THE UNIVERSITY OF QUEENSLAND

Design and Evaluation of a Beacon Guided Autonomous Navigation in an Electric Hauler

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Submission date: 27 June 2019

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Executive Summary

Heavy diesel mining haulers are still industry standard within the mining sector. However, conventional haulage can be optimized by reducing maintenance and refueling times, by designing a more efficient powertrain and optimizing the overall haul cycle. Mining3's Dr. Erik Isokangas proposed a novel concept for an electric mining hauler that maneuvers autonomously and recharges on the move by utilizing inductive charging.

A mobility scooter sized proof of concept model of the proposed mining hauler was be developed by four full-time and one part-time student working in different topics, as a base before further up scaling.

This particular project's aim is to develop a proof of concept autonomous navigation for the small scale mining hauler, guided by wireless Ultra-Wideband (UWB) beacons.

The first part of the project was about developing a UWB beacon system, including hardware and developing the positioning algorithms.

Multiple sensors such as the UWB beacons for positioning, wheel encoders and an inertial measurement unit for orientation were fused together to provide a more stable position estimate.

The whole sensor system was integrated within the Robotic Operation System and controller for the navigation system was developed.

The concluding tests evaluated the UWB positioning system which achieved a mean accuracy of 0.3 meters, the orientation was tested with 10 degrees in accuracy.

It was found that beacon should maintain line of sight contact to the hauler in order to yield accurate positioning results. Several mitigation approaches for this issue were presented in the future work section.

The navigation algorithm works with the current stage of the hauler and moves the hauler from a start point to a goal location and back to the start point. For the future it is recommended to add the Robotic Operation System navigation stack for Ackermann vehicles for collision avoidance and further path planning.

As a conclusion the system is suitable for up scaling to a car sized vehicle, by following the recommendations made in the conclusion section.

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1. Introduction

1.1 Project Context

Hauling materials is a key operation in the mining operation chain. Depending on the type of mine, hauling in open pit mines is usually performed by heavy diesel trucks in the 100-240 tons payload range [1]. In underground mines depending on the mine structure typically combined load haul dump (LHD) trucks or conveyor belts are used due to the small height clearance of the tunnels. Having an efficient transport cycle is vital to minimize costs during the haul cycle.
In a white paper from 2017, Mining3 Program Director Dr. Erik Isokangas identified several problems with conventional mining haulage, which are summarized below [2]:

- High costs in fuel and maintenance
- Need for wide and low in slope haul roads, high transportation times
- Productivity affected by refueling, maintenance and idle times
- Inefficient and not sustainable use of diesel engines

To address these problems, Isokangas proposed the development of a light electric autonomous hauler (AEH). As electric motors have a efficiency of up to 89% compared to 40% with a diesel engine [3], an electric powertrain decreases cost for fuel and allows maneuvering steeper slopes due the higher torque output. The autonomous electric hauler has an inductive charging system which can charge the vehicle on the move, allowing for a productive haul cycle and thus maximizing operation time of the vehicle. This is achieved by the placement of inductive coils in the ground supplying power into the batteries of the vehicle.
The picture below shows the setup of the autonomous electric hauler here operating in an open pit setting. However the hauler should work in underground mines as well.

Figure 1: Proposed System Architecture of Autonomous Hauler [2]

The hauler loads material underneath a mobile feeder platform and navigates with the help of a local positioning system autonomously back to the guidance wire which the truck follows along until it is close to the dump site. Then again the hauler maneuvers autonomously to the desired dump location utilizing this project’s autonomous mining hauler navigation system.

1.2 Purpose

The purpose of this thesis is to develop a proof of concept method to solve the problem of navigating the electric mining hauler in both an underground and open pit mining setting. Due to the underground mine environmental constraints, this thesis utilizes localization methods aside from GPS to provide autonomous navigation.
This thesis is done on a smaller scale version of a concept mining hauler. However building the actual vehicle itself is not the purpose of the project. Instead, it is the knowledge gained with this project and technology can be than transferred to a full scale vehicle later on, upon success of this project.
The ultimate, overall purpose of the whole project is to showcase the autonomous navigation methods as well as the other technologies the project's team members developed such as on wire navigation, inductive charging and power management. The project will be demonstrated to a technical committee of Mining3's industry and institutional members who are also part in funding this project.

1.3 Scope of Project

The overall scope of the project is defined by the projects goals, requirements, development objectives to reach the goals and deliverables.

Project Goals

The overachieving main goal of this semester placement project is to develop a proof of concept autonomous driving system for a small scale mining hauler, which can navigate the hauler from guided wire tracks to a mobile feeder to load material and back to the guidance wire within in a 30 meter range. The same process happens vice versa upon the unloading process. Below picture depicts the area of autonomous operation addressed in this project:

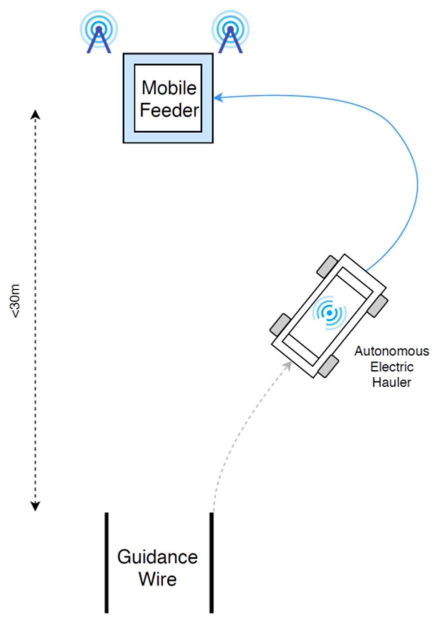

Figure 2: Autonomous navigation from guidance wire to respective load and dump zones

To achieve the main goal following sub goals to be reached in the development process in order to fulfill the main goal:

- Obtaining the absolute position of vehicle within the load and dump zone with an accuracy of <30 cm to be able to provide suitable navigation
- Successfully obtain the current relative orientation of vehicle towards the desired target orientation with <5° degree error
- Deliver path planning algorithm which takes in pose sensor data and controls the vehicles actuators to move it towards the goal and avoids collisions on the way

This project's success can be defined by its ability reach or exceed those goals.

Project Requirements

The requirements are formed by the general framework of the proposed mining hauler such as the mine environment that the hauler will operate in, limitations due to the choice of electric propulsion and safety requirements:

- Provide autonomous navigation for mobility scooter sized electric mining hauler
- Vehicle needs to reach the target location in predefined heading/angle to successfully execute tasks of loading and unloading, maneuvering back to the guidance wire
- Vehicle can locate itself within 30m an navigate autonomously in that range
- Autonomous navigation system has to flexible to constantly changing environments
- Sensor setup that is mobile and not fixed to a location
- Vehicle must be able to navigate in dust, limited brightness and in an underground environment with no GPS reception
- Safe operation needs to be ensured at all times, remote control and emergency switch
- Detect possible collisions before impact

Taking the goals, requirements and resources into consideration, the following table lists objectives to develop the off wire navigation for the autonomous electric truck project and seperates it from out of scope tasks.

In Scope	Out of Scope
• Analyzing current state of the art systems for vehicle localization • Development of sensor system for absolute localization in x and y coordinates • Development of sensor system for orientation • Design of a sensor fusion algorithm for orientation and localization sensors • Optimization of sensor system using filters and correction algorithms • System Integration of sensor system with robotic operating system (ROS) • Design of the path planning/navigation algorithm • Risks assessment of system • Testing and evaluation of system	• Mechanically construct vehicle chassis • Implementation of fleet control system • Development of mapping algorithms of the mines to guide navigation • Implementation of payload distribution tracking and controlling • Developing an autonomous navigation algorithms for full scale mining hauler • Developing Inter-vehicle connectivity

1.4 Deliverables

During the course of the project runtime the deliverables outlined below are the outcome a successful project.

- Interim Report:
  Is a review of the progress made in the project and will report about an updated literature review, current state of the project and planned remaining tasks
- Working proof of concept model:
  Has positioning sensor system mounted on mining hauler and runs software algorithms to control the vehicle autonomously
- Project demonstration and presentation:
  Showcasing the projects current status and capabilities of the autonomous electric hauler to Mining3's Industry and Institutional partners on the 04.06.2019
- Final report:
  Is a comprehensive document containing all project outcomes and a complete documentation of the project progress and methods
- Presentation at The University of Queensland:
  Presenting the main outcomes of the project to UQ project supervisors, participating students and EAIT staff

2. Literature Review

The following literature review follows a logical structure to research the most suitable autonomous navigation for the mining hauler. Firstly, an overall state of the art review for autonomous navigation methods in commercial mining haulers is conducted. On top of that knowledge, to fulfill the projects requirements of an accurate underground as well as on surface localization, viable indoor localization sensors and methods will be surveyed.
Following, methods on obtaining the vehicles pose will be examined. Finally, given the location and heading a review of path planning algorithms will be conducted.

2.1 Industry Review of Autonomous Mining Hauler

Looking at the current industry adoption, Rio Tinto is using a share of 20% autonomous vehicles in its Pilbara mine as a pilot project. Contrary to this project the vehicles are large and are reliant on an ongoing GPS connection. Leading manufactures supplying solutions for autonomous mining haulers are Caterpillar fitting their Cat 793F, 227 tons mining hauler with autonomous functionality [4]. Similarly, Komatsu focuses on heavy mining haulers in the 200-400 tons payload range [5].
Hitachi released a technical report on their system infrastructure they are testing as an add on module on their current diesel powered EH5000, 296 tonnes mining truck [6]. The truck combines the use of GNSS, a common global navigation satellite system for positioning within the mine. The desired load and dump locations can be selected which a function and their system computes a path to get there. To get a more accurate location the position system is supported by an initial measurement unit which collects and integrates the vehicles movements over time and thus assists the GNSS system to achieve a higher accuracy [7].

For collision detection their system utilizes a combination of millimeter wave radar and laser radar to detect obstacles that come into way. The autonomous unit in the hauler communicates with their base station, which assigns paths and manages movements of the fleet.

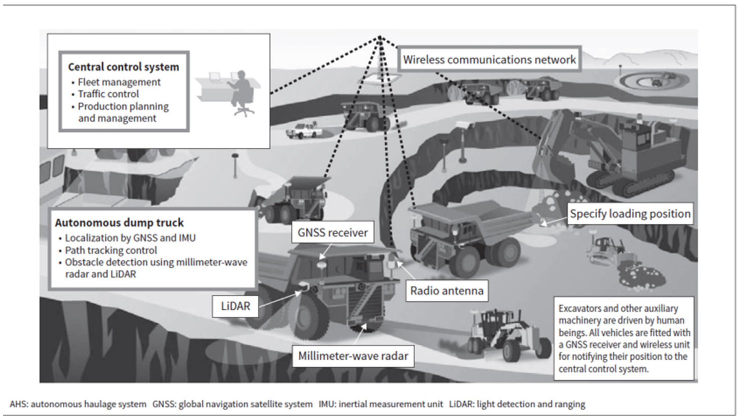

Figure 3: Hitachi Autonomous Haulage Setup [6]

For underground mine operations there are three commercially available products, which can be installed as an add on to a regular load haul and dump machine (LHD). providing underground navigation released from Sandvik, Caterpillar and Atlas Copco [8]. All of them use a Lidar based system, gathering scans of tunnel walls to provide positioning within the mine. Odometry information is gained from wheel encoders and inertial measurement units.
Caterpillar uses a reactive navigation, by comparing the current tunnel structure with a map and doesn't follow a predefined path [8]. However, for this project reactive navigation can't be used since tunnel walls may not be present in all operating modes such as in open pit operation.

2.2 Evaluation of Indoor Positioning Systems

To find a more suitable solution for accurately tracking the mining hauler underground and on the ground without the reliance on localization via GPS and laser radars as in most commercial systems an adapted method has to be found. As pointed out in the constraints section it needs to be accurate within <30cm and work underground as well as outdoor. A paper by Yassin (2017) surveys current indoor positioning systems in regards of accuracy, cost and complexity, thus addressing the problem of finding a suitable indoor localization system [9]. The author mentions the use of radio based systems as a means for achieving high accuracy in localization. The paper lists challenges in radio based positioning systems such as clock synchronization and multipath interference which can occurs mostly in a reflective indoor environment. Applied to this project's case this would be rough and uneven rock walls in underground mines causing possible reflections and multipath. Hence possible radio based localization sensors need to be tested in multipath prone environment, to prove suitability. The chosen method for indoor localization should therefore be less vulnerable to multipath.
Yassins survey results are extended by another indoor localization survey by Zafaris (2017) paper on wireless indoor localization systems. Zafari compares advantages and disadvantages of localization techniques and lists possible hardware solutions and methods to for an indoor location system [10]. Given the range of indoor positioning systems presented in the two previous papers and from additional papers, the next paragraph lists methods performances based on accuracy and range of indoor positioning implementations. The indicated ranges and accuracy are based on reports of performances in the respective referenced paper for each technology.

Technology	Accuracy	Range	Method	Suitability in Mining Environment (underground and open pit mines)
Camera Motion Tracking [11]	<1cm	<15m	Computer Vision	Expensive, time consuming setup, not very portable system
Optical IR Beacons [12]	50-100cm	<10m	Triangulation	Prone to Interference in high lighting conditions (outdoor)
Vision based Fiducial Tracking [13]	N/A Range dependent	<40m	Computer Vision	Is reliant on good visibility of target, can be affected by dust
Bluetooth [11]	1m	20m	RSSI	Accuracy not suitable
Passive RFID [14]	<10cm	5m	Cell Recognition	Range not suitable, Accuracy relies on closely spaced grid of tags on ground. Setup not feasible for mining
Wifi [15]	1m	50m	RSSI	Accuracy not suitable
Ultrasonic [16] [17]	<10cm	5m	Time of Flight	Dependent on undisturbed acoustic channel, Multipath Interference, Range to short

UWB [18] [19]	<10cm	40m	Time of Flight	Suitable, good accuracy and good range. Doesn't require line of sight during operation. Has mobile setup
Magnetic Localization [20]	<10cm	10m	Magnetic Field Analysis	Short range, needs Tx and Rx coils to be exactly positioned, possible interference with inductive Charging
LIDAR Localization [21]	<15cm	200m	Simultaneous Localization and Mapping	Lack of natural landmarks for guidance in open pit mines, unsuitable for solely localization aspect

Upon the performances listed in this table, it can be seen that Ultra-Wideband (UWB) technology could be a suitable choice of positioning system for this project. Yassin states UWB due to its short pulse duration is less prone to multipath effects compared to other RF localization technologies [9]. This is especially favorable this project, since the positioning system needs to work in underground mines which are naturally a reflective environment. The range and accuracy and the lower vulnerability to multipath effect make UWB a suitable technology choice for sensing the absolute location of the mining hauler for navigation.

2.3 Ultra-Wideband Beacon Localization System

UWB indoor positioning systems operate on a large bandwidth of 500 MHz and in the frequency range of 3.1GHz up to 8.5 GHz and can operate within centimeter level applications, as summarized by Rahayu (2008) [22]. A possible setup of a UWB based indoor positioning system is shown in Figure 3.

For absolution localization a minimum of three fixed UWB anchor beacons are placed at previously known locations. Then the absolute location of the tag (T1) can be determined by measuring time of flight of a signal between the tag and each anchor (A1-A4) within this world frame, as shown by Decawave (2014) [23].

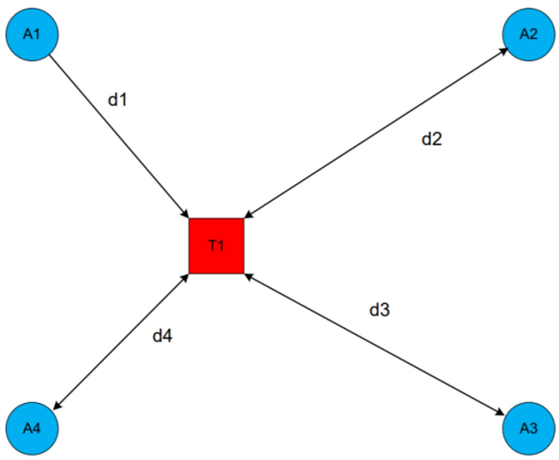

Figure 4: UWB Beacon Setup with mobile Tags(T1) and stationary Anchors(A1-A4) [23]

Yassin points out that Ultra-Wideband (UWB) beacons can be used to provide accurate indoor localization for mobile robots. Furthermore, the paper highlights a use case where accuracies in the range of 2-3cm could be archived with a UWB system [9].

Concerning a use of a UWB system in multipath prone environments, Yao (2017) investigated a method to mitigate effect on multipath. The author combined inertial measuring unit and a Ultra-Wideband beacon system with a sensor fusion approach with an Extended Kalman Filter (EKF). Yao states that the position accuracy has improved by 100% using the sensor fusion approach, which also removed spikes and glitches compared to the raw Ultra-Wideband position data [24].
This result is confirmed by Marquez (2017) who also used a sensor fusion approach of a UWB module and an IMU with an EKF and achieved a by 75% lower error, compared to the raw UWB localization data. The author mentions UWB as an accurate localization technique within a few centimeters range for the use in autonomous robots [25].
Applying the UWB technology to a project in a comparable setting like this project Tiemann (2016) presents a paper that maneuvers a car autonomously with guidance of three UWB beacons. The author achieves a position error lower than 10 cm with a 95% confidence interval.

Observations on UWB Multipath Effects and Non-Line of Sight conditions

In the last section papers mentioned multipath effects through an obstructed signal path in UWB were compensated using sensor fusion.
A paper by Chen (2016) examines multipath properties of UWB further and comes to the conclusion that in particular path loss increases when the signal path is obstructed by high conductivity materials. Also the difference in time between the first and last multipath component, referred to in the paper as the delay spread. Chen concludes that the delay spread increases as the distance between to UWB nodes increases, as well when the signal path contains materials of high conductivity. He also mentions that the delay spread is higher in non-line of sight operation of the beacons, which slows down the data rate. [26]
Kietlinski (2011) mentions in his PhD thesis that non line of sight (NLOS) conditions are one of the greatest problems for UWB indoor positioning, since time based range measurement rely on detection of the direct path component, whose delay between sender and receiver node is the range measured by the beacons.
He underlines that non line of sight errors occur when the direct path between two UWB beacons is blocked, causing a multipath signal being received at the one beacon.
This in turn is then falsely interpreted as direct path, causing a significant error [27]. Therefore, for the mining hauler project it needs to be made sure that sufficient coverage by anchor beacons provide constant line of sight localization or in case of a blocked path, the localization needs to rely on sensor fusion by other sources such as odometry or IMU units.

Decawave (2014), the manufacturer for the UWB beacons used in this thesis provided some examplesof how non line of sight operations would affect the range accuracy. The authors state, that range errors occur in a situation where the direct path signal has a lower amplitude than the detection threshold. Therefore the beacon would detect to a later arriving multipath signal if it has an amplitude above the detection threshold and thus would give a wrong result for the range measurement.

To give some direct examples for attenuation, the manufacturer states the human body can attenuate the signal by 15-30dB at 4GHz, a concrete wall of 10cm would give 23dB attenuation to the signal [28].

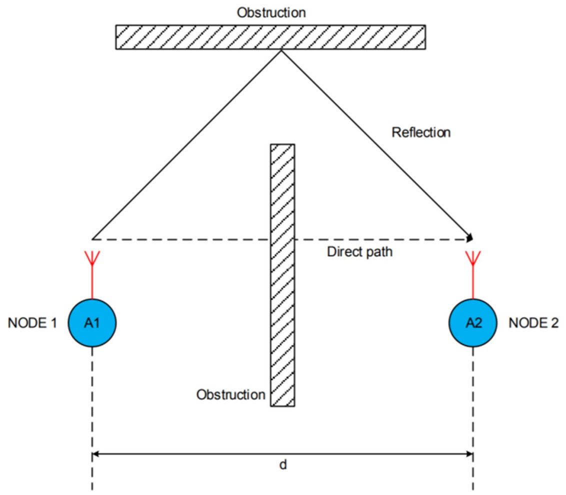

Figure 5: NLOS condition with multipath [28]

Possible errors induced by multipath signals with higher amplitude, show the importance of maintaining line of sight during operation of the UWB localization beacons to maintain a good accuracy.
For the context of the mining hauler project this means the antenna of the mobile beacon has to be placed at the highest point of the vehicle in order to facilitate line of sight communication in between the mobile tag and stationary anchor beacons.

Obtaining Relative Orientation of Vehicle

Lensund (2018) utilized multiple UWB beacons mounted on an outdoor mobile robot in order obtain the relative angle of the vehicle toward the target. However, the author reports with a measurement error of 5cm of the UWB beacons will result in an angle error of 10° given his geometry of the UWB beacons. Lensund suggests the use of a digital compass for obtaining the orientation [29].
Corke (2011) states that the pose of a vehicle can be estimated with dead reckoning, by the vehicles observed speed and direction. The author suggests the utilization of a gyroscope, differential wheel encoder or an electronic compass to estimate the vehicles current heading [30].
Park(2017) combined the insights of both previously mentioned papers and realized an Ultra-Wideband indoor navigation system that obtains the absolute location from UWB beacons and the absolute orientation from a digital compass. The absolute position information is used to compensate relative position information obtained by the vehicles IMU and wheel encoder.

2.4 Navigation Techniques for the Hauler

Corke (2011) defines robot navigation as the problem of guiding a robot towards a goal [30]. In the context of the autonomous mining hauler, the vehicle needs to go from a start location which is the end of the guidance wire to the target being the dump/load site and the back to the guidance wire. The following section will introduce a navigation control algorithm that is suitable for the task of moving the vehicle to a position in a certain direction.

Firstly, a control loop which takes in the current vehicle pose and outputs control variables as the vehicle heading and speed will be introduced.
In order to get a control loop the vehicles kinematic model needs to obtained. Length and width of the wheelbase is needed for to model Ackermann steering.
The haulers model can be described by the following system equation [30]:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} cos\theta & 0 \\ sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \gamma \end{pmatrix}$$

The parameters x and y give the position of the hauler in the world frame, θ gives the current heading of the vehicle obtained from sensors mounted on the vehicle. v is the speed of the vehicle and γ indicates the angle.

Corke (2011) shows a method to guide a vehicle to a goal location with a pre specified orientation, given its current, heading location and speed [30]. This aligns with the vehicles requirements to navigate to respective load and dump location with a certain orientation starting from the guidance wire. A coordinate transform of the system equation into polar coordinates yields the following [30]:

$$\begin{pmatrix} \rho \\ \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} -cos\alpha & 0 \\ \frac{sin\alpha}{\rho} & -1 \\ -\frac{sin\alpha}{\rho} & 0 \end{pmatrix} \begin{pmatrix} v \\ \gamma \end{pmatrix}$$

The angle alpha is the vehicle's relative angle to the goal, which would be the loading or dump zone in the case of the AEH. Beta is the angle to the goal orientation relative to the coordinate system frame.

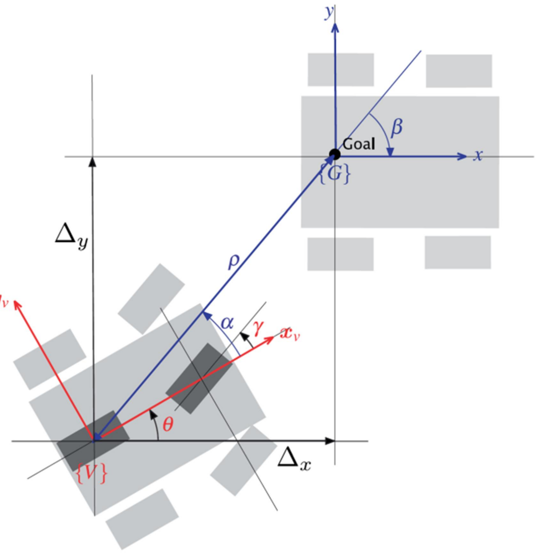

Figure 6: Schematic of vehicle pose control system [30]

4. Project Methodology

4.1 Overall System Architecture

The implementation of the beacon guided autonomous hauler system can be split into three major parts, which structure this description of methodology. Firstly the location of the hauler must be known in a local reference frame measured by sensors. Then, data from sensors is fused to get a reliable estimate of the haulers pose. Lastly the navigation algorithm directs the hauler from the start point via a unload/load point to the end point.

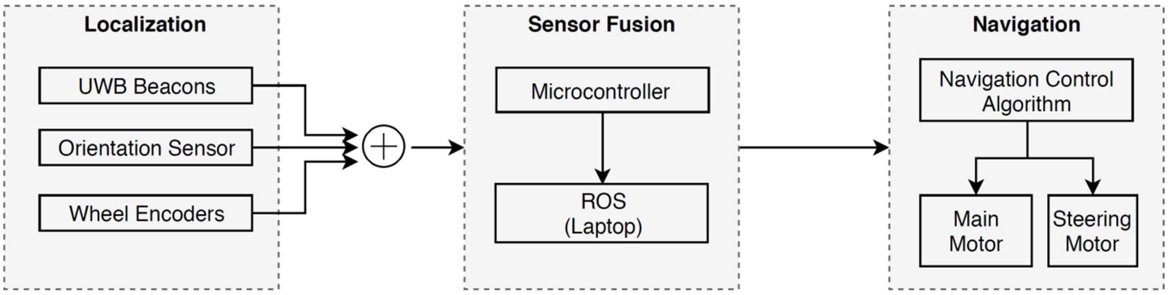

Figure 7: System Architecture

Firstly, the Localization section will depict how the Ultra-Wideband Beacons estimate the location of the hauler by measuring distances. An orientation sensor and wheel encoder will supplement the absolute location obtained from the beacons. Secondly, the Sensor Fusion section will show how sensor data is collected by microcontroller, processed and send to a Laptop running Robotic Operation System.
The last section describes how the navigation algorithm computes the desired steering angles and motor speeds based on the current pose of the vehicle.

4.2 Localization with Beacons

The Ultra-Wideband beacons used in this project are composed of an UWB module on an integrated circuit and an Arduino pro mini microcontroller for serial communication with the IC. This project uses the DWM1000 module by Decawave, which supports 4 RF bands from within 3.5GHz to 6.5 GHz, it comes with an onboard clock and a RF antenna. [19] The Arduino Pro Mini was chosen because it supports a logic level voltage of 3.3V, which is the same as the UWB IC. To ensure a small and mobile form factor a printed circuit board which combines the microcontroller and the IC module on a single board with pin connectors. The printed circuit board was designed in EAGLE CAD. The PCB contains a USB mini socket as a power supply, a linear voltage regulator to step down on 3.3V and capacitors and resistors. The microcontroller and the UWB module communicate via SPI bus. The beacons will be powered by a common USB power bank as that keeps the cost low and the mobility high.

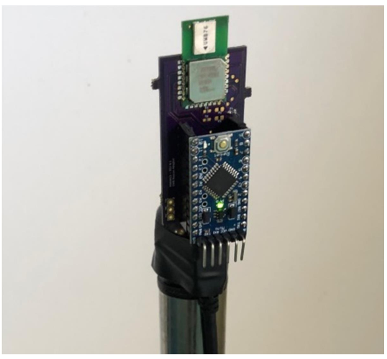
Figure 8: UWB Beacon with IC and Microcontroller

In summary, localization with UWB Beacons works by measuring distances between the mobile Tag Beacon to the stationary anchor Beacons that are placed at known positions in the area.
The mobile beacon sends out a range request with a timestamp to all of the receiver beacons. As soon as the response from the stationary beacons arrives to the mobile beacon, the time of flight can be measured.
With the time of flight of the signal in between the beacons an estimate of the distance can be computed. To minimize clock drift between beacons a time measurement called asynchronous two way ranging is applied, which means that time measurements in between beacons are conducted twice and then averaged.
With the measured distance to each of the stationary beacons the position of the mobile beacon can be computed by a method called trilateration or intersecting circles.
This project looks at positioning with two and three stationary beacons to keep the mobility high and the number of stationary beacons low.

Positioning with two stationary Beacons

With a topology of two stationary beacons (Anchor) and one trackable beacon (Tag), two distances can be measured.
Given a distance d_{left} between Tag and Anchor left, the location of the Tag can be anywhere on a circle with the radius of the measured range. Introducing a second distance d_{right} between the Tag to Anchor right, the position of the Tag can be on two points where both distance circles intersect. In this setup the distance between anchor left and right is known, and the assumption is made that the vehicle is only allowed to drive in front of the beacons, such that there is only one solution.

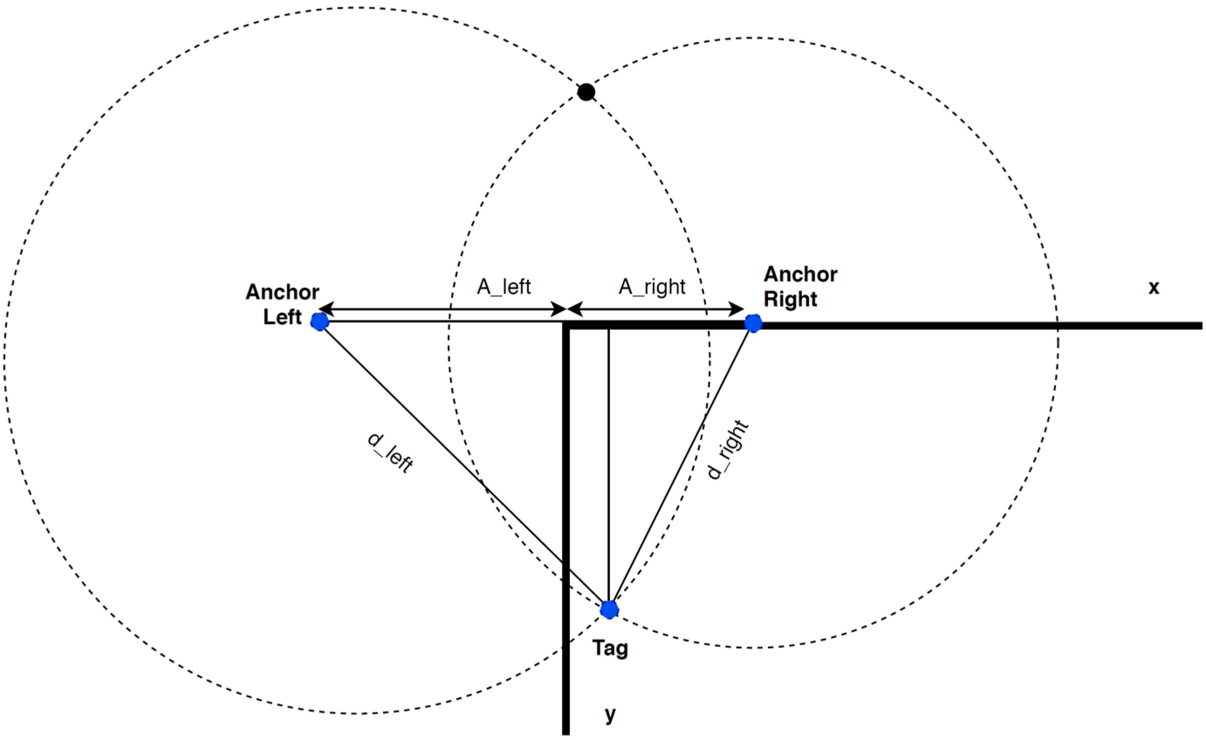

Figure 9: Lateration principle with 2 anchor beacons and 1 tag

The position of the Tag can be found be setting up an equation system of both circle distances and the distance between both beacons [31]:

$$d_{left}{}^2 = A_{left}{}^2 + y^2$$
$$d_{right}{}^2 = A_{right}{}^2 + y^2$$
$$d_{l\_r} = A_{left} + A_{right}$$

This equation system can be solved with:

$$A_{right} = \frac{\left(-d_{right}{}^2 + - d_{left}{}^2 - d_{lr}{}^2\right)}{-2d_{lr}}$$
$$x = d_{rig}\quad{}^2 - A_{right}{}^2$$
$$y = \sqrt{d_{right}{}^2 - A_{right}{}^2}$$

Positioning with three stationary Beacons

Given the architecture of 3 stationary beacons (Anchors) and 1 mobile beacon (Tag) as introduced in literature review section 2.3, the 2D position of the Tag beacon can be determined explicitly. The schematic below shows the principle:

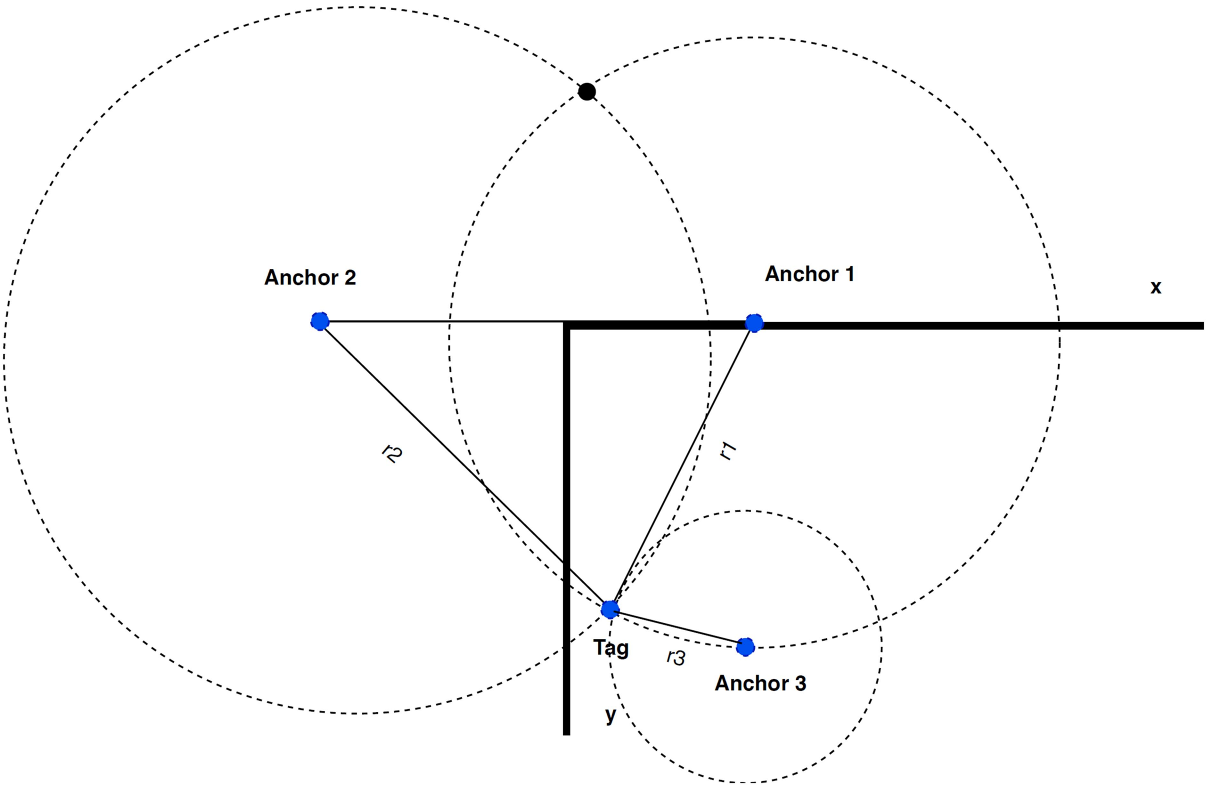

Figure 10: Trilateration principle with 3 anchor beacons and 1 tag

With only one range between a tag and anchor the estimated position is on a circle. With a second anchor and respective range to the tag, the estimated position of the tag has two solutions on both intersections of the circle. With a third anchor the 2D position can be determined explicitly.
In theory, the intersection of these circles can be analytically determined by solving a system of three quadratic equations, which each correspond to a circle.
However, in practice the ranges are subject to noise and therefore the circles around a beacon would not reflect the true range. This would lead to a not solvable equation system, given that there is a measured noisy range at the tag that doesn't intersect with the ranges from the other anchors.

The mobile tag receives distance information r_1, r_2, r_3 of each of the three stationary beacons.
Given an arbitrary initial position X_p, Y_p, Z_p of the tag and the known positions X_b, Y_b, Z_b position of the beacons of all distances the d_1, d_2, d_3 have to be computed, which corresponds to the Euclidian distance between an arbitrary point and the stationary beacons.

$$\begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix} = \begin{pmatrix} \sqrt{(X_{b1} - X_p)^2 + (Y_{b1} - Y_p)^2 + (Z_{b1} - Z_p)^2} \\ \sqrt{(X_{b2} - X_p)^2 + (Y_{b2} - Y_p)^2 + (Z_{b2} - Z_p)^2} \\ \sqrt{(X_{b3} - X_p)^2 + (Y_{b3} - Y_p)^2 + (Z_{b3} - Z_p)^2} \end{pmatrix}$$

In order to find the location of the mobile tag this distance function is called continuously with varying values of (X_p, Y_p, Z_p) which are found by the optimization algorithm which minimizes a cost function.
The cost function corresponds to the square error of the distance function of an arbitrary point (X_p, Y_p, Z_p) in the map to the range (r_1, r_2, r_3) to each respective stationary beacon. The goal is to minimize the cost function such that a close estimate to the real tag position (X_p, Y_p, Z_p) is computed, which is the result of the lowest cost.

$$c(X_p, Y_p, Z_p) = (d_1(X_p, Y_p, Z_p) - r_1)^2 + (d_2(X_p, Y_p, Z_p) - r_2)^2 + (d_3(X_p, Y_p, Z_p) - r_3)^2$$

This minimization step is computed with a downhill simplex algorithm, which calls the distance function with optimized values of (X_p, Y_p, Z_p) constantly updating to cost function until convergence. The algorithm is implemented in python, in the scipy library. That is a simple, yet effective approach. The higher computational cost of this algorithm is negligible since the computation is running in python on a laptop and not on a microcontroller.

4.3 Measuring Orientation

For the navigation aspect of this engineering task it is important to know the vehicles current direction towards the goal.
This project examines two approaches to measure the current orientation of the vehicle, complementing the x and y position estimates of the positiong algorrithmn of the UWB beacons.

Measuring Orientation Estimate by Positioning Trajectory

The algorithmn constantly updates a buffer of 10 of the most current position estimates from the UWB beacons.

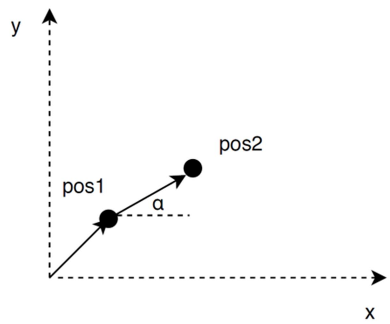

Figure 11: Orientaion Algorithm

The vehicles orientation relative to the coordinate system can the be computed by the arctan2 function which yields a orientation within $[-\pi, \pi\ ]$

$$\tan 2(\alpha)^{-1} = \frac{position2[y] - position1[y]}{position2[x] - position1[x]}$$

The advantage of this method is that no further sensors and calibrations are needed, however it is expected that the measurements fluctuate. Also the orientation can only be updated as long the vehicle is moving.

Measuring Orientation with an Inertial Measurement Unit (IMU)

An IMU is an electronic component that combines sensors that measures acceleration, magnetic field, angular velocity and temperature. An IMU as it can provide orientation at a high sampling rate without relying on any other devices or landmarks in the surroundings.
This project uses the BN055 inertial measurement unit, which provides on chip sensor fusion of accelerometer, gyroscope and magnetometer. It yields absolute orientation in Euler angles and quaternions.
Angular velocity measurements from the gyroscope drift over time, this is being compensated by fusion with magnetometer data which can measure the magnetic north as steady value. Absolute Orientation, meaning the direction of the sensor to the magnetic north can then be computed. The accelerometer is used to compensate a possible tilt of the device when measuring the orientation data in reference to the ground.
The system was calibrated near the mount position on the hauler and calibration offsets for each sensor were saved and are loaded into the IMUs registers upon each startup of the chip. The

calibration process is important, especially for the magnetometer which is subject to interference from nearby metal parts.

4.4 Robotic Operation System

This project utilizes Robotic Operation System (ROS) deployed on a laptop. It is an open source software framework offering commonly used robotic libraries, visualization tools and a data distribution system with messages and topics.
ROS serves as the central unit within the AEH system, obtaining data from each sensor mounted on the vehicle. Several functionalities and packages of ROS are implemented into the vehicle as described below:

- **Nodes and Communication:** ROS uses a concept of nodes, which are processes that perform computations and run programs. Data is exchanged in between nodes with topics that contain messages. The messages are sent and received by the nodes by a concept called publishers and subscribers.
  The great advantage of this concept is that it allows executing program scripts time and platform independently of each other. Hence, it allows run different scripts on Arduinos and the Laptop at the same time, while maintaining a constant communication within these programs.

- .**Coordinate Frame Transforms:** This project uses three coordinate systems to organize sensor data for the sensor fusion algorithm. The *base_link* is a frame that is locally fixed to the vehicle and moves with it. Sensors such as the Wheel Encoder and the IMU are integrated within this frame.
  The *odom* frame is a fixed global frame, and contains the vehicles relative position from its starting point based on wheel encoder data and orientation data gathered from the IMU. The data in this frame is continuous but subject to drift over time.
  The *map* frame is a fixed global frame and contains the absolute position information from the UWB beacons which are the haulers positioning system. The position can contain jumps but is not drifting over time.

- **Robot Localization Library for Sensor Fusion:** The position data from the continuous *odom* frame and discrete *map* frame are fusioned by the robot localization library which provides an implementation of an Extended Kalman Filter. Within the configuration file of the library, coordinates frames, their sensor sources and their specific sensor values can be configured for data fusion.
  As an output, two filtered positions are being published. Firstly, relative odometry position estimate in */odometry/filtered*. Secondly, an absolute position estimate within the map frame will be published under the topic */odometry/filtered_map.*

- **Rosserial, Arduino with ROS:** With the rosserial package the four Arduino Microcontroller used in the hauler are able publish sensor information to the ROS mainsystem on the laptop.

- **Actuator Communication with ROS:** Both, the steering motor and the driver motor are controlled by a VESC, which is an electronic speed control for motors. The ROS VESC package subscribes to throttle and steering commands from the navigation algorithm from the laptop which are then executed.

4.5 Fusing Sensor Data in ROS

This section will describe the implementation, structure and sensors used in the sensor fusion algorithm which aids the localization system in providing filtered pose estimate.
As discussed the literature review section of UWB localization system implementation in practice, it is useful to fuse multiple sources of position estimates together to stabilize and smooth the position obtained from the UWB beacons.
A common practice choice in robotics and for robot localization is the use of an Extended Kalman Filter (EKF) [32]. The EKF is an algorithm that keeps track of the previous state of a system and current sensor measurements, which are weighted with a covariance matrix, to give a likely estimate for the current state.
The implementation of such a filter is not the focus of this placement semester, therefore this project will utilize as implementation of an EKF for robot application from the ROS robot localization library. The robot localization library allows to fuse sensor data, as long as it is transmitted in a data format that is conform with ROS standards.
The sensor values which are going to be fused can be initialized in a parameter matrix within the configuration file:

$$P = \begin{bmatrix} X & Y & Z \\ \alpha & \beta & \theta \\ V_x & V_y & V_z \\ \dot{\alpha} & \dot{\beta} & \dot{\theta} \\ a_x & a_y & a_z \end{bmatrix}$$

In this project sensor readings for roll and pitch (α, β) as well as the absolute Z value will be ignored, as the position is only needed in two dimensions x and y.

- Process Error Matrix: Reflects the noise that is added to the error after each filter prediction, higher variance values in it causes the filter to trust the sensor data more than the kalman filters state prediction.
- Initial Estimate Matrix: The initial estimate matrix gives a starting confidence value to the first sensor readings. It is constantly updated with each state prediction, the right values lead to faster convergence.
- Sensor Covariance Matrix: Contains the uncertainties of the respective sensor. Highly influence how much the EKF weighs the sensor reading in comparison to other sensor readings of the same variable. In the case of this project, the UWB sensor matrix will be lower in covariance than the wheel encoder matrix, such that the UWB readings are weighed more into the Position estimate in X,Y as the data does not drift unlike the wheel encoder and IMU readings.
  As a starting value the UWB measurement error of 0.3m was chosen and squared to get the variance. However, it showed that tuning of the covariance matrix by testing and looking at the fused filter output provided better results.

The data will be published in ROS specified message formats and initialized with covariance matrices. These matrices contain information about the measurement and process error. The filter uses this to determine uncertainty of sensor data, to order to achieve a smoothly fused output out of multiple sources.

The ROS sensor fusion node is composed out of two different Extended Kalman Filters, one for estimating position out of data gathered from the wheel encoders and the IMU. The second EKF stage will take the absolute position obtained from the UWB beacons into account and will be fusing them with local position estimates from the inertial measurement unit and the wheel encoders.

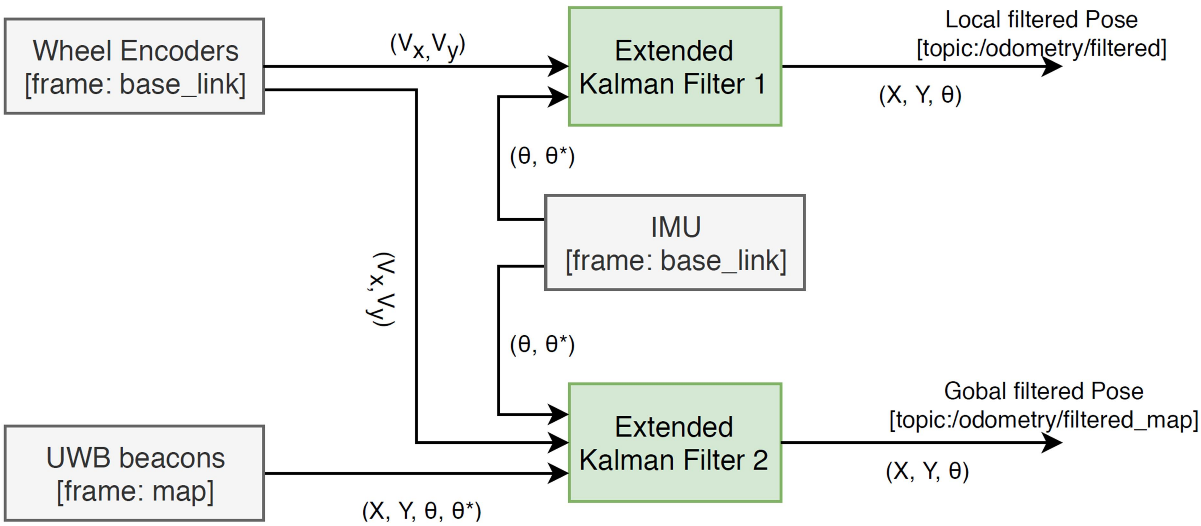

Figure 12: Sensor Fusion Architecture

The outputs of the filtering system are two separately filtered positions published in two different ROS topics:

- Local Filtered Pose: Yields the odometry position estimate, collected from the fused vehicle speed and vehicle orientation and angular velocity. The filter collects this data at the sampling time and integrates it over time, to yield an estimate about the vehicles position based on sensor information.
  The position drifts over time as the vehicle undergoes wheel slippage and orientation and wheel speed measurement error accumulates, as the time goes on due to the nature of constant summing in the integral.
  The local filtered robot pose will be published to */odometery/filtered*

- Global Filtered Pose: Yields the global position estimate, uses same sensor data as the EKF 1 but complements it with absolute position information from the UWB beacons. Fusing with different covariance and orientation sources is being optimized in the project. This position estimate is not subject to drift over time.
  The global position will be published to */odometry/filtered_map*.

The navigation algorithm will be using the global position since that reflects the pose of the vehicle in the real world which is not subject to accumulating errors from wheel encoders and IMU data, since its fusion is being complemented by the absolute position value of the UWB beacons.

4.6 Vehicle Platform and ROS Integration

The proof of concept small scale mining hauler built on the platform of a former mobility scooter. The seat, steering wheel as well as the body was removed to make space for installation of sensors and actuators.
It features a 450 Watt standard DC motor. The steering bar was replaced by motor powered steering, controlled by steering angle sensor which serves as feedback variable for the steering controller. To avoid steering above the physical possible angles, the motor has two limit switches as a safety measure when a certain steering angle is exceeded.
The back wheels feature two wheel encoders who measure the speed of both wheels. The IMU is situated in the center of the vehicle and measures angular velocity and relative orientation of the vehicle.
The vehicle is currently fully remote controllable at all times for safety reasons and also has an E-stop, accessible at the top of the vehicle.
Currently the autonomous electric hauler has three driving modes, a fully remote control mode, an autonomous mode with selectable on or off wire navigation.
The last mode is a test configuration where certain parameters in wheel speed and steering angle can be set to the respective controller and tested on the hauler.

To collect sensor data the hauler features four Microcontrollers:

- Top mounted Arduino: This microcontroller manages serial communication with the vehicle mounted UWB tag beacon. It was chosen to be a 32 Bit ARM core microcontroller, because it was initially planned to compute the positioning algorithm on the platform itself. However this task was moved to the Laptop running ROS, due to the better acess to numeric libraries in python.

- Back mounted Arduino: Converts the incoming analogue signals from the RC receiver to digital, also measures the wheel speed with the wheel encodes. No other tasks, to keep the sampling rate for the RC system as high as possible to respond fast to inputs from the remote controller.

- Front mounted Arduino: Preprocesses incoming measurements from the IMU to a ROS acceptable format, is also responsible for collecting data from the steering angle sensor. Also, controls a Neo pixel LED status bar for the hauler.

- Front mounted Sensorbar Arduino: Processes data from induction coils for the on wire navigation part of the electric hauler project of my teammate.

Safety and Fail Safe methods:
The main python script of the hauler does constantly monitor each Arduinos status. In case of a failure the throttle and steering commands are set to zero and the hauler stops.
Also the installed E-Stop cuts off all power immediately.

The ROS node structure can be visualized in following simplified form:

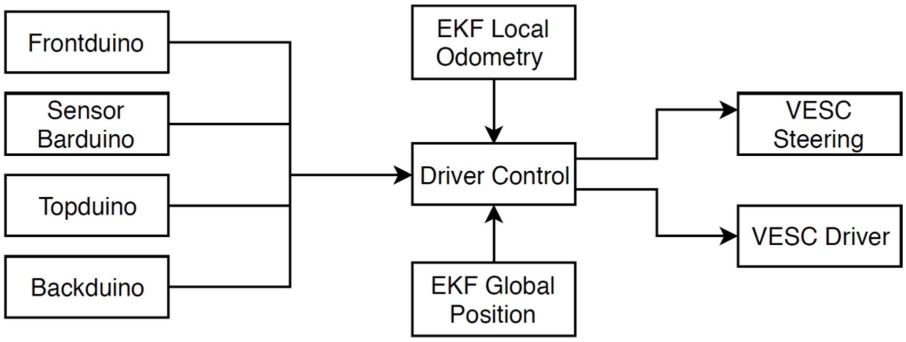

Figure 13: ROS Node Structure

On the left side the four microcontroller nodes can be seen which read in the sensors data and publish data to the main node *Driver Control* which runs the main python script within ROS.
Localization nodes *EKF local Odometry* and *EKF Global Position* publish filtered pose data to the main node.
Depending of the current operation mode of the hauler including RC, Autonomous ON or OFF Wire Navigation, the main node then publishes duty cycle commands to steering and driver *VESC* speed controllers for the motors.
The ROS launch file initializes all of the haulers ROS nodes and tests communication with them.
As seen in the simplified schematic below the hauler features several nodes:

Figure 14: Small Scale Mining Hauler Platform

The picture below shows the current setup of the Autonomous Electric Hauler Platform. The platform is based on a former mobility scooter and measures 0.70m in width and 1.4m in length.
Central for this thesis is the mobile UWB beacon with antenna mounted in front of the load tray on a pole.
The power steering motor that the navigational controller interfaces with by a VESC speed controller

can be seen on top of the front axle. The back axle contains the drive motor which is interfaced with the VESC speed controller and the navigation script running in ROS. The IMU is mounted in the center of the handlebar in front of the tray.
The Wheel encoders can be seen in the inner rim of the rear axle.

4.7 Testing Methodology

This projects aim is to provide beacon guided autonomous navigation to a mining hauler. As discussed in the scope section the project requires a positioning system that yields an accuracy of within 0.3 meters in a minimum range of 50m. The tests aim at evaluating all of the sensors and algorithms that were presented in this project methodology section.
Throughout the tests UWB beacon ranging and localization performance will be first evaluated, then behavior in difficult conditions analyzed in different environments. Subsequently, the performance of sensor fusion algorithms will be examined, given their trajectories. Lastly, the navigation controller will be tested in different positions.
To verify that the UWB beacon localization performance is accurate enough to satisfy the projects requirements, the following tests will be evaluated in the results section of this report:

- UWB Range Testing
- UWB Localization Testing in two beacon topology
- UWB Localization Testing in three Beacon Topology
- Orientation Sensor Testing
- Moving in a Straight Trajetory
- Moving in a Rectangular Trajectory
- Non-Line of Sight Operation with obstructed beacon
- Navigation to goal and back to Start
-

The testing will be concluded in a Mining3 office building as well as outdoor on a wide grass area. The picture below shows the outdoor testing area for the UWB localization beacons. There are 3 beacons placed in the corners of a 13x8 m rectangular area on the grass. Ground truth measurements are taken with a long tape measure and marked trajectories on the grass.

Figure 15: Outdoor Test Environment for UWB Beacons

5. Project Results and Evaluation

The project evaluates the question whether, beacon guided autonomous navigation is suitable for an electric hauler in the mining environment?
The first section presents the outcomes of the design of a proof of concept UWB guided positioning system, which is tested for range, accuracy, beacon topology and its behavior in obstructed signal path conditions.
The second section of this presents the performance of the implemented sensor fusion in terms of positioning error and orientation error. Then the whole system is tested when a beacon operates in non-line of sight conditions.
Lastly, the results of beacon guided autonomous navigation algorithm will be evaluated in multiple test runs and trajectories.

5.1 UWB Beacon Positioning Evaluation Test Results

This section presents results from taken from the raw, yet unfiltered UWB localization beacon data.

UWB Range Testing between two Beacons

The first test examines the performance of ranging or localization on just 1 dimension, the x plane. It is important to see how accurate the beacon performs and to spot if there is any drift or noticeable offset at a certain range.
The measurements were obtained by taking respectively 50 range samples per meter between a UWB Tag beacon and an UWB Anchor beacon. Ground truth ranges are taken by hand with a tape measure.

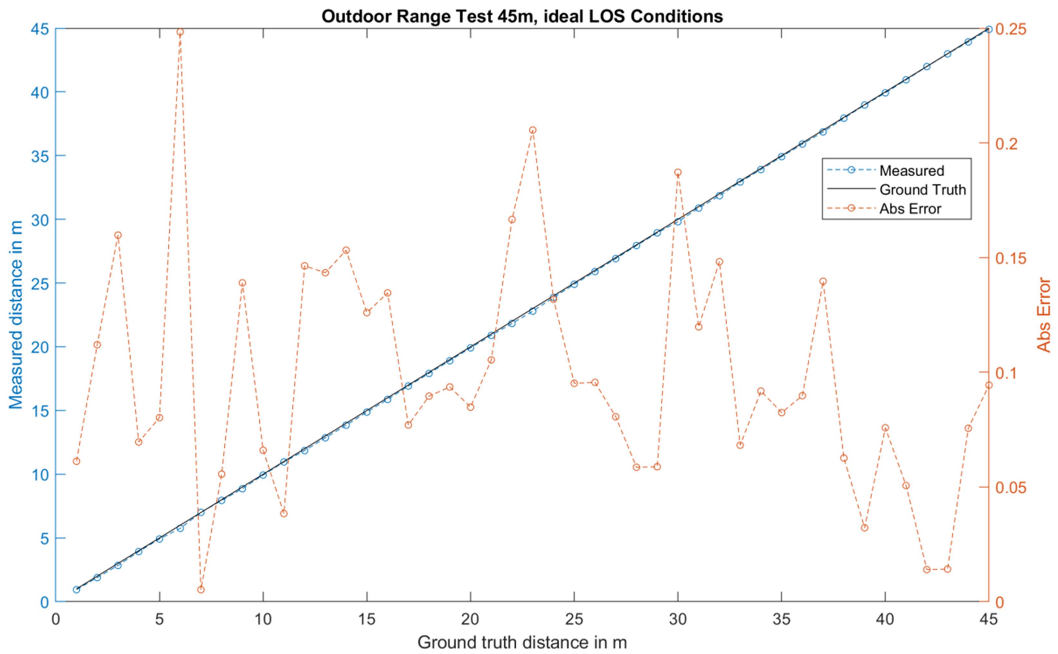

Figure 16: Beacon Range Test

The absolute error which can be seen as the orange line in the graph fluctuates at a constant level, with a mean absolute error of 0.098 meter throughout the whole range spectrum. This indicates that this method of localization does not have a drift in therefore is suitable for tracking a vehicle as global localization within the operational area bounds.

With the project requirement requesting a localization of the mining hauler within 30m this test exceeds the specification. With an ideal path and antenna direction range measurement stopped at 62 meters with a received signal strength of -104 dB. At the lowest level of signal strength the average accuracy shown in the graph above was still maintained, making it not dependent on the range.
The reason that measurement stops at 62 meters in this test is due to the fact that signals below a threshold are ignored by the UWB beacons [28].
To examine the error distribution, the range error meaning the difference between measured and actual distance was evaluated at 10 meters with a total of 700 samples.

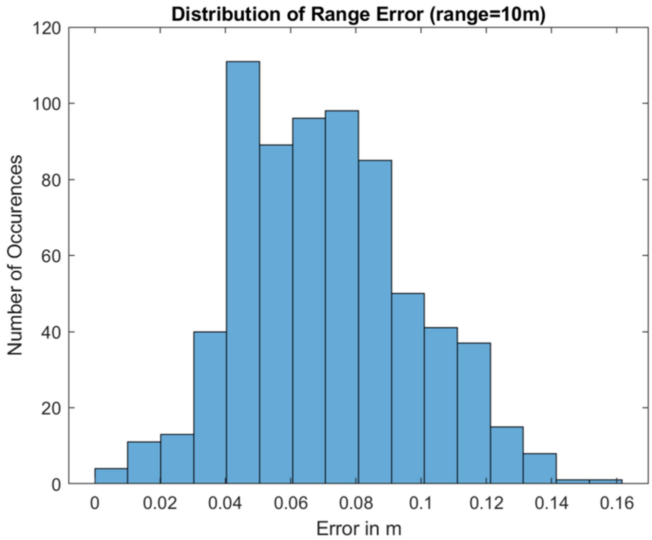

Figure 17: Beacon Error Distribution

The mean of the error amounts to 0.075 meters and the standard deviation is 0.026 meters. As it can be seen the sensor yields Gaussian distributed data. This statistical property, position measurements without drift over time and the fact that the positioning sensor has a relatively slow update rate of 10Hz makes it ideal to be complemented with a fast updating, prone to drift error IMU and wheel encoders.

UWB Localization Testing in two Beacon Topology

The following plot will evaluate the raw UWB localization Performance with the two Anchors positioning algorithm introduced in the methodology section. The mobile beacon was moved in a rectangular trajectory two times. Received signal strength was color coded in the plot.

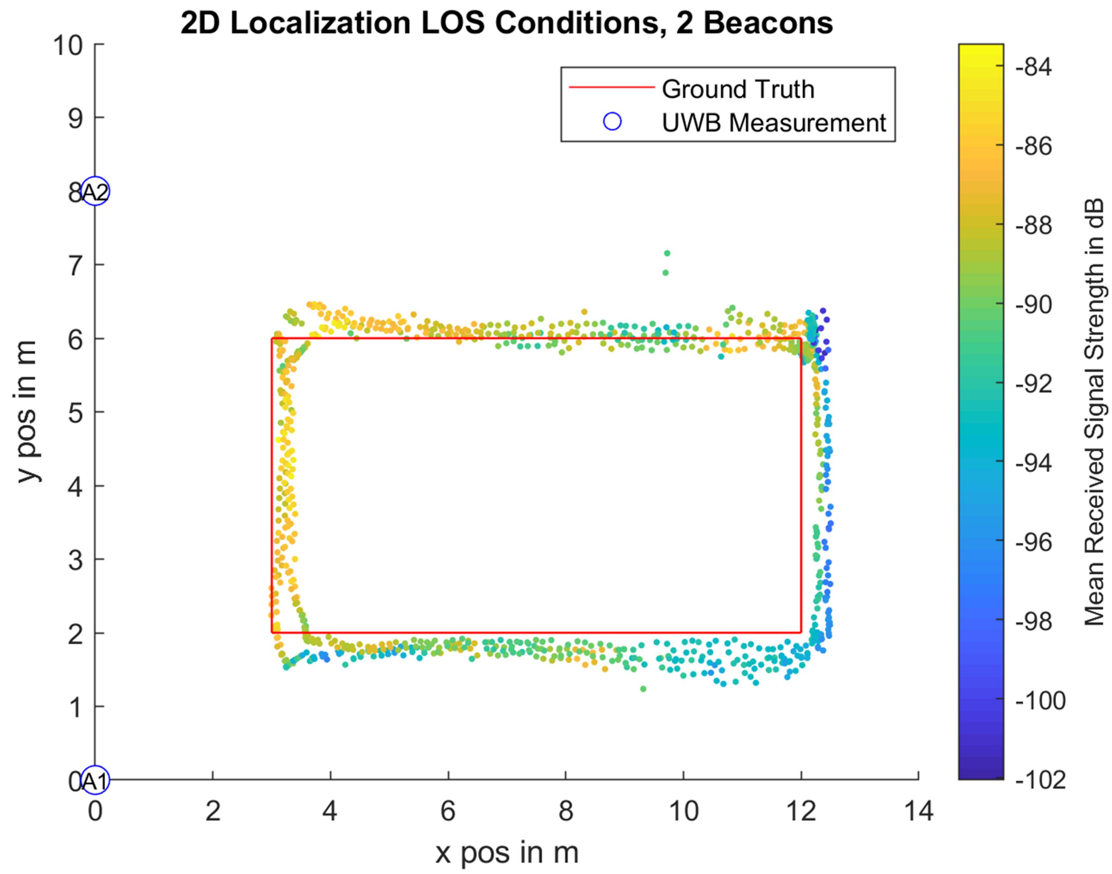

Figure 18: Positioning Accuracy for 2 Beacons

The mean error amounts to 0.24m, and the standard deviation is 0.16m.

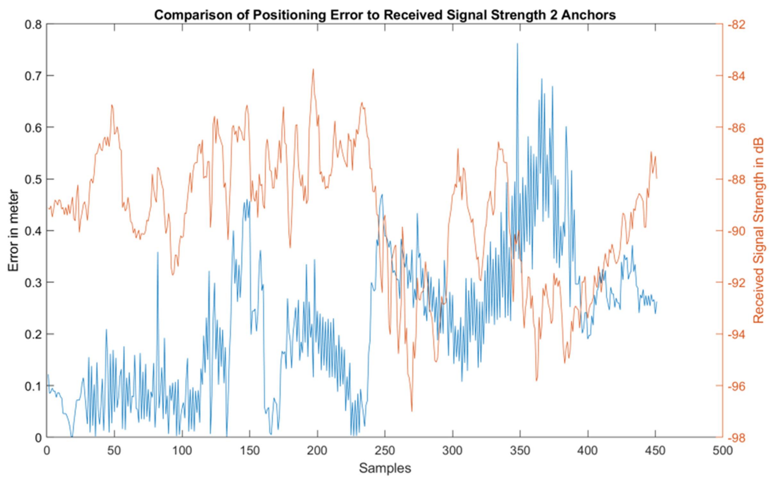

Figure 19: Position Error Statistic for 2 Beacons

UWB Localization Testing in three Beacon Topology

The following paragraph will present test results, measuring with 3 anchors beacon (A1-A3) and one to be localized tag beacon. The tag beacon gets three ranges from each anchor beacon, performs the trilateration algorithm mentioned in the projects methodology section and the outputs the estimated position in x and y coordinates in meters of a coordinate frame spanned by the anchors.
The individual samples of position estimates are color mapped respective to the mean received signal strength in dB of the 3 range signals that their position estimate is computed with. That allows to identify areas of poor signal coverage in the map.
The test was carried out moving the tag beacon at a speed of about 1 m/s, while received position estimates at a frequency 9.4 Hz. During the test the tag beacon was moved around the square shape trajectory 5 times in total.

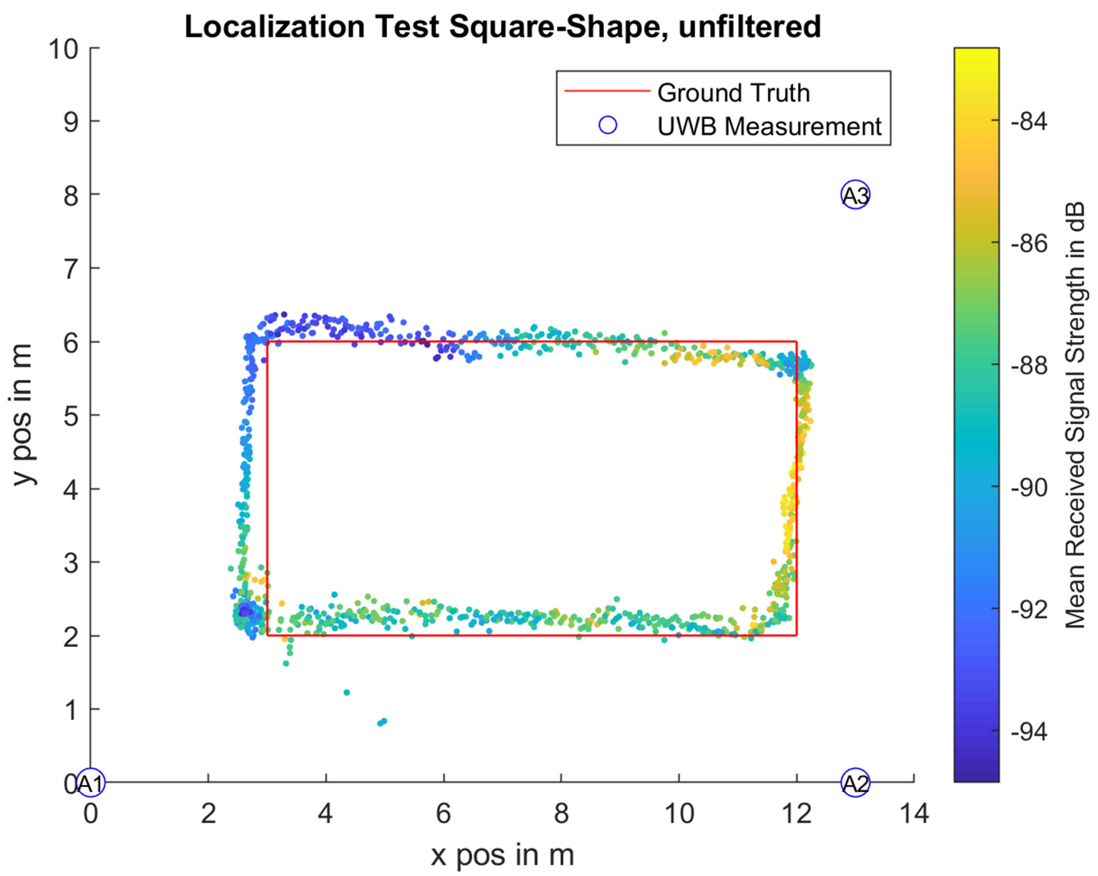

Figure 20: Localization test, moving on rectangular trajectory

The positioning test moving the mobile tag beacon in a square shape trajectory lasted 169 seconds with 1525 location estimates being computed, yielding a sampling frequency of 9Hz. It can be seen that the position estimates depict the ground truth in a reasonable way. The mean error in this measurement amounts to 0.21m and the standard deviation 0.14m.

The next test is about moving the tag beacon in an s shape trajectory, which can be seen in the graph below:

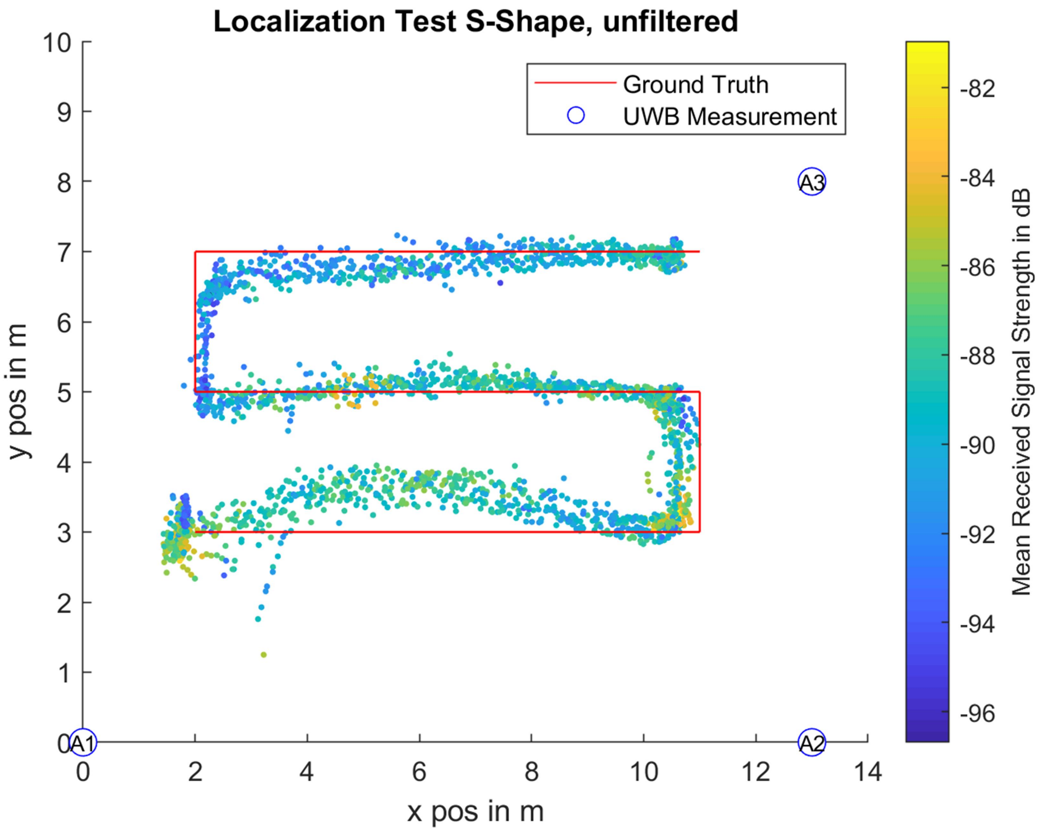

Figure 21: Localization test, moving on s shape trajectory

During the 270 second duration of the test, 2545 position estimates have been computed which equates to a sampling frequency in location estimates of 9.4 Hz. This graph contains positioning data from 5 cycles of moving on the trajectory. The localization has an absolute mean error of 0.21m and a standard deviation of 0.19m in tracking the movement in an s-shape trajectory.
As it can be observed the signal strength is the highest nearby the anchor beacons which are marked as A1-A3 in the graph. It can be observed that the signal strength is a bit weaker in the top left corner, which is the furthest position from a nearby beacon. Empirically, a slightly increasing positioning error can be observed with increasing distance from a nearby anchor beacon.

To examine this further, positioning data from the movement of one s-shape trajectory was extracted. The absolute positioning error in meters to the ground truth trajectory was computed and compared with the respective received signal strength. As it can be seen in figure 18 below, the error correlates only weakly with a computed correlation coefficient of 0.077 to the received signal strength. Decawave, the manufacturer of the UWB beacons states that as long as the direct path signal has the highest received signal strength, later arriving multipath signals do not do not affect the positioning accuracy [28].

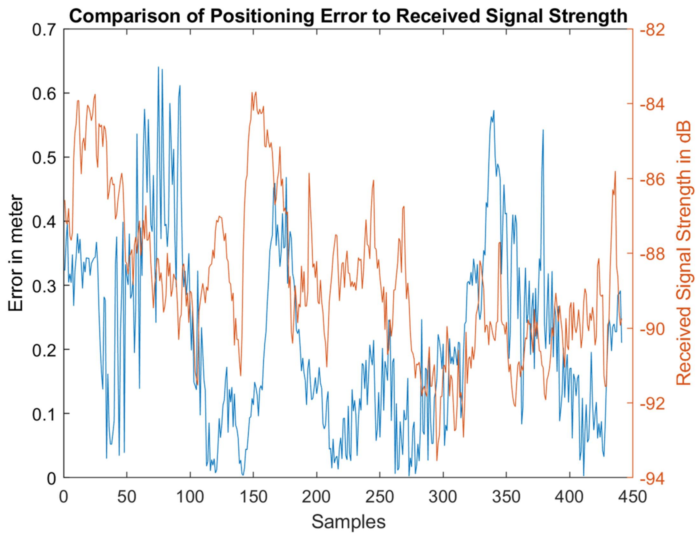

Figure 22: Positioning error of s-shape trajectory, one cycle

Summary of two Beacon Topologies

Stationary Beacons	2 Anchors	3 Anchors
Accuracy	0.24m	0.21m
Coverage	50m	50m
Complexity	Geometric Algebra	Minimization Algorithm

Effective Beacon Range and Performance under non-line of Sight Conditions

Research in the literature review advised that the UWB method compared to other indoor localization methods is very stable in regards to multipath distortion effects on the ranging signal. However, as indicated by Kietlinski, operating the beacons in non-line of sight conditions (NLOS) to each other causes UWB beacons to lose their accuracy. [27].
In context of this project, different obstacles were tested to cause a non-line of sight connection between two UWB beacons.
In a first test simple range measurements between two beacons were conducted, however this time with obstacles 1m in front of a beacon in the direct signal path.
The table on the next page, shows how different obstacles affect the maximum range of the UWB beacons.

Table 1: Examining UWB performance, with obstruction in the signal path

NLOS Obstacle	Absorbed Signal Strength	Maximum range / Position Error	Signal strength
Person (3m) to Beacon	15dB	40m / 0.1m	-102dB
Car	100%	N/A	N/A
20mm Wood	11dB	15.8m / 0.1m	-102 dB
3mm Steel	23dB	8.6 / 0.7m	-100dB

It can be seen that the earlier found maximum range of 62m in ideal conditions, decreased substantially depending on the type of obstacle. However the positioning error is still in the normal range of 0.1m, as shown in the previous range testing without obstacle. However with the steel plate as an obstacle in the direct path, the positioning error increased. That is likely an a multipath effect, where the direct path signal was attenuated that much by the steel plate that a reflected multipath signal had a higher signal threshold than the direct path signal, thus causing a range measurement error.

To also test the UWB beacon system in two dimensions upon no line of sight conditions, three beacons (A1-A3) were placed at the marked spots near walls in the office. Walls are each about 40mm drywall.. It can be seen that in the right area of the office the location can be still tracked well, however as the mobile tag beacon moves through the door toward the left area of the office, the beacon A2 loses connection, the position estimates becomes highly inaccurate since position estimates only relies on two beacons now.

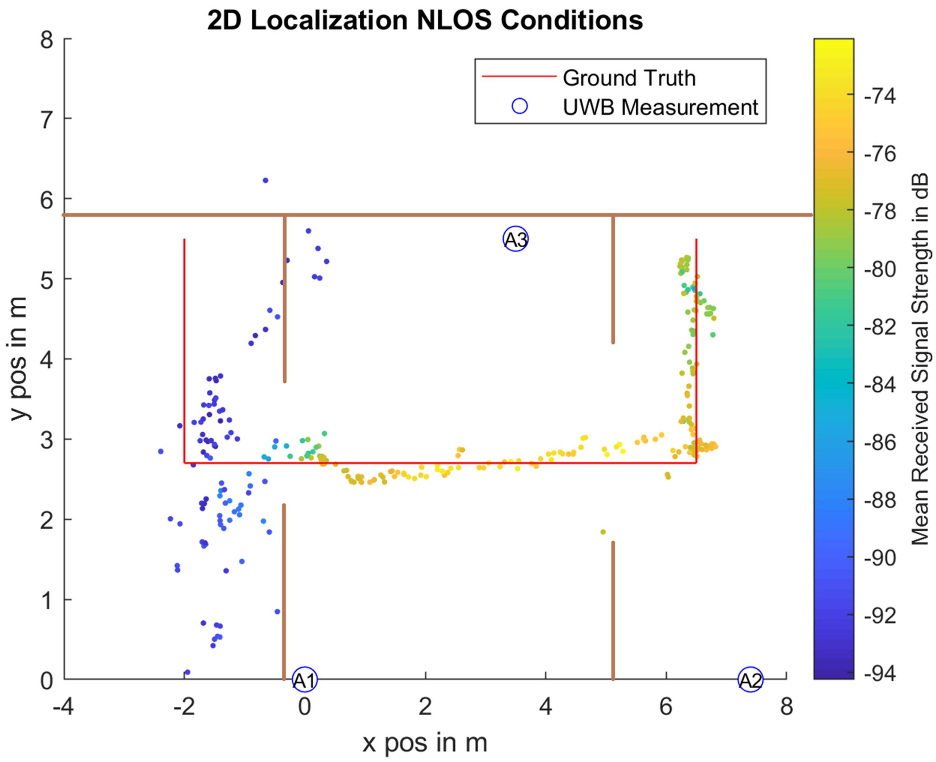

Figure 23: Beacon NLOS Conditions in Indoor Environment

Given this result of the behavior it becomes more evident that the localization of the mining hauler should not rely on a single sensor, thus making sensor fusion a need. An IMU and wheel encoder will be used to aid the localization. Also, this result confirmed the systems need of a line of sight connection.

Measuring Orientation

This section will outline results in finding the current orientaiton of the vehicle to supplement the position found by the uwb beacons for the navigation algorithmn. Two sensors, the IMU and UWB beacons are evluated for their performance and accuracy in providing the vehicles orientation.

	UWB Orientation	IMU Orientation
Sample Rate	10Hz	25Hz (supports >100 Hz)
Outliers	At slow speed, upon starting of movement	With insuffiecent calibration
Advantages	No extra calibration required, finds orietnation in respect towards beacons	High resolution, high sample rate
Problems	Needs motion to update, less accurate	Influenced by iron in near surroundings

As discussed in the methodology the UWB navigation determines the vehicles heading with two averaged subsequent position measurements.
The below graph shows a comparison between in orientation data, which was gathered by walking 4 meters in a straight line. It shows two results, one by estimated the UWB beacons and the second was obtained of the IMU.

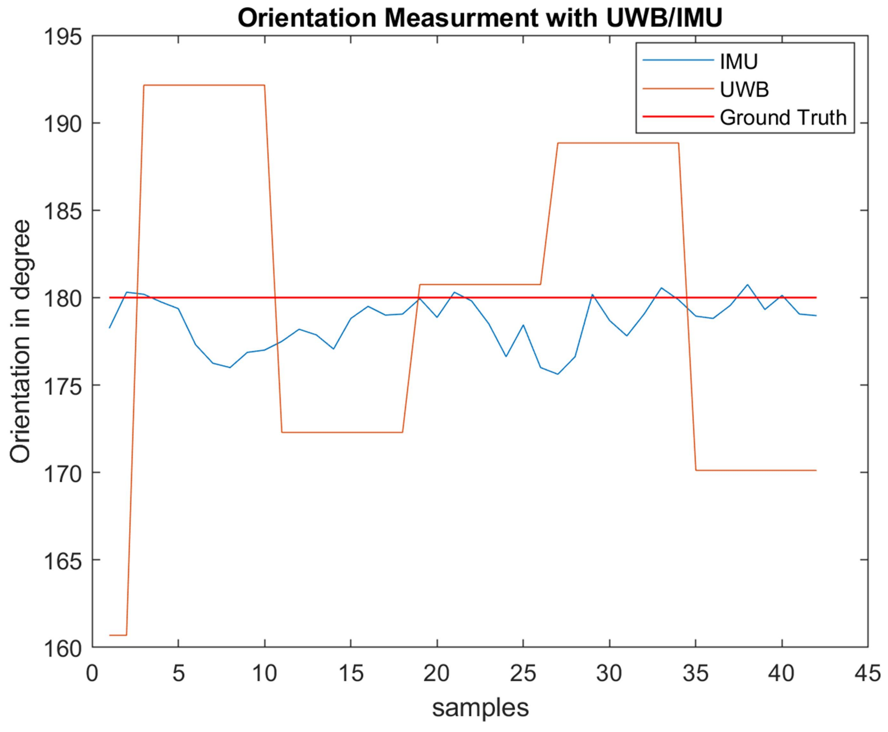

Figure 24: Orientation Sources Comparison

It can be seen that the IMU has a higher update rate than the UWB beacons can provide an estimate of the current vehicle heading. The slow update rate of the of the UWB beacons is a cause that the system need to gather at least two subsequent position data sets to estimate one heading value.
Also the accuracy to the actual vehicle orientation is much higher using the orientation data of the inertial measurement unit, it is also still in the range of <5° orientation error of the projects requirements. Therefore the autonomous navigation will obtain the mining haulers heading from the IMU.

5.2 Position Filtering Results

Determining Sensor Fusion Components

In the next test the vehicle was being moved in a straight line from position (2,1) to position (14,1) to compare raw sensor data with different combinations of data fusion. The absolute position error in y for each data configuration is shown on the y axis.

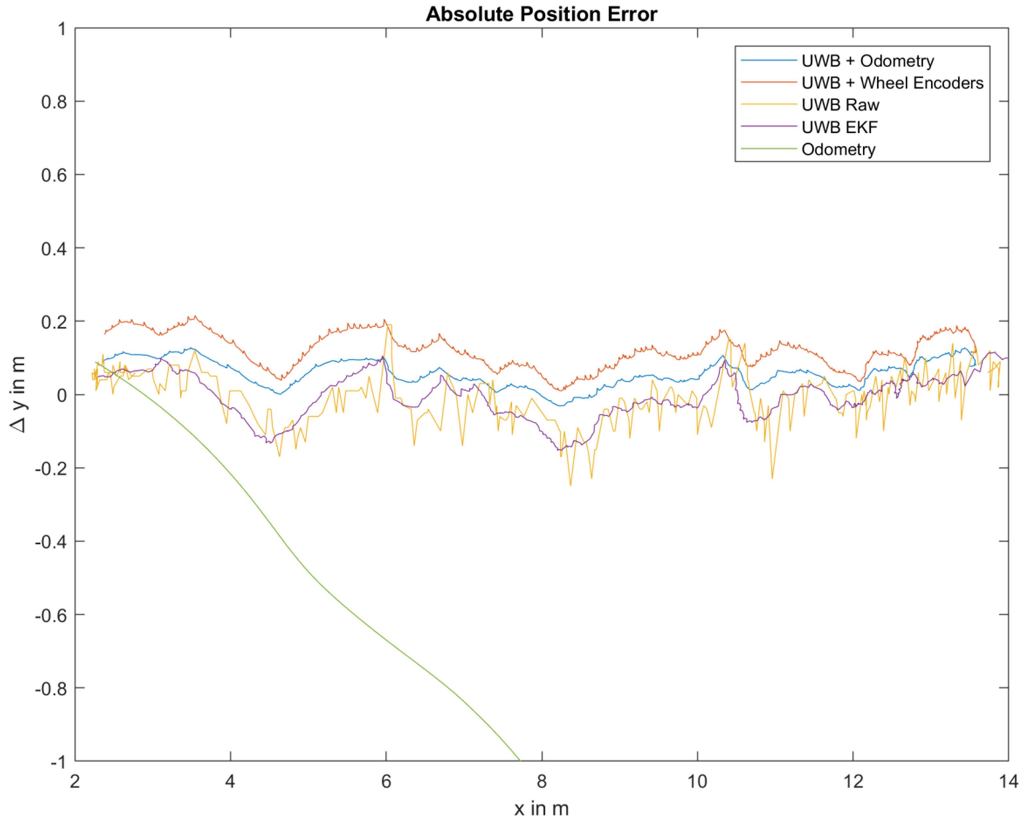

Figure 25: Sensor Fusion Comparison

At first glance it can be seen that the relative odometry position estimate is drifting, that is because the IMU outputs a slightly negative heading which is an error that therefore accumulates without getting absolute position data.
UWB data is fairly accurate without filter in this case, however is subject to spikes and has therefore a higher standard deviation. The combined filtering of UWB data plus Odometry data, smoothens out the position estimates while still maintaining absolute positioning without drift. Results of one test run can be seen in the table below:

Data Source	Y Position Mean Error (m)	Standard Deviation (m)
UWB + Odometry	0.06	0.04
UWB + Wheel Encoders	0.1	0.04
UWB Raw	0.01	0.06
UWB EKF	0.01	0.06
Odometry	N/A	N/A

The graph shows the orientation error upon moving into a straight line. It can be sourced from the UWB beacons or the Inertial Measurement Unit (IMU).
It shows the global EKF orientation estimate by different data respectively. The IMU on its own, the estimated IMU orientation on its own, the IMU differential change fused with the UWB orientation estimate and the UWB orientation estimate on its own.

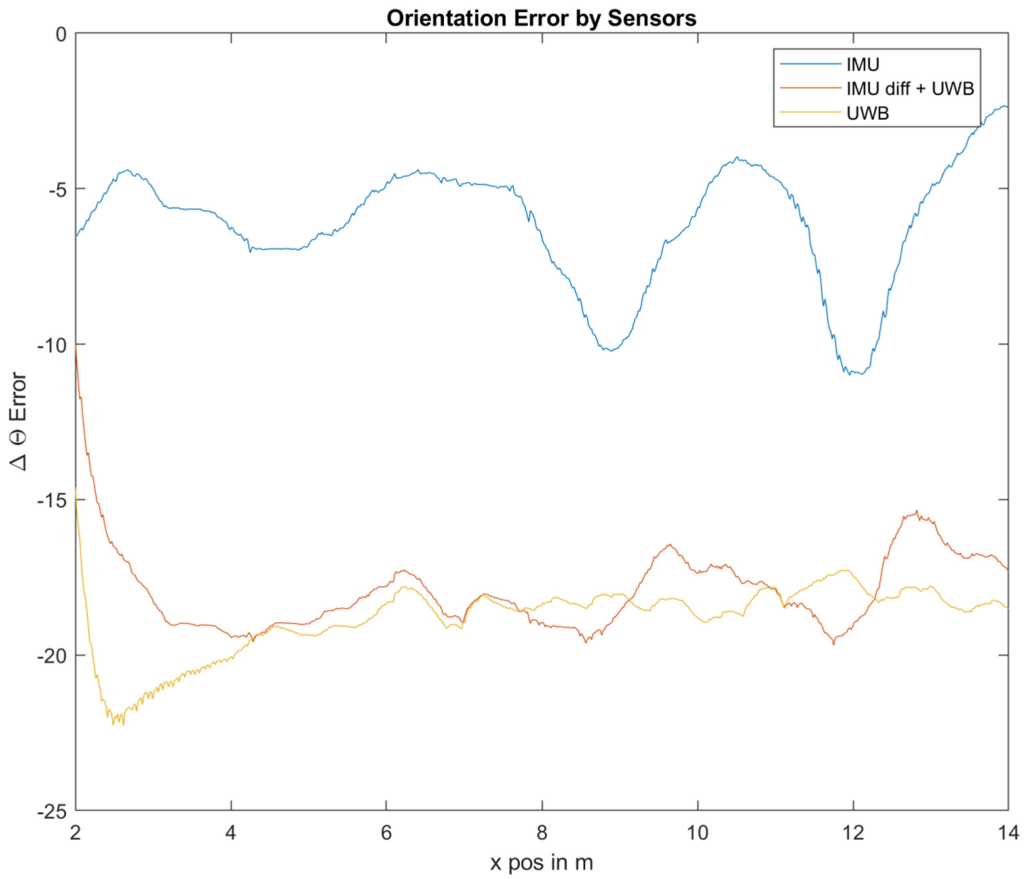

Figure 26: Orientation Error in different Sources

The differences in measurement can be seen, the UWB based orientation measurements has a large spike as the vehicle starts moving. Since the algorithm, relies on moving positions to compute the orientation. The IMU based measurement is closer to the real orientation with a lower mean error. The change small in heading may come from a not perfectly straight recorded driven line. The results of the plot can be seen in the table below:

Criteria	IMU	IMU diff +UWB	UWB
Mean Error in Degree	6.1	17.9	18.1
Std Deviation in Degree	1.9	1.3	1.09

Moving in a Rectangular Trajectory

In the next test the vehicle followed an 11 x 6m rectangle, the ground truth data of position and orientation is collected at 6 points throughout the rectangle and compared to the measured data by the sensors.

The graph features three sources of positioning in comparison:

- UWB as raw data from the positioning algorithm
- Odometry EKF, a position estimate predicted by the local EKF from the vehicle speed and IMU orientation and angular velocity data
- Global EKF, a position estimate predicted by the global EKF from wheel encoder, IMU orientation and angular velocity data and UWB Beacon positioning

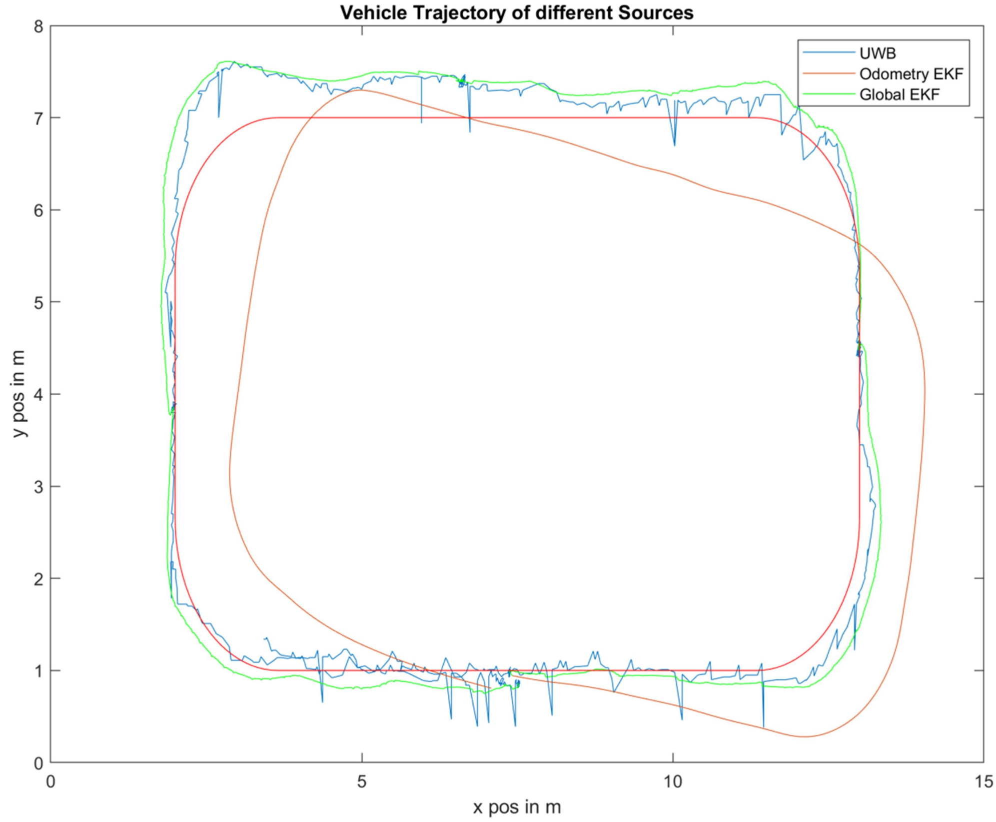

Figure 27: Vehicle Trajectory with filtered and raw data

An estimation of the ground truth trajectory is marked in red in the plot, however an actual ground truth reference can't be given as this would require an exact camera motion tracking or laser ranging to known landmarks. However the position of the hauler will be compared in six discrete points spread evenly around the rectangle, the results are presented in the table below.

Position(x,y)	(3,1)	(10,1)	(4,13)	(10,7)	(3,7)	(1,4)
X error	0.29	0.41	0.12	0.16	0.14	0.09
Y error	0.05	0.12	0.03	0.32	0.26	0.12
Orientation Error	7.1°	11.2°	9.1°	13.1°	10.4°	12.9°

As this plot shows the second lap of the vehicle moving around the rectangle, the drift of the local EKF can be seen. The estimated current orientation of the vehicle has an offset to the real orientation, as the orientation error accumulated throughout the test. However, the wheel encoder seems to be working quite accurately as the distances between the ground truth data and the odometry estimation line up.
The global EKF manages to smooth out the spikes of the UWB measurement in real time, yet however is limited to a degree to the accuracy of the UWB beacons. However, the measured trajectory has no drift and resembles the actual drive route better than the sole UWB data.

The orientation accuracy is evaluated piecewise in the next plot as there is no ground truth data available for the curved turns the vehicle makes, but only on the straight lines the vehicle drove.

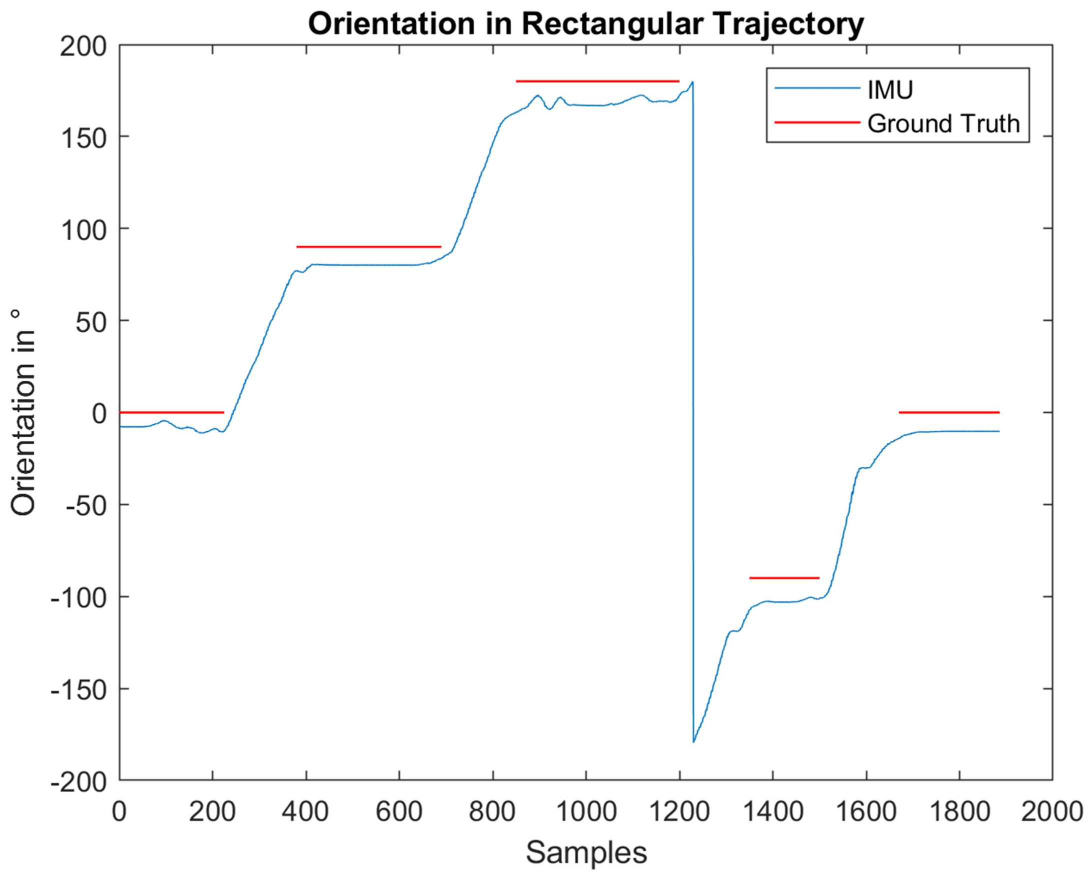

Figure 28: Orientation evaluation compared with ground truth

The IMU yields very stable orientation values, with a slight constant offset. The mean error computed on all ground truth segments is 9.32 degrees. It shows that the orientation sourced from the IMU data combined with the Extended Kalman Filter is a stable way to measure the vehicles heading.

Non line of sight operation with obstructed beacon

As discussed in the literature review section operating UWB beacons in non-line of sight conditions with each other still can cause problems. This test replicates an two meter obstacle in the direct path of the beacon signal. It is a 10mm thick whiteboard that was placed five different distances from the beacon at position (0,8).

Figure 29: Whiteboard as test obstruction in front of the beacon

The vehicle was moved along the rectangular trajectory as earlier, the output position estimate of the global Extended Kalman Filter can be seen for a respectively different spaced obstacle. For better visibility the first plot contains the path output for obstacles 1m and 2m away from the beacon and the second plot obstacles placed at 3m, 4m and 5m. The obstacles are marked in the plot as straight lines.

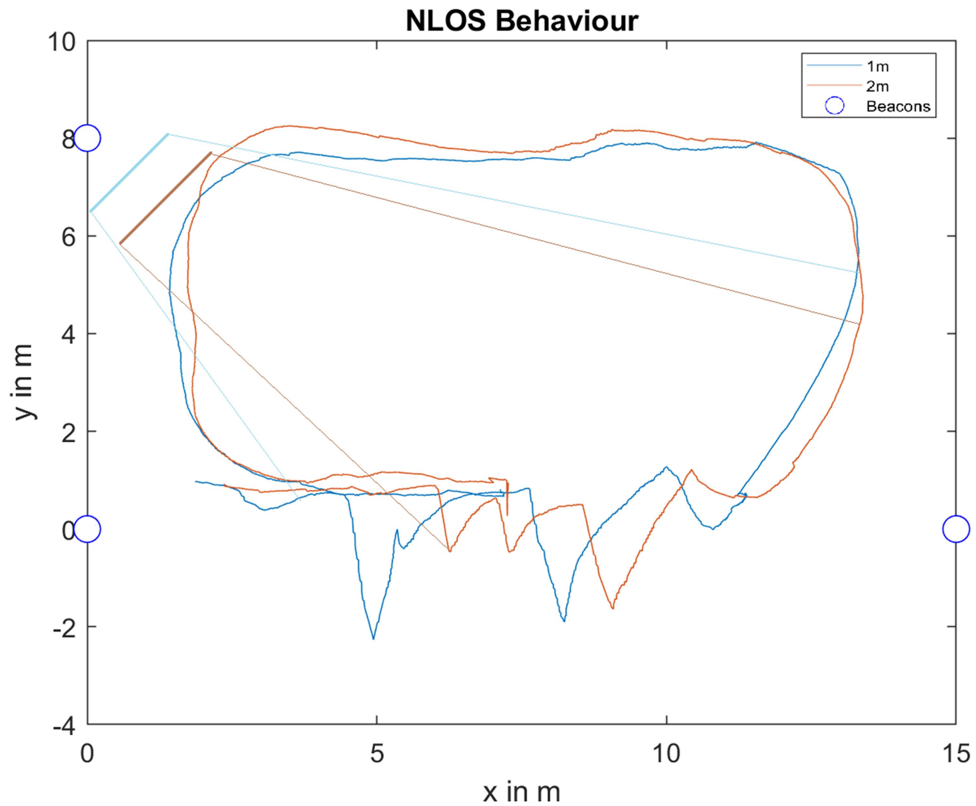

Figure 30: Filtered Position upon obstructed beacon

With the obstacle only 1m away from the beacon the position estimate becomes heavily affected by positioning errors as it can be seen by the large blue spikes in the bottom section of the rectangle. They the connection to the beacon was shortly lost at the two big spikes but quickly restored. Placing the obstacle at 2m away from the beacon, position errors are still present, as the covered angle of NLOS operation became smaller, the error affected path segment is shorter this time.

The second plot shows the vehicle position estimate with the obstacle placed at 3, 4 and 5 meters respectively.

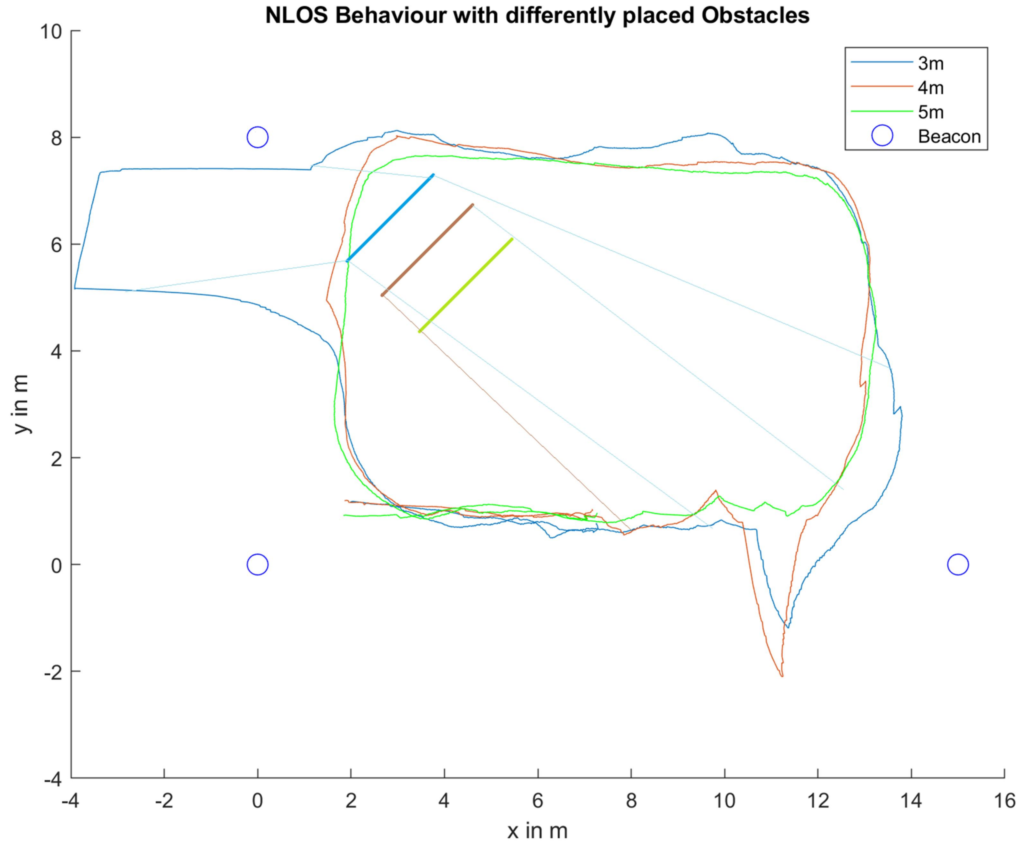

Figure 31: Filtered Position upon obstructed beacon

With the obstacle at 3m, Anchor 1 also experiences NLOS conditions now as the vehicle is passing by behind the obstacle at around position (2,7). This multipath error has a larger magnitude, which may come from the fact that Beacon 1 is about 17 meters away from the vehicle.
Again, there are small spikes visible with the obstacle of 4 and 5 meters away.

However, with the obstacle being 5 meters away from Beacon 3, the system has no NLOS induced positioning errors anymore.

Obstacle Placement	Occurrence of Position Errors	Affected Beacons
1 meter from Beacon	3	1
2 meters from Beacon	3	1
3 meters from Beacon	2	2
4 meters from Beacon	4	1
5 meters from Beacon	0	0

5.3 Navigation Results

In the last test section the results of the navigation controller will be evaluated. The vehicle was moving at a velocity of 0.3 m/s, the controller was adapted from the literature review section and implemented in python.
The different trajectories in the graph below represent the filtered global Position Data from the EKF. The vehicle was put to different start position along the y axis to give indication that the navigation algorithm works from multiple start positions. It then navigates to position (13.5, 4.5) where the simulated dump/loading site is located and moves to the position () in the center left.
The plot below shows the trajectory of 8 different test runs moving to the goal and back to the center.

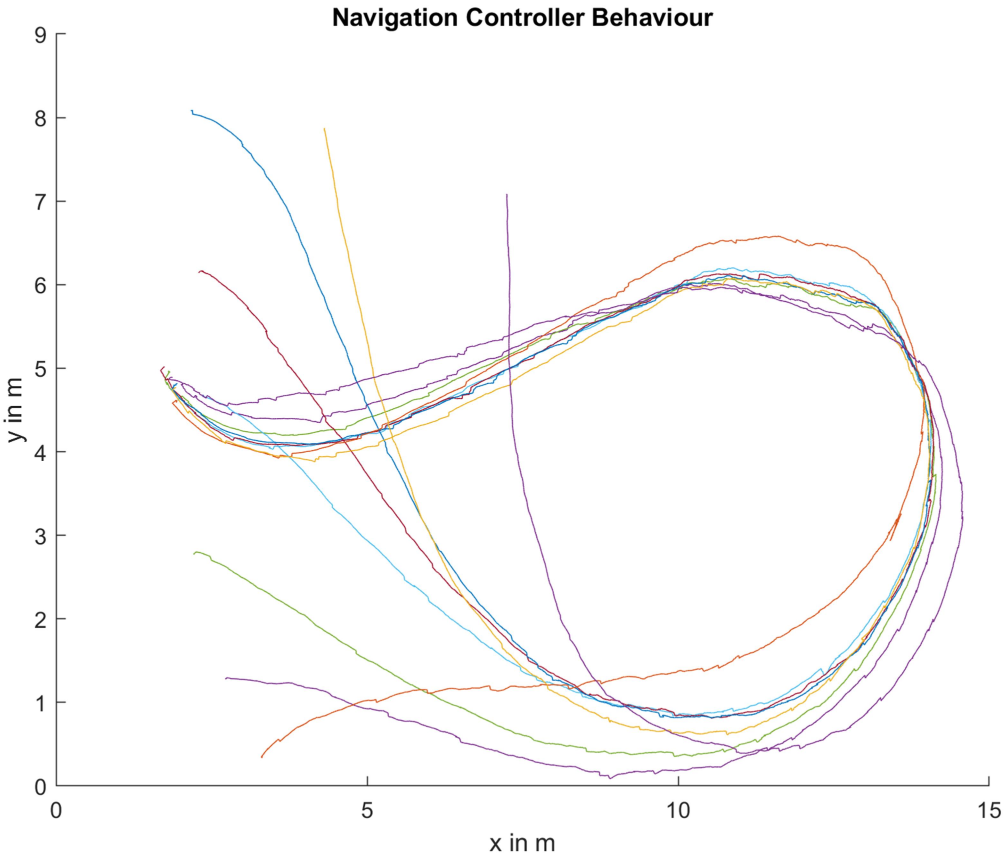

Figure 32: Self Driving Vehicle Trajectories

To evaluate the performance the table below compares positioning errors, it is compared with measured ground truth data on both locations:

	Load/Dump Zone	End Point (Guidance Wire)
Mean Position X Error	0.3 m	0.2 m
Mean Position Y Accuracy	0.2 m	0.4 m
Mean Orientation Accuracy	18°	35°

The results from the plot and table show that the navigation achieves greater accuracy at the Load/Dump zone location than the end point.
This was found to be an orientation issue, as the measured orientation value is within 10° to desired orientation. However, when measuring the actual orientation there is an error of about 25°, which is a calibration issue of the IMU.

6. Conclusion

A novel approach by guiding autonomous mining haulers based on UWB beacons was discussed in this thesis. The proof of concept model is able to navigate from a fixed point and moves to the goal at the desired orientation and is able to return to the starting point on its own.

The results from the positioning part of this project show a maximum range of 60 meters for the UWB beacons under direct path conditions. The mean positioning error under line of sight conditions was found to be beneath 0.3 meters which fulfills the project requirements. For both two and three stationary beacons positioning algorithms this could be achieved. Therefore, needing that few beacons this positioning provides a highly mobile means of localization, with short set up time and knowledge required to install the system. It is not reliant on sufficient illumination and not affected by dust making it suitable for underground mining as well.
The indoor localization tested showed that the UWB positioning algorithm works in a reflective environment, as the long as line of sight operation was ensured.

However, the testing results of the beacons operating under non line of sight conditions in the result sections shows a need for maintaining line of sight contact to the vehicle possibly at all times.
In the these conditions connection losses to obstructed beacons could be registered, which then in turn lead to large positioning errors of up to 2 meters. Since the positioning algorithm requires three beacons to perform the trilateration algorithm.
In a mine this could occur when another vehicle is parked or moving in the direct vicinity of the operation zone as well and is in the way of the signal path of one of those beacons. This could be solved by putting the stationary and mobile beacon antennas at the highest possible point or covering the area with more than 3 beacons to ensure that there is always a minimum of 3 beacons maintaining a connection to the vehicle.

The sensor fusion approach achieved a more stable and smooth positioning results. Fusing relative vehicle odometry information consisting out of wheel encoder data and IMU orientation with absolute positioning from the UWB beacons was successful.
It provided a stable position estimate with lower standard deviation compared to the raw UWB signal data. The aspect of complementing the UWB orientation estimate with the IMU estimate provided great accuracy with a mean orientation error of only 10.6° orientation error.

The navigation of the vehicle has simple functionality at this stage, the vehicle can move from a start point to the dump/loading point in a desired orientation and then move to the end point. It is guided by fused UWB and odometry pose data. In tests the navigation control algorithm successfully guides the vehicle from 8 differently tested start positions and orientations to the goal, with a mean position error below 0.5 meters. The algorithm has no set collision avoidance mechanisms or shortest path planning implemented, which could be on realized on the base of this project in the future. Robotic Operation System has the TEB local planner navigation stack which also supports Ackermann Steered vehicles like this projects vehicle.
Also a fully integrated system switchover between on wire navigation and off wire navigation can be tested in the future.

Upscaling Recommendations & Future Work

The work done in this thesis was the development of a proof of concept beacon guided navigation on a small scale mining hauler. For upscaling the system to a full size car vehicle following tasks are worth to consider:

- Detection of positioning errors by beacons operating in non-line of sight conditions: Currently the beacon status indicates a beacon that has lost connection. In such event the uncertainty of the UWB position prediction for the sensor fusion algorithm could be set to a high value by dynamically changing the covariance matrix in such event to make the position prediction solely based on relative odometry information for the duration of the event.

- For the localization purposes in underground mines the hauler could be complemented by a laser radar and automatic map creation around the operational area. This would complement the positioning algorithm by adding one more source of localization. Because of the modular structure of ROS this system could be integrated in the existing sensor fusion algorithm

- For collision avoidance of a up scaled system a laser radar would also increase safety and view angle and range compared to regular ultrasonic sensors.

- The current navigation algorithm can be improved by utilizing the ROS navigation stack for Ackermann steered vehicles, using the TEB local planner module. Then, the vehicle could avoid obstacles on the way while still maintaining the shortest path to the goal.

- If the loading/dumping zone operational area of the hauler needs to exceed 50 meters from the UWB beacons, cells of 3 beacons each could be implemented. Depending on the current hauler beacon cell the hauler is in a cell offset could be applied to obtain the global position in respect to all cells.

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7. Appendix

7.1 Appendix A - Risks Assessment

The following section will assess risks that may arise upon the project's lifecycle containing construction and development and testing. Risks that arise in a daily operational use in a mine will not be assessed since this project's aim is producing proof of concept prototype for research purposes. Risk ratings outlined here will be determined using Mining3's risks assessment matrix in figure 7.

Occupational Health and Safety Risks

This project will in involve mechanical and electrical labor during installation of sensors of the vehicle. Furthermore, the project contains field testing of the autonomous driving of a mobility scooter sized vehicle, requiring for careful risk assessment prior to the test runs.
The OH&S of this project risks as well as mitigation methods are listed in the table below.

Table 2: OH&S Risk Matrix

Occurrence of Risk	Hazard/Consequence	Mitigation Method	Risk Rating
Testing electronic equipment (<30 V DC)	Thermal burns, hazardous smoke creation	Ensure intact cable insulation, follow safety rules	21(L)
Heavy lifting of machine equipment during construction of Hauler	Muscle or Ligament injury	Limit lifting to a maximum of 20kg per Person	21(L)
Soldering electronics	Thermal burns, Solder in eye Inhalation of fumes,	Use safety glasses, Use fume extractor and lead free solder	18(M)
Battery explosion during charging or operation	Thermal burns, risk of fire, hazardous smoke	Charging in LiPo safe bags, Never let battery charge unattended	18(M)
Drilling holes and using other manual equipment	Hand or body injury, cuts	Prevent entanglement by removing jewellery on body, use of safety glasses and safety gloves	21(L)
Vehicle collision with person during testing	Bruises or severe body injuries	Operate vehicle only in taped or enclosed area. Visual warnings on vehicle, limit speeds	17(M)
Strong Electromagnetic field during inductive Charging operation	Can cause fatal pacemaker malfunctions	Show warning signs, limit amount of electric field admittance during with directional coils	20(M)
Vehicle not controllable during operation or out of range of remote control	Serious hazard due to kinetic energy for surrounding persons and environment	Install fail safe, stops car immediately when it loses connection Install external/remote emergency kill switch	17(M)

Updated Project Completion and Commercial Risks

During the engineering cycle of the AEH multiple sensor systems will be implemented, tested and integrated to the vehicles operating system environment. The vehicle relies on a working subsystem of sensors and algorithms to function. Risks in scheduling and time allocations that may arise during the engineering cycle are presented in the table below:

Table 3: Project Completion Risk Matrix

Occurrence of Risk	Hazard/Consequence	Mitigation Method	Risk Rating
Implementation of path planning takes longer than anticipated	Delays in completion of work, may change outcome of project	Make weekly updates to Gantt chart. Tracking progress constantly, discuss possible adjustment with supervisors Use guidance of colleagues early on if needed	18(M)
Individual mechanical or electrical component failure on vehicle	Delays in project progress, Failed function can't be showcased in project demonstration	Keep spare parts of wearing parts. Choose parts that are available from multiple distributors	22(L)
Path planning turns out to be unsuitable or inaccurate	Major delay in project progress, putting project completion at risk	Test suitable path planning algorithms early enough, to make adjustments and possible filtering to sensors	18(M)
System Integration between On-Wire and Off-Wire Navigation causes delays	Autonomous hauler can't change between on and off wire navigation subsequently in time	Allocated more time in Gantt Chart for debugging. Modular testing	18(M)
Project exceeds budget	Project can't continue	Check prices prior purchasing any parts, evaluate price-usability ratio and due diligence Leave buffer for unplanned expenses	23(L)
Lost data during development	Endanger project progress, major delays	Use of cloud based backups and version control systems such as git	21(L)
Autonomous Hauler collides with Mining3 assets during testing	Financial loss because of damaged assets	Install external/remote emergency kill switch Test vehicle in safe, closed off environments	21(L)

Project Opportunities

As shown in the literature review, this project bears a lot of opportunity to research, develop and optimize an indoor navigation system and corresponding path planning for autonomous navigation. During the lifecycle of the project following opportunities listed below can occur:

- The localization sensors provide enough accuracy to be used in further use cases within the mining industry apart from navigation of mining haulers
- The proof of concept version of the autonomous hauler gets interest of investors and a full scale version of it can be developed in the next engineering cycle
- The autonomous hauler vehicle concept achieves high productivity in field tests, providing a new approach to haulage systems
- Autonomous vehicle can be used in underground mines, thus enhancing the safety of miners in dangerous areas of the mine
- The technology used in project can be commercialized leading to a financial opportunities for Mining3

Risk Assessment Matrix

		Hazard Effect/ Consequence				
Loss Type		1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
(P) Harm to People		Slight injury or health effects – first aid/ minor medical treatment level	Minor injury or health effects – restricted work or minor lost workday case	Major injury or health effects – major lost workday case/ permanent disability	Permanent total disabilities, single fatality	Multiple fatalities
(E) Environmental Impact		Environmental nuisance	Material environmental harm	Serious environmental harm	Major environmental harm	Extreme environmental harm
(A) Asset Damage & Other Consequential Losses		Slight damage <$5000. No disruption to operation	Minor damage $5000 to $50,000. Brief disruption to operation	Local damage $50,000 to $500,000. Partial shutdown	Major damage $500,000 to $1M. Partial loss of operation	Extreme damage > $1M. Substantial or total loss of operation
(R) Impact on Reputation		Slight impact – public awareness may exist but no public concern	Limited impact – some local public concern	Considerable impact – regional public concern	National impact – national public concern	International impact – international public attention
Likelihood	Likelihood Examples (use only as a guide for evaluation of uncontrolled hazards)	Risk Rating				
A (Almost certain)	Likely that the unwanted event could occur several times per year at this location	15 (M)	10 (H)	6 (H)	2 (Ex)	1 (Ex)
B (Likely)	Likely that the unwanted event could occur several times per year in Mining3; or could happen annually	19 (M)	14 (M)	9 (H)	4 (Ex)	3 (Ex)
C (Possible)	The unwanted event could well have occurred in the mining industry at some time in the past 10 years	22 (L)	18 (M)	13 (H)	8 (H)	5 (Ex)
D (Unlikely)	The unwanted event has happened in the mining industry at some time; or could happen in 100 years	24 (L)	21 (L)	17 (M)	12 (H)	7 (H)
E (Rare)	The unwanted event has never been known to occur in the mining industry; or is highly unlikely that it could ever occur	25 (L)	23 (L)	20 (M)	16 (M)	11 (H)

Risk Matrix Rating	Risk Level	Mining3 Risk Management control guide
1 to 5	(Ex) – Extreme - Immediate correction required - Eliminate, avoid or implement specific plans/ Standards to manage & monitor	Recommend implementation - minimum of 2 hard control Barriers and 2 soft controls
6 to 13	(H) – High - Should receive attention as soon as possible - Proactively manage	Recommend implementation - minimum of 2 hard control Barriers and 2 soft controls
14 to 20	(M) – Medium - Should be dealt with as soon as possible but situation is not an emergency - pro actively manage	Recommend implementation - minimum of 1 hard control Barriers and 2 soft controls
21 to 25	(L) – Low - Risk is normally acceptable - Monitor & manage as appropriate	Monitor and Manage

Figure 33: Mining3's internal risk assessment matrix

7.2 Appendix B – Project Managment

The projects timeline was visualized in a Gantt chart, to enhance visibility of the tasks durations. The work on the mining hauler is a team project of 4 full time working students and one part-time working student. The other teammates tasks are the development of the wireless power transfer system, the haulers energy management, mechatronics and the haulers navigation on a guidance wire.

Update Personal Gantt Chart for first development phase and second development phase

With the submission of this interim report it can be seen that the first development phase of implementing a wireless beacon localization system is now completed. The second stage of implementing the autonomous path planning for the hauler builds on top of the developed positioning system of stage 1.

Task Name	Duration	Start	Finish	Predece	Re: Na
Off-Wire Navigation	**71 days**	**Thu 28/02/19**	**Thu 13/06/19**		
Literature Review	**10 days**	**Thu 28/02/19**	**Thu 14/03/19**		
Prelimary sensor analysis	5 days	Thu 28/02/19	Thu 7/03/19		Paul
Literature review	1 wk	Thu 7/03/19	Thu 14/03/19	54	Paul
Location Sensor Implementation	**21 days**	**Thu 14/03/19**	**Fri 12/04/19**		
Developing sensor architecture	5 days	Thu 14/03/19	Thu 21/03/19	55	Paul
Learn documentation of sensor	3 days	Thu 21/03/19	Tue 26/03/19	57	Paul
Integrate sensor/microcontroller driver	8 days	Tue 26/03/19	Fri 5/04/19	58	Paul
Debugging/testing of localisation sensor	5 days	Fri 5/04/19	Fri 12/04/19	59	Paul
Orientation Sensor Implementation	**10 days**	**Fri 12/04/19**	**Wed 1/05/19**	**56**	
Implement orientation sensor interface	5 days	Fri 12/04/19	Tue 23/04/19		Paul
Implement IMU	2 days	Tue 23/04/19	Fri 26/04/19	62	Paul
Debugging/testing of orientation sensoring	2 days	Fri 26/04/19	Tue 30/04/19	63	Paul
Implement Kalman Filter	1 day	Tue 30/04/19	Wed 1/05/19	64	Paul
Autonomous Navigation and Path Planning	**30 days**	**Wed 1/05/19**	**Thu 13/06/19**		
Design of path planning algorithm	3 wks	Wed 1/05/19	Thu 23/05/19	61	Paul
Integrate navigation with ROS/python	3 days	Thu 23/05/19	Tue 28/05/19	67	Paul
Test and Debug	2 wks	Tue 28/05/19	Tue 11/06/19	68	Paul
Integrate with On-wire	2 days	Tue 11/06/19	Thu 13/06/19	69	Paul

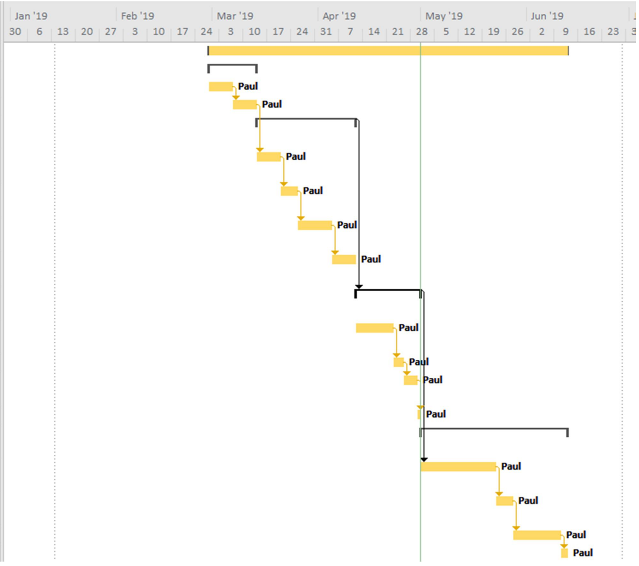


Figure 34: Gantt Chart containing the first development phase and second development phase

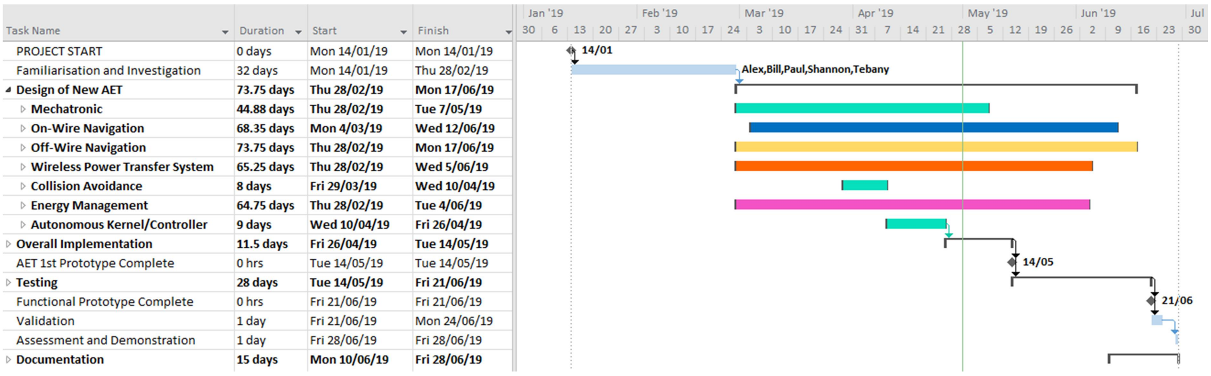
There was a delay in realizing the first development stage. The main reasons for that are:

- The software driver of the UWB beacons had to be modified in order to allow accurate range measurements for more than one beacon
- The approach of obtaining the orientation with two trackable beacons turned out to be not accurate enough, therefore the plan changed by implementing an IMU for orientation which order process and implementation caused delays
- The time to learning how to use ROS (Robotic Operation System) was not factored in the initial Gantt chart

However, as this first stage was crucial for the success of the next development stage, it is good for further project progress that more time was spent in completing out the first stage properly.

Updated General Team Gantt chart

To give a perspective on the whole autonomous project, the Gantt chart below contains the schedule of the team.



Task Name	Duration	Start	Finish
PROJECT START	0 days	Mon 14/01/19	Mon 14/01/19
Familiarisation and Investigation	32 days	Mon 14/01/19	Thu 28/02/19
Design of New AET	73.75 days	Thu 28/02/19	Mon 17/06/19
Mechatronic	44.88 days	Thu 28/02/19	Tue 7/05/19
On-Wire Navigation	68.35 days	Mon 4/03/19	Wed 12/06/19
Off-Wire Navigation	73.75 days	Thu 28/02/19	Mon 17/06/19
Wireless Power Transfer System	65.25 days	Thu 28/02/19	Wed 5/06/19
Collision Avoidance	8 days	Fri 29/03/19	Wed 10/04/19
Energy Management	64.75 days	Thu 28/02/19	Tue 4/06/19
Autonomous Kernel/Controller	9 days	Wed 10/04/19	Fri 26/04/19
Overall Implementation	11.5 days	Fri 26/04/19	Tue 14/05/19
AET 1st Prototype Complete	0 hrs	Tue 14/05/19	Tue 14/05/19
Testing	28 days	Tue 14/05/19	Fri 21/06/19
Functional Prototype Complete	0 hrs	Fri 21/06/19	Fri 21/06/19
Validation	1 day	Fri 21/06/19	Mon 24/06/19
Assessment and Demonstration	1 day	Fri 28/06/19	Fri 28/06/19
Documentation	15 days	Mon 10/06/19	Fri 28/06/19

Figure 35: Overall Gantt chart, containing team progress

Within the development cycle of the project, several resources were utilized to reach the projects goals. These can be categorized into general, hardware and software resources.

General:

- The literature review contains the key insights of academic papers which form the basis of development in this project
- Electronics Laboratory to perform soldering and basic work on electronics
- Closed off test environment to run autonomous operation tests
- Access to basic hand tools to mount sensors onto vehicle
- Frequent communication with project director Dr. Erik Isokangas
- Frequent communication with team members working on different technologies of the electric hauler

Hardware:

- Mobility scooter electric vehicle to perform testing and evaluation of the autonomous navigation
- Microcontroller to interface sensors (Arduino)
- Sensors to perform localization (wireless beacons, IMU, digital compass)
- Electronic testing equipment (multimeter, laboratory power supply)

Software:

- MATLAB to perform simulations of control algorithms for autonomous navigation
- ROS robotic operation system for integrating sensors into the vehicles software framework
- Arduino development environment for rapid prototyping
- C++ development environment for sensor driver
- Gazebo to perform simulations on the autonomous driving operation

7.3 Appendix C – Professional Development

At the end of this placement it is time to reflect about the competencies of a professional engineer that I have developed and learned. This section will reflect on the developed key skills and their respective learning events from this placement so far.
The following section will present respectively three developed key competencies for both engineering application aspects and professional/personal attributes. References to reflective journals in the appendix are mentioned in brackets with corresponding number and month.

Professional and Personal Attributes

E.A. 3.5 Orderly Organization of Self:

This project has been quite insightful in showing the difference in working each day for a company compared to learning in an university environment. This was reflected in the learning event when investors and researchers, which form the technical committee, visited Mining3. (#1 March Reflection)
It underlined the accountability of an employee, having to produce value toward a third party. As a university student this is normally not as omnipresent.
Also, I learned to manage my time better at work. The experience of writing a project proposal while working towards the project, was a valuable learning experience. (#5 March Reflection)

E.A. 3.4 Professional Use and Management of Information

Throughout the project lifetime and especially close to deadlines I learned the importance of obtaining the needed information in academic papers and reports efficiently. I noticed while researching throughout the later stages of the project that my efficiency in reading academic papers increased. (#1 and #5 March Reflection)

E.A. 3.2 Effective Oral and Written Communication

Looking back at the learning event about meeting new colleagues and attending learning lunches in February, this turned out to be a valuable learning event. In a project like this it was always helpful to get inspiration from colleagues of how things can be done and seeing a different approach to it. It was also good to have someone to check my printed circuit board design before having it manufactured. (#3 February Reflection)
Furthermore learning events like the project supervisor meeting, showed that it is vital to be able to present and communicate. That’s situation of having a professional meeting does not usually come up at university and it definitely developed my ability to communicate in a workplace environment and knowing what to expect in a meeting. (#4 March Reflection)

Engineering Application Competencies

E.A. 2.1 Application of established Engineering Methods for Problem Solving

Building and evaluating an autonomous navigation on a yet rarely used UWB beacon system involves engineering problem solving. I noticed that on the beginning of the project when I read papers about indoor positioning systems, their complexity and several ways of filtering the data obtained from them. (#3 March Reflection)
Also, upon testing of my first implementation of the UWB beacon positioning algorithm I noticed some rare unexpected outliers, which can be filtered out by sensor fusion with other sensors on the vehicle. (#5 April Reflection)
Writing the progress and result section of this report has also improved my ability in analyzing measured positioning data, looking at statistical parameters and researching possible meanings of sources of errors in this data from academic papers.

E.A. 1.6 Understanding the Engineering Practice

This competency was especially developed by learning about how risk assessment is handled in a professional environment. The frequent safety share meetings and the high risk environment in mining got underlined the importance of a safe engineering practice for me. (# 2 April Reflection)
The creation of a risk assessment for this project as well as discussing the risks in a meeting with the project supervisor developed my understanding for a safe engineering practice. (#2 February Reflection)
I learned that maintaining safety is an essential aspect of being a good engineer.

E.A 2.2 Fluent Application of Engineering Techniques

Since this project is really about application of practical knowledge and building a small scale autonomous vehicle, I have learned and developed multiple engineering techniques.
I developed my skills in printed circuit board design work in EAGLE program (#3 April Reflection), and gained knowledge in selecting and ordering electrical components (#4 February Reflection).
Also during the work with the localization and other sensors I have improved my abilities in programming in MATLAB and python. I have also learned to integrate sensors and microcontrollers into ROS (Robotic Operation System), such that they transfer data with each other (#5 April Reflection). Throughout this design and development process it was very valuable sometimes to hear advice and opinions on things from my teammates and colleagues, which definitely helped for more efficient application of the engineering tools. (#3 February Reflection).

February Reflective Journal

Learning Event	EA Stage 1 Competencies Developing	Description of Learning Event
1. Working Abroad	**EA 3.5** Orderly management of self	My placement at Mining3 is my first time working full time in a country other than my home country. It seemed unfamiliar before starting here, but I found the work ethic, customs and culture at work to be comparable to Germany. This experience increased my confidence of working abroad, helping in my professional development. However, since my worksite is located in a more isolated part of Brisbane, I learned how to take travelling times, food planning, as well as site specific hazards like snakes into account for my workday.
2. Attending an Induction and Performing a Risk Assessment	**EA 1.6** Understanding the principles and norms of contemporary engineering practice **EA 3.1** Ethical conduct and professional accountability **EA 3.5** Orderly management of self	In my first week at Mining3 I attended several safety inductions, which made me aware of the hazards that can occur on site. Also, I received an induction for the electronics laboratory. I learned about the company's risks assessment procedure, by filling out take-5 checklist upon carrying out a potentially hazardous task or labour. I learned this risks management approach is different compared to a home project, as a strict risk assessment before for example soldering, welding and drilling is required. By reflecting on risks, necessary precautions can be taken to mitigate risks, which is an important part of a safe engineering practice.
3. Meeting Colleagues and Attending a Learning Lunch	**EA 1.4** Knowledge development within the engineering discipline **EA 3.2** Effective oral and written communication **EA 3.3** Creative, innovative and pro-active demeanour	I found it really valuable getting to know some of my colleagues and the fields that they are working in. It is helpful to extend my own perspective, because they have different ideas and approaches to solve a problem, coming from different areas such as Physics, Mechatronics and Electrical Engineering. Especially insightful was a lunch and learn event, in which an experienced engineer presented two products that he has developed. He presented about how detonations in a mine are initiated and possible safety risks and hazards that come along with it. After this I saw how my project of developing an autonomous mining hauler can be very useful in improving safety at a mine site.
4. Ordering Electrical Components	**EA 1.4** **EA 2.2** Fluent application of engineering techniques, tools and resources.	Within my project, we as a team of students need to purchase electrical components. I learned how to perform research by reading the parts datasheets, reading papers, checking project requirements and making decisions based on the due diligence done.

	EA 3.6 Effective team membership	Careful analysing and selecting parts is crucial to successful design. As a team, we coordinated orders and executed them using the company's purchase order process. Another thing I learned was taking shipping times into considerations for my time management and workflow.
5. Analysing and Evaluating a Complex Project	**EA 1.4, EA 2.1** Application of engineering methods **EA 2.3** Application of systematic engineering synthesis	See details below

SEAL Analysis of Learning Event 5 – Analysing and Evaluating a Complex Project
Situation:
In the first week I researched the scope of my project and the specifications it needs to fulfil.
I felt a little bit lost at first, since developing the autonomous navigation of a mining hauler contains many areas to understand, such as computer vision and sensors, path planning, control systems and an industry level software framework for controlling robots.
I have never applied this in a professional project before and my goal is to design the autonomous off wire navigation for a mining hauler.

Effect:
Being met with the previous work done on the mining hauler and the need to understand the workings of it was quite daunting at first, since I didn't know where to start. The amount of topics to know about sounded enormous which made me feel under pressure. I knew i had to understand previous work at first to capture the current performance and challenges in order to design a more capable, system that fulfils the specifications better.

Action:
To get started developing a new control system for the robot's navigation, I had to understand existing technology from the past project. This involved reading the documentation and reports about the project and talking about it with my teammates.
I used a bottom up approach, when analysing the project. Therefore, I started with the sign detection, moved on to the camera and sensors, followed by the algorithms evaluating it and finally learned about the robotic operation system and higher level code controlling the vehicle. I tested the vision system and the controls and kept track of the robots performance and weaknesses.

Learning:
I learned how to approach a pre-existing complex project effectively by breaking it into parts and understanding them first, before trying to understand everything at once. Moreover, I learned how to analyse and evaluate a project systematically. Both are substantial skills in engineering in order to develop a product that exceeds the previous version. Learning from this experience I increased my effectiveness for the next time I start working on a large project. This will definitely help in the future when I am working on my Master's Thesis and especially for my future work in an Engineering firm.

March Reflective Journal

Learning Event	EA Stage 1 Competencies Developing	Description of Learning Event
1. Technical committee on site	**EA 1.6** Understanding of the scope and accountabilities of sustainable engineering practice **EA 3.5** Orderly management of self, professional conduct	In the first work week of march selected Mining3's corporate and institutional partners and investors were on site to attend meetings. They also discussed Mining3's different projects and their progress. It was a reminder and learning event about the accountability we as team of BE/ME students working at Mining3 have, to finish our project in a successful and timely manner to be of value for the company. Also, it underlined the importance of presenting oneself in a professional way in communication, clothing or workplace tidiness in a professional environment.
2. Single component failure in mining hauler	**EA 1.5** Knowledge of the engineering practice **EA 2.2** Fluent application of engineering techniques **EA 2.4** Application of systematic approaches for management of engineering projects.	During preliminary testing of the powertrain system of the prototype electric vehicle used in this project, a component broke. It was the differential, which had worn gears caused it to get stuck sometimes. This resulted in the electric vehicle not being able to move. I learned about a risk of single component failure that reinforced my understanding for the need for a comprehensive risk analysis to mitigate the effects of unforeseen events for the project. Also, from the engineering side it important to analyse how such errors occur and can be prevented in future.
3. Obtaining relevant information of an academic paper	**EA 2.1** Application of established engineering methods **EA 3.2** Effective oral and written communication **EA 3.4** Professional use and management of information	During the literature review and research phase for the project proposal I was reading multiple academic papers on indoor localization methods and navigation. However, it was quite challenging and consumed a lot of time. Since there was a lot of information to read and group multiple relevant articles together for the research in the literature review. I learned how to interpret abstracts and conclusions better in order to work more efficiently for the project proposal. Also, it improved my ability to categorise relevant literature and link it with other research done.
4. Attending a project supervisor meeting	**EA 1.6** **EA 3.2** **EA 3.5** **EA 3.6** Effective team membership and team leadership	On the 20th of February a meeting was held on site with academic supervisors, EAIT staff, program directors and the CEO of Mining3. It was quite a learning experience speaking about the project in front of so many people and answer questions about the project. However, it helped to gain other perspectives on the own project. Also, I learned how to present and communicate about the project in a

		professional environment, which is quite different and harder than in university presentations.
5. Writing a Project Proposal	**EA 2.1** **EA 3.2** **EA 3.4** **EA 3.5**	See details below

SEAL Analysis of Learning Event 5 – Writing a project proposal and working on a project

Situation:
Being met with the project proposal deadline nearing while working on projects sensor implementation to make progress at work, I ran in to time management issues.
While rewriting and refining my literature review to for the project proposal, i noticed especially this part takes much longer than anticipated. Also, formatting and referencing seemed to take a long time.

Effect:
The effect of this was that the last two weeks prior to the proposal were quite stressful, while initially not making good progress on the writing part of the proposal. I knew i that I won't be able to put that much time in the proposal from what I originally planned, which put me off a little. I knew needed to step up my time on working with the project proposal change in order to hand in good report.

Action:
In order to get work and university commitments done, I made a reverse schedule calendar starting from the due date to the current date. It contained tasks that I needed to have done to hand in my project proposal in time, while progressing at work at the same time. That meant working on weeknights and weekend for long hours for the project proposal and working at Mining3 during the day. I realized that could have been easily prevented knowing the commitment work takes and planning in more time consistently on documenting my progress.

Learning:
Contrary to working for just a university project I learned that writing a thesis while working full time on a project in a company is quite challenging.
In university I could just focus on writing the thesis without having the accountability of producing value for a company and being a productive employee. However, I learned that it is a still a similar situation even in university, because there is also accountability but mainly just for one self not for a third party like a company.
For the future and especially in regards to the upcoming interim and final report i will take two hours out of my time each week to document the progress done in project in the report. This will help to also keep up the progress on the reports in addition to the progress made at work. Also, this experience improved my ability writing technical reports effectively.

April Reflective Journal

Learning Event	EA Stage 1 Competencies Developing	Description of Learning Event
1. Monday Morning Safety Share in Meeting	**EA 1.6** Understanding of the scope and accountabilities of sustainable engineering practice **EA 3.4** Professional conduct **EA 3.6** Effective Team membership	Every Monday morning meeting at Mining3 contains a safety share component, in which colleagues share any hazards or dangerous events they have encountered in- or outside of work. In one share a colleague spoke about accidently short circuiting a lithium polymer battery while working on it. He had lower degree burns as the battery started catching fire. It made me think about paying even more attention now when I am working with these batteries since they are a part of my project.
2. Risk Assessment Meeting with Supervisor	**EA 1.6** Understanding of the scope and accountabilities of sustainable engineering practice **EA 3.5** Orderly management of self, professional conduct	In order to keep the company's current risks assessment for this project up to date our team met up with our workplace supervisor. We discussed any new risks that came up within the ongoing development of the autonomous mining truck. This meeting reemphasized the focus on workplace safety and made me think how to minimize risk during the autonomous testing stage of the project. This can be done by the utilising fail safe systems and operating only fenced off areas. I learned to keep risk management constantly in mind throughout the whole development cycle of the project.
3. Designing a PCB with EAGLE	**EA 1.3** In-depth understanding of specialist bodies of knowledge within the engineering discipline **EA 2.1** Application of established engineering methods **EA 2.2** Fluent application of engineering techniques	As I have completed my testing stage of my sensors it was time to migrate the breadboard sensor interface prototype to a more organised printed circuit board. I gained knowledge in using EAGLE which is a graphical layout editor for designing schematics and their corresponding printed circuit board design. This contained choosing suitable electrical components such as voltage regulators, resistors and capacitances. Also, I learned about creating custom device footprints in eagle and placing them on the board and connecting them with PCB traces. After I finished my design I had an experienced colleague to check my design and I sent it to fabrication. Knowing how to design a printed circuit board is a vital skill to have when working in the electronics sector.
4. Insights about career options in the Mining Industry	**EA 1.5** Knowledge of the engineering design practice **EA 3.2** Effective oral communication	During some of the lunch breaks a conversation about career paths came up and project leaders shared their experiences about working within the mining industry. I learned about graduate programs in mining industry and the advantages and disadvantages of working at remote

		mining sites. My key takeaway was them emphasizing that one's personal satisfaction in the work is more important than financial aspects of a job.
5. Testing Sensors and Problem Solving	**EA 1.4** Discernment of knowledge development directions in the engineering discipline **EA 2.1**	See details below

SEAL Analysis of Learning Event 5 – Testing Sensors and Problem Solving

Situation:

The most valuable learning event for this month occurred when I was testing my implemented localization sensors, which determine the absolute position of the vehicle.
I set up a test area that I walked with the wireless localisation sensors and was able to achieve good position accuracy. However, I did not expect the occurrence of rare to occasional outliers that would yield a position error of two meters.

Effect:

Upon evaluating the test results, I thought about if my method of locating the vehicle was still a feasible option. The thought of changing my localisation approach would cost me time and would leave me with a delay in my planned schedule, was not appealing to me.

Action:

I spoke with my supervisor about issue and read multiples papers on filtering wireless localisation sensors. In order to mitigate the occurrence of these outliers it is of course a common practice to low pass filter data. However, as a more effective method to remove outliers, papers suggest the fusion of several sensors to obtain the position information of the vehicle. Many authors use the relative position estimate gathered from the wheel encoders to assist the absolute positioning by wireless beacons and remove outliers. I therefore started to implement code estimating the position based on the vehicles wheel odometry data and the current steering angle. It was able to achieve accurate positioning data, which I can merge with the wireless beacon position data.

Learning:

My key takeaway from this experience was that in Engineering there are always problems coming up that are not considered beforehand. However with knowledge of common engineering solving methods it is possible to come up with solutions to it. This will help me in the future, because these principles apply to all areas of engineering.
Also, I learned for the future I learned to take unexpected delays caused by problem solving more into account when planning my project schedule. This will be especially helpful when debugging to complete system at a later stage of the project

May Reflective Journal

Learning Event	EA Stage 1 Competencies Developing	Description of Learning Event
1. Client on Site /Lab visit	**EA 1.4** Discernment of knowledge development **EA 3.2** Effective oral communication in professional domains **EA 3.5** Orderly management of self, professional conduct	A client, a senior engineer from a company which retrofits 40 tonnes mining trucks with electric motors and autonomous driving capability came to visit and see our small scale electric hauler. It was quite interesting to network and learn how a major engineering company does the work that me and my teammates do on a larger scale. I learned the different factors that need to be considered for a full size model such as extended fire suppression for batteries, breaking energy dissipation and the use of neural networks for safety systems. It underlined how current and relevant our project is to the mining industry.
2. Evaluation Methods in Engineering	**EA 1.2** Conceptual Understanding of the mathematics, statistics in the engineering discipline **EA 2.1** Application of established engineering methods	For the evaluation stage I needed to find performance criteria for the localization system and analyse and interpret positioning results. I learned the usefulness of statistical measurements such as mean and variance in a practical context in order to make observations. Given the my results and the preliminary literature review I was able to understand where some of the localization errors came from which in turn helped me in improving the design and architecture in positioning the beacons.
3. Version Control Management for Software Development	**EA 2.2** Fluent application of engineering techniques tools and resources **EA 3.6** Effective team membership	Upon my implementation of the code of a new sensor, the power steering stopped working. My teammate was implementing another feature at the same time. With the help of git, a version control system we could revert the current code commits and go back to a clean codebase to figure out faster what the problem was. With the increasing complexity of the project I learned to appreciate the effectiveness of version control when working in a professional environment. This is different from University where I mostly work on not as large programming projects.
4. Project Progress and Time Management	**EA 3.5** Orderly management of self, professional conduct **EA 2.4** Application of systematic approaches for management of engineering projects	Comparing the projects current state with the Gantt chart, I noticed the project is slightly delayed. I analysed it and found that i haven't factored time for debugging and tasks for the project that were necessary but didn't directly contribute to my project. To improve that i will update and review my progress weekly with respect to the allocated time and goals in the Gantt chart. Also, I have improved my ability to separate tasks worth pursuing from unnecessary time consuming tasks. Due to the bigger

		scope of tasks in the work environment it was quite insightful compared to University.
5. Learning ROS (Robotic Operation System)	**EA 1.4 EA 2.2 EA 2.3 EA 3.4**	See details below

SEAL Analysis of Learning Event 5 – Learning ROS (Robotic Operation System)

Situation:

The project has gotten to the stage, where readings from various sensors and microcontrollers had to be processed by a central unit which in this project is a PC.
One of the most impacting learning event, was learning how use robotic operation system. ROS is a software framework that includes commonly used libraries, toolboxes and modules that are frequently used in robotics. The complexity of ROS is large and therefore I was very surprised I haven't learned about it at University yet. Therefore I had to learn it from scratch myself.

Effect:

During the still ongoing learning process of ROS there were a number of setbacks which were demotivating. Functions just would not work or give wrong results, fixing them took longer than anticipated. However, the learning curve was motivating and as well as seeing the benefits of ROS for this project.

Action:

To learn the framework as fast as possible I first of started doing tutorials from the official ROS wiki which were unfortunately very broad and did not give much insight into the program. However, there is video series which helped me a lot in my understanding modules in localization and filtering data. Also, continuous testing and implementing new sensors and function with ROS for the hauler helped me the most in the learning process.

Learning:

Learning with this toolbox made me realise the great advantage ROS has in robotic projects, as it allows modular testing, communication with messages between different platforms (PC/Microcontroller/Sensors) and the access to already in build toolboxes for data visualization, recording which helps to understand data in the development process.
In University projects involve usually fewer devices and dependencies which would make the use of this framework unnecessary.
Therefore, learning ROS with this project is a great chance to improve my skills in understanding larger software frameworks in more complex software projects. The use of ROS and similar frameworks will help me in my professional career as it accelerates development with its modularity and access to toolboxes and libraries.

June Reflective Journal

Learning Event	EA Stage 1 Competencies Developing	Description of Learning Event
1. **Attending a Launch Event of an Electrical Mining truck**	**EA 1.4** Discernment of development within the engineering discipline **EA 3.2** Effective oral communication in professional domains **EA 3.5** Orderly management of self, professional conduct	Our Mining3 student team went together with our supervisor to a launch event of a commercial light electric mining truck. It provided an excellent opportunity to see the design of a professional grade electric mining vehicle. Compared to our project of a small scale mining hauler, i learned that the bigger dimensions have a huge impact on designing speed controllers, cooling and safety vehicle standards in mining. Also it provided the chance to speak to other industry professionals and learn about current developments. This event also taught me about how to represent the company in events and how to approach professional meetings like this.
2. **Learning about Control Systems**	**EA 2.1** Application of complex engineering problem solving methods **EA 2.2** Fluent application of engineering techniques tools and resources	For the first iteration of the autonomous driving capability in my project, i implemented a PID controller. It is written in python and uses the position and orientation of the vehicle and controls steering angle and motor speed, such that the vehicle reaches a waypoint. I learned to transfer knowledge learned in University about control variables and tuning proportional, integral and differential gains for a stable control circuit in a real world application, which was rewarding. It also improved my ability to plan experiments and test setups in order to optimize my parameters for the control systems.
3. **Internal Lunchtime Research Seminars**	**EA 1.1** Comprehensive, theory based understanding of the engineering discipline **EA 2.1** Application of complex engineering problem solving methods	A senior engineer of Mining3 guides a series of lunchtime workshops about research methodology. Based on examples of his PHD thesis, i learned in a practical way about the research cycle of making an observation, forming a hypothesis, experimental setup and the importance of data interpretation, which helps me in writing my final report. It was quite insightful to hear from an experienced professional about this matter and how to avoid common mistakes in experiments.
4. **Soldering Surface Mount Devices (SMD)**	**EA 2.2** Fluent application of engineering techniques, tools and resources. **EA 3.6** Effective team membership	Having finished the prototype stage of my sensor, i moved the electric circuit from temporary breadboard to printed circuit board, with soldered on electrical components. With a brief explanation of one of my teammates, i learned how to apply solder paste onto the board, place electrical components and solder it using a SMD hot air rework station. In University I did not learn SMD soldering, therefore it is quite useful skill to have when working in the

		field of embedded systems and electronics to test and build components the own.
5. Self-assessment about spent time and outcome	**EA 2.3** Application of systematic engineering processes **EA 2.4** Systematic Management of Engineering Projects **EA 3.5**	See details below

SEAL Analysis of Learning Event 5 – Self Assessment about spent Time and Outcome in a Task

Situation:
I moved on into the last stage of the project by implementing the autonomous control algorithm. It moves the vehicle to a waypoint being given the current vehicle location obtained by wireless sensor beacons. In the past I allocated a lot of time in achieving an accurate location with my sensors.

Effect:

In hindsight optimizing the code and setting up calibration routines for my location sensors took me two work weeks. I now realized the time spent was not worth the effort, since the testing of the autonomous driving does not need that amount of accuracy <0.3 meters in absolute values, since it is also testable with a higher error because it is only the relative location that matters.

Action:

This experience encouraged me to critically asses the time it takes to do a task compared with the expected outcome.
Therefore, being behind schedule I decided to continue on working on the path planning algorithm after work at home in simulations, in order to make up for the time lost on the calibration of the localization system.

Learning:

This applies to university and work life likewise, since the time available needs to be focused on what makes the current project or endeavour move forward the most. In this particular case it would have been the right decision to spend less time on accurate sensor calibration and start earlier on the implementation the autonomous driving controller.
For the future I learned to plan task ahead in terms of time spent and critically evaluate expected outcome with the available time.
It made me realize once more that time is the most valuable asset.