runs on the external device and receives and processes the images. It also sends the acknowledgement to signal the client to send another picture.

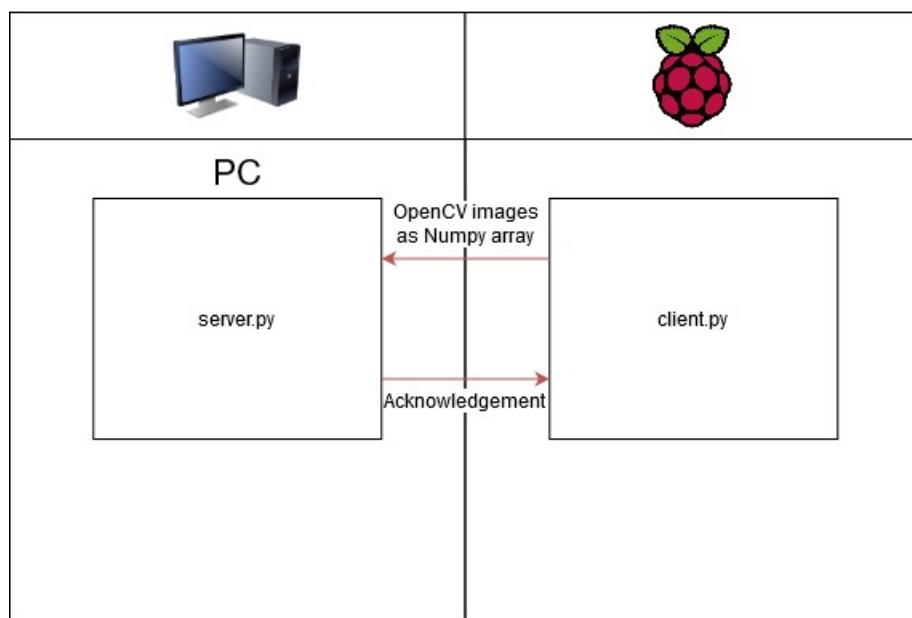


Figure 10: Server client communication

#### 4.4.1 Server.py

The server first initializes the socket to receive the images and the connection to the “Object\_hunt\_base” process. Then the network will be initialized and the objects to consider.

The marker for a found object will be set to False before the loop. In the loop the image will be received if there is a connection. If the device is not already known, it will be added to the “lastActive” list. The image will be resized and then processed by the network. If an detection of the desired object occurred and the confidence is higher than the defined threshold, the presentation will be build. The bounding box will be added to the picture and the number of detected objects will be updated. This image will then be shown on the external device. The loop is also interrupted and the connection to the object\_hunt\_base process will be established to send the message of successful object detection. Then the picture of detection will be shown, until the user interrupts the script.

#### 4.4.2 Client.py

The client initializes the connection to the server and initializes the camera. In an endless loop the client will send the images to the server.

### 4.5 Results

We could realize all the requirements we set for our object detection task. Our project has shown, that for real-time object detection it is possible to let the image processing run on an external device and still get sufficient results. Our object detection is flexible in detecting different classes, it is possible to choose one of all COCO classes. To get better accuracy and better performance an own dataset will be needed. With an own dataset, the network would only predict two different classes, the background and the desired object, which result in much less predictions and therefore better performance.

## 5 Routing & Mapping

A further part of the vehicle is to log the driven route and build a map by detecting the environment. As shown in figure 5 the vehicle drives autonomous through an unknown environment. During the ride all objects besides the vehicle will be detected by sensor. The driven route will be logged by storing the events of drive like orientation changes.

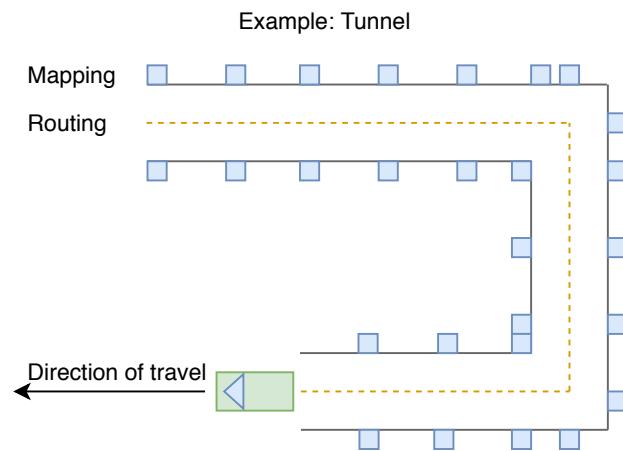


Figure 11: Routing & Mapping

### 5.1 Detection

#### 5.1.1 Routing

By the installed hardware it is possible to measure the current orientation (angle) and the current speed. These values can be used to calculate the movements of the vehicle.

At the start of the processes and the vehicle an initialization will be proceeded, which sets the current position on an imaginary coordinate system at the point (the coordinates) (0,0)[x,y]. From this point the movements of the vehicle will be logged by calculating every new position respectively coordinate in a list.

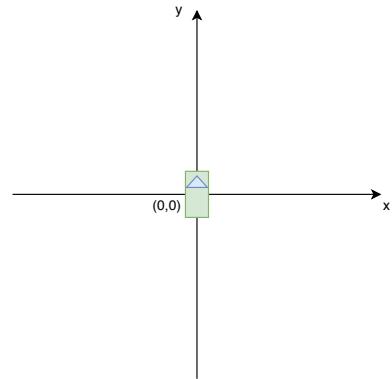


Figure 12: Initial position

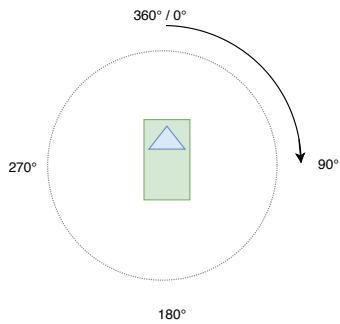


Figure 13: Vehicle orientation

The vehicle provides an revolution sensor by which one the current speed  $v$  of the vehicle can be measured. Every time the speed changes the current time will be stored. With speed  $v$  and the time slot  $t$  the driven distance  $s$  during this time slot can be calculated by  $s = \frac{v}{t}$ .

By using the smart movement sensor the orientation respectively the angle of the vehicle can measured, in relation to the initial position / orientation which is  $0^\circ$ .

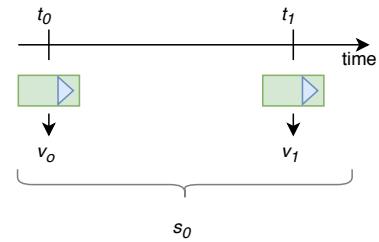


Figure 14: Calculated driven distance

By the resulting driven distance and the orientation of the vehicle the coordinates (related to the initial position and the following positions) can be calculated. The order of these coordinates results in the driven route.

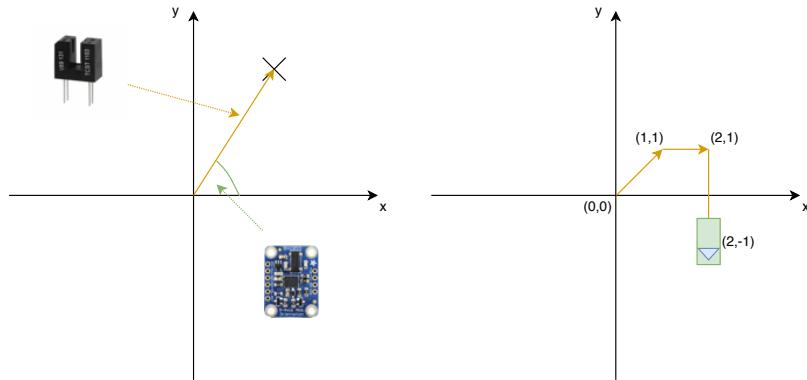


Figure 15: Logged route information

By the information of the driven route the current position of the vehicle is known.

### 5.1.2 Mapping

To detect object around the vehicle respectively the environment ultra sonic sensors are used. On the vehicle four sensors are installed, one at the front, rear, left and right.

The detected objects will be also logged by coordinates in relation to the current position and orientation of the vehicle.

In the beginning the sensor data will be read. These data will be stored in coordinates which will be adjusted by adding the orientation of the vehicle to calculations. Finally, the calculated coordinates will be added to the current position coordinates of the vehicle to result the object position in relation to the

initial point (0,0).

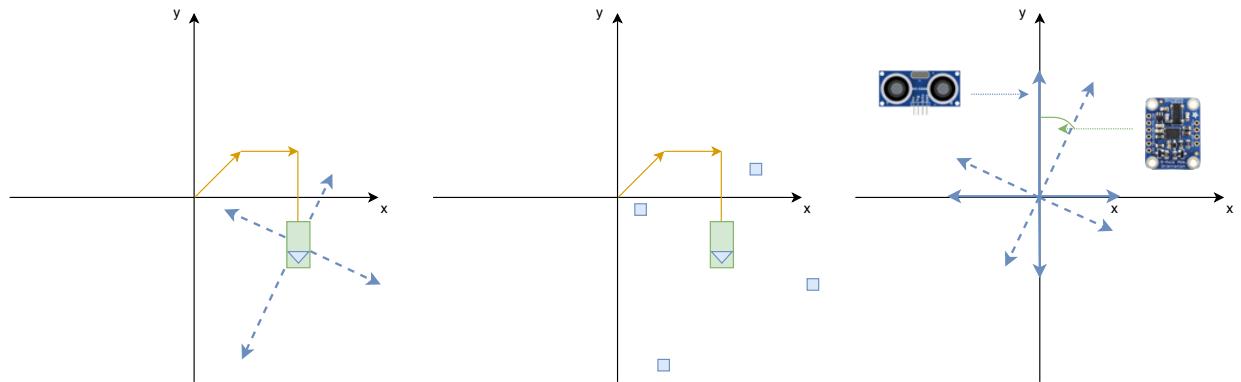


Figure 16: Smart movement and ultra sonic sensor

## 5.2 Software

The routing & mapping progress is a self-contained process as described in the beginning of this report and has been developed with Java.

It contains several classes which will be show following:

Class	Description
ProcessMain	Includes the main-methode to start the process by calling the method <i>processControl()</i> of the class ProcessControl. It also may be used call additional method of further classes which may be added.
ProcessControl	Calls the relevant methods to run the important tasks.
SystemData	Stores the system relevant information like port or communication codes.
NetworkInterface	Establishes the network communication with the navigation process.
LogFile	Creates and edits the log files.
MessageAnalysis	Checks the received messages and their contents and handles the following processing
MapData	Stores and handles the data for the route and map building.
Calculations	Offers the methods for the calculations.
DrawRoute	Includes the methods for the route.png to be created.
DrawMap	Includes the methods for the map.png to be created.

Table 2: Process classes

As described before the relevant methods for this process will be called by the method *processControl()*, which is shown below. To describe this the sequence more understandably the program sequence is graphically shown in figure 1

```
1 public void processControl() {  
2     processInitialisation();  
3     while(!system.endOfProcess) {  
4         analysis.checkMessage(network.readSocket());  
5     }  
6     System.out.println("\nBuilding route...");  
7     drawRoute.buildMap(mapData.routeX, mapData.routeY, "Route", routeCoordinates);  
8     System.out.println("route.png created.\nBuilding map...");  
9     drawMap.buildMap(mapData.mapX, mapData.mapY, "Map", mapCoordinates);  
10    System.out.println("map.png created.\n");  
11  
12    System.out.println("System ends.");  
13}
```

Listing 1: Method *processControl()*

In the beginning an initialization process will be proceeded. This includes the establishment of the network communication with the navigation process. Also, the first data of the sensor will be received to initialize the start position of the vehicle and respectively the center of the coordinate system (0,0).

The code of the process includes a boolean variable which will be set true if the navigation process wants the process to be ended. This variable will check every time the while-loop start at the beginning. After this check the process wait for a message to be received in depend on the type of information to be received.

There are two options of informations to be received. The message could have the length of one byte, then this byte gives informations if the process has to stop, the vehicle rotates or which type of values will be send in the message. With that type of information the knows the byte array length of the next message. If the message is longer than one byte the message includes sensor data and can be directly transfer to the methods which handle value data.

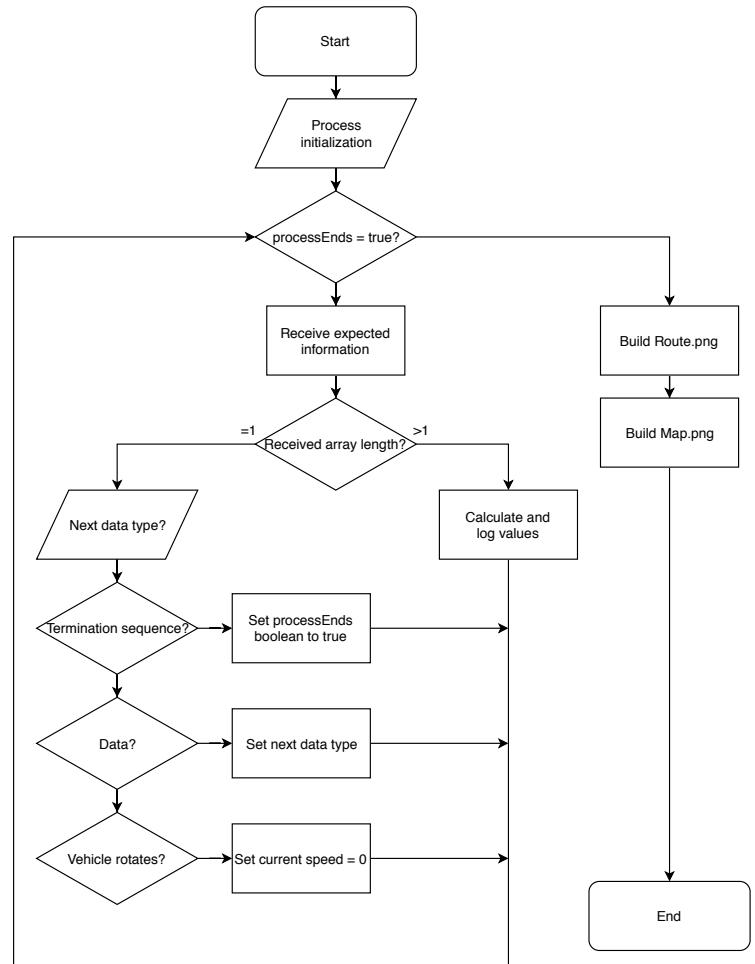


Figure 17: Program sequence

Finally the while-loop start at the beginning till the navigation process sends the termination sequence. If this sequence will be received the while-loop stops and the methods to build the graphical files for the route and the map will be called.

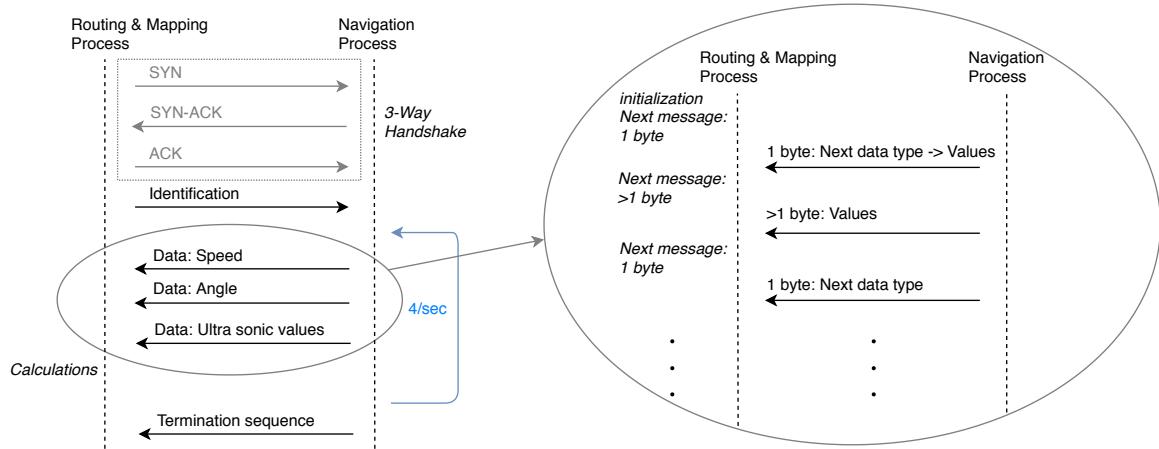


Figure 18: Principle communication

During the process run all the calculated coordinates of the route and the map respectively the objects will be stored in log files. At the end of the process the classes DrawRoute and DrawMap read the named files to get the coordinates. By these coordinates the wanted .png files will be created as shown below.

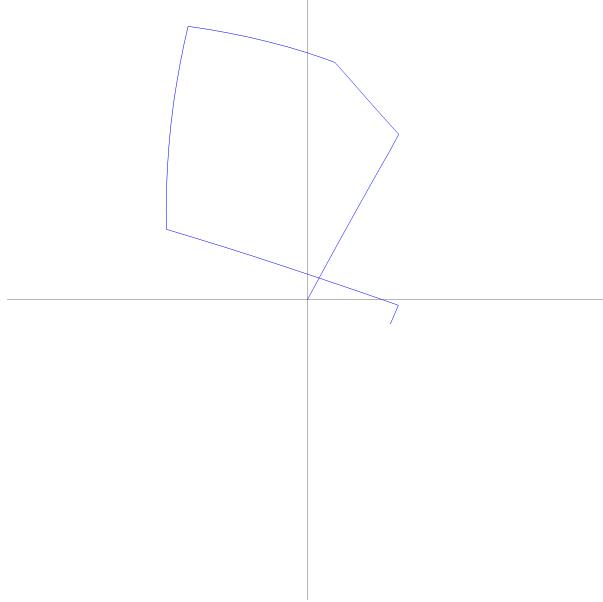


Figure 19: Route.png

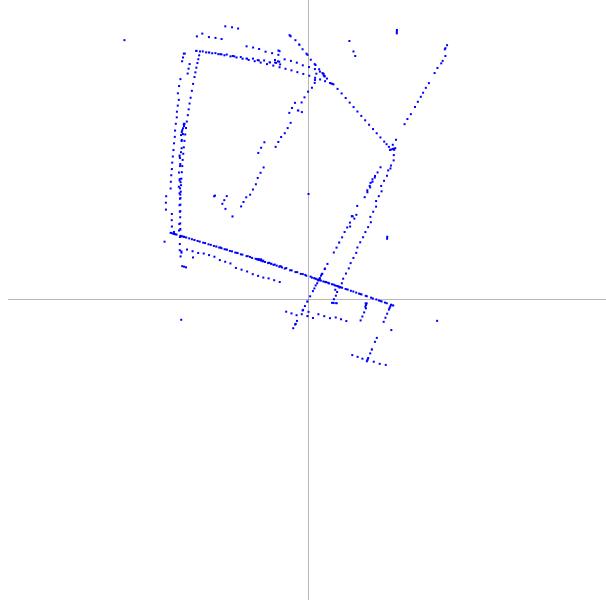


Figure 20: Map.png

### 5.3 Problems

Unfortunately some problems with the ultra sonic sensors occurred.

The measured distance of the objects are not continuously correct respectively useful. By this error it is not possible to build an adequate map. The main object which are visible in the map build the shape of the route. The object in which direction the vehicle drives will be detected several times but with kind of random values. This causes the visible shape of the route in the map.

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