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Person Recognition System for Construction Vehicles in Tunnelling and Mining

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Diese Arbeit ist in englischer Sprache verfasst.

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Abstract

In the course of this master's thesis, a prototype for person recognition to detect endangered persons in underground construction was implemented and evaluated. Different sensors suited for person recognition were analysed in preliminary tests. Cameras and distance sensors provided data for person detection algorithms for the area surrounding the vehicle.

This work's focus was to develop a suited system architecture to make sensor fusion of all components possible for person recognition algorithms. A human machine interface was designed to show results of person recognition to vehicles operator in form of a live stream. The interface was simple and intuitive and was providing warnings to vehicles operator if persons were recognised by the system.

Usability, reliability and capability of the system in underground specific situations was examined in test series. High speeds for different sensor combinations were determined, in order to stop the vehicle to avoid an accident.

Test runs performed under real working conditions have shown, that the task of person recognition in real time is possible, but that there is also a lot room for improvement. The system gives good support in situations with a high accident risk and might be able to help preventing fatal accidents. Furthermore, an analysis of strengths and weaknesses of the system was possible and meaningful insights were given for working situations, drivers behaviour, single components and the person detection system as a whole.

Kurzfassung

Im Rahmen der Masterarbeit wurde ein Prototyp für ein Assistenzsystem für Baufahrzeuge zur Erkennung von gefährdeten Personen im Baustellenbereich entwickelt und evaluiert. In Voruntersuchungen wurden ausgesuchte Sensorprinzipien zur Verwendung für die Personenerkennung analysiert. Eine Auswahl an kameraoptischen- und Distanzsensoren lieferten Daten aus der Umgebung des Fahrzeuges.

Der Fokus der Arbeit lag auf dem Entwurf einer geeigneten Architektur, um alle im Assistenzsystem verwendeten Komponenten und Module für Personenerkennungsalgorithmen zu fusionieren. Im prototypischen Aufbau wurde die Mensch-Maschine-Schnittstelle in Form eines Live-Kamera-Streams, mit eingeblendeten Warnungen in einer einfach zu verstehenden und verwendbaren Benutzeroberfläche, integriert.

Im Zuge von Testreihen wurde die Leistungsfähigkeit des Systems bei verschiedenen Fahrzeuggeschwindigkeiten untersucht. Für Kombinationen von eingesetzten Sensoren wurden höchste zugelassene Geschwindigkeiten ermittelt, damit das Fahrzeug zum Stillstand gebracht werden kann, um einen Unfall zu vermeiden.

Testläufe unter möglichst realen Bedingunen haben gezeigt, dass Personenerkennung in Echtzeit durchgeführt werden kann, aber auch viel Raum für Verbesserungen vorhanden ist. Fahrer werden in Situationen mit hohem Unfallrisiko gut vom System unterstützt und sind dadurch in der Lage Unfälle zu vermeiden. Außerdem wurden die Stärken und Schwächen des Personenerkennungssystem analysiert und es konnten detaillierte und wichtige Informationen über Arbeitssituationen und -abläufe, Verhalten von Fahrern, einzelnen Komponenten und dem gesamten System gewonnen werden.

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Abbrevations

ABS Anti-lock Braking System. 1

ADAS Advanced Driver Assistence System. 1, 2, 5, 9, 11, 13, 14, 19

BBT Brenner Base Tunnel. VII, 3, 11, 12, 20, 25, 26, 41, 47, 58–61, 66, 67

CAN Controller Area Network. 19, 29

ECG Electrocardiogram. 31

HMI Human Machine Interface. 19, 20, 23, 25, 26, 29–31, 50, 52, 54–57, 59, 63, 64

IR infrared. 20, 21, 43, 50, 52, 58, 59, 64

KAT3 Koralmtunnel. 3, 13, 20

RFID Radio Frequency Identification. 1

RGB Red Green Blue colour model. 20

TOF Time-of-Flight. 21

UPS Uninterrupted Power Supply Unit. 23, 25, 61

Glossary

blasting heading The process of advancing a tunnel by blasting. (dt.: Sprengvortrieb). 11

broken ground Loose rocks and material, broken out by blasting. 13, 38, 44, 47

cavern A cave in the tunnel or a side cave from a traffic route for turns or evasive manoeuvres of vehicles. VI, 13, 17, 31, 38, 44–47, 51, 55, 56

excavated material see broken ground. 44

heading face see working face. 16, 38, 44

lidar Light Detection And Ranging. A method for measuring distances with laser. 21, 22

motion blur Fuziness on images caused by moving objects. (dt.: Bewegungsunschärfe). 20, 45, 47

mucking The process to bring all broken ground away from the working face after blasting. (dt.: Schuttern). 13, 14, 16, 18, 27, 38, 41, 44, 51, 55, 56

working face The place in a tunnel where advancing through blasting or by machine is done. (dt.: Ortsbrust). 13, 14, 27, 44

1 Introduction

As long as people are involved in dangerous activities, safety is and will always be an important factor. This is in particular true in the construction sector, where the danger level and accident risk for persons is extremely high. The danger potential is even higher in underground construction.

ADAS have been present in automobile industries for a long time now. One of the first ADAS was the Anti-lock Braking System (ABS) launched 1978 [Bengler et al., 2014, ch. 2]. The use of cameras in Park Assistent Systems and sensors for distance measurement in a vehicle has become a common thing in everyday life. Due to growing interest in autonomous driving, camera and sensor technology made huge steps in the past few years, bringing innovation into a qickly changing automobile industry which knows the potential of these technologies as Liu [2011, ch. 1] and Bengler et al. [2014, ch. 2] describe.

Based on the progress in the automobile sector, construction sectors and especially construction vehicle manufacturers began to use systems as well with the intent to make construction sites safer. Reverse cameras found their way into heavy machines very quickly. Complete Assistant Systems for Collision Detection and Blind Spot Views are on the rise, not at least because of steady growing size of machines and developments in autonomous driving. Sifferlinger [2016] highlights a lot of progress in Radio Frequency Identification (RFID) technologies with Proximity Detection Systems, specialised for heavy machines in the construction sector. He also recaps that such systems are introduced and improved all around the world, after legal aspects of this systems were and are still sorted out.

Automatic person recognition, in particular in tunnelling, is still a very challenging task and is currently not in use in common systems. Due to high computation costs and the complexity of person detection, the question is raised if person recognition can even be done in real-time under conditions like in underground construction. Other factors such the environments, most common accident causes, critical situations and the characteristics of the mining staff, have needs that require thorough analysis in order to develop a best-fit prototype assistance system for construction vehicles.

Zhou et al. [2015] made a systematic review to identify research gaps and discover a lack of construction safety research at task level. Some organisations, such as Working Group Health and Safety [2011] and Safe Work Australia [2013] try to raise awareness among working staff of this important topic. This paper deals with the most critical objects prone to accidents, human beings.

1.1 Research Question

The overall goal is to develop a prototype of a user-friendly, reliable and accurate working system that operators can trust to build a base for possible future work in this area. However, this thesis focuses on the tasks of prototype architecture, testing and collecting and analysing data. There is need to research if automatic person recognition in real-time is possible in conditions like underground construction and mining. Additional benefits of such a system, in the context of safety and working environment, shall also be analysed.

Is it possible to build an ADAS for construction vehicles in underground construction?

First of all, the main goal is to analyse if it is even possible to construct and implement an ADAS operating in tunnelling. Environmental conditions are harsh and can have a big impact, as common working procedures. Hardware and software have limits regarding person recognition in real time in situations like underground construction.

Does such a system help to prevent accidents in underground construction?

To investigate if such a system can help to prevent fatal accidents, it is mandatory to understand working processes and common dangerous situations in underground construction. The system is built, tested and evaluated for real working conditions in often occurring dangerous situations in underground construction. To answer this question, test scenarios will be designed, executed and analysed.

Datasets

Before performing test runs, the circumstances of the test shall be laid down. There are a few parameters which shall be considered to create good data results. The design of test runs will allow to evaluate points mentioned in sections 3.1 and 3.2.

Analysis of critical vehicle speeds for cameras and sensors

It is expected that at a specific speed of the vehicle, person recognition could cause problems. The reason is that camera systems may not be able anymore to deliver images of sufficient quality. Effects of in-motion unsharpness (Motion Blur) and lighting differences can occur, which make it hard or impossible to detect individuals. It is important to know where the limits of the system are, because higher speed also means higher braking distance.

ADAS under real conditions

One of the main objectives of this work is to find out, under which conditions and situations an ADAS is most helpful for drivers and when it is not. Therefore, it should be stated when person recognition is not working properly and can lead to misbehaviours.

Analysis of emergency braking process

It is particularly interesting, how active person detection influences driver's reactions. Especially timeframes beginning with recognition of a person and/or detection through the driver, initiating the braking process to standstill of the vehicle. Statistics including all needed parameters shall give a good picture about the interaction of system and operator.

Pattern recognition

If possible it should be analysed if specific actions or situations, such as people shovelling, can be assigned to patterns. This should give information if it is possible that specific scenarios could be recognised again by the system and give the driver special hints or warnings.

1.2 Structure

After the introduction, a short overview of ADAS is given in chapter 2. Components, such as cameras and distance sensors, are described as well as sensor fusion and person detection methods. The chapter is concludes with a state of the art of ADAS in construction vehicles.

Chapter 3 deals with parameters in tunnelling, which can influence component choice, setup and architecture of the prototype system. Leading accident causes in underground construction and danger situations are discussed for design of the test plan and testing itself.

In chapter 4, first some of the requirements are stated before the results of preliminary tests are presented, followed by the section about the installation of the prototype system on the experimental vehicle. In the end, the test plan designs for tests in Koralmtunnel (KAT3) and especially for the final tests in BBT are illustrated.

The evaluation is done in chapter 5. This chapter is divided in sections for test evaluation, driver feedback and the evaluation of single components as well as of the system as a whole. Furthermore, driver's reactions and behaviours is examined and how this has influenced braking distances.

2 Advanced Driver Assistance Systems

Sensor Systems in vehicles, better known as ADAS, are common practice in the modern automotive industry. ADAS are aiming to improve comfort, economy and safety. This work deals with the safety aspect of such systems.

2.1 Introduction

There are many types of Assistance Systems including Park Assist, Reversing View, Blind Spot Detection, Lane Departure Warning, Emergency Braking and Adaptive Cruise Control. Other systems, like Intersection Assists, Collision Turnout Systems, Traffic Jam Assist and active Pedestrian Security in though situations, are still under development. Bengler et al. [2014, p. 8]. An evolution overview of ADAS is provided in Figure 2.1. There are many different sensor types and cameras used in a automobile nowadays. The technical execution of the components is very specific for each assistance system as different tasks have different requirements.

ADAS try to recognise critical situations warn and assist the driver, if such situations occur. As mentioned in Kämpchen [2007, p. 6], usually acoustic, visual or haptic signals are used to assist the driver. Furthermore, a detailed and accurate environment description and a wide field of view is needed. In order to accomplish this proposition, cameras and sensors are used around and in the whole vehicle as shown in Figure 2.2. Objects surrounding the vehicle in the immediate and further surroundings, are as important as the vehicle itself. When looking at the complete environment, an ADAS can give the best possible assistance to the driver. [Liu, 2011, ch. 1.3]

One of the most needed parameters from sensors is the distance to an object. Depending on the needed range and the current situation, different sensors are used, including radar, lidar and ultrasound. Important properties for sensors and object or person detection are for example opening angle, indicators, range, environmental influence and pollution sensitivity, like mentioned by Bayless et al. [2014, p. 18] and Stüker [2003, ch. 2.2]. Camera systems provide the base material for object and person detection, since detection algorithms are typically image processing algorithms. Distance sensors and some camera systems provide distance information. With all collected data from those components, sensor fusion can be done, which brings all pieces together. Usually, sensor data is used to measure distances and

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[1] http://www.bdti.com/

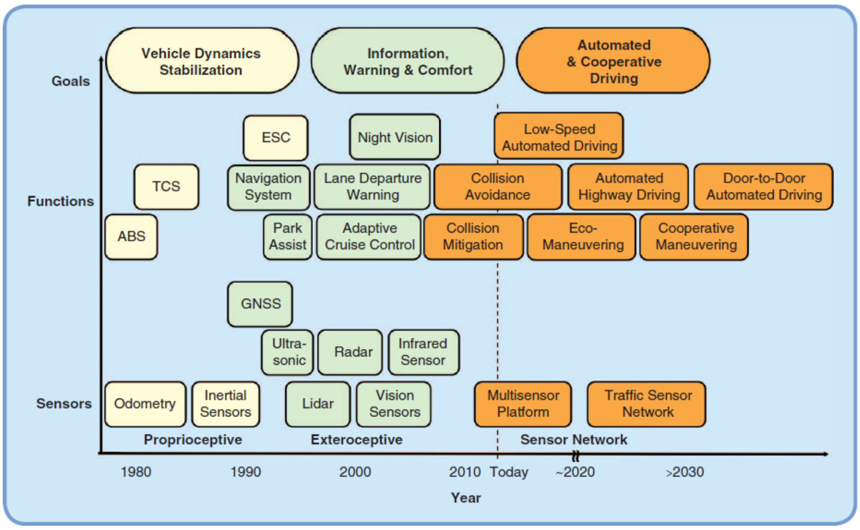

Figure 2.1: Past and potential future evolution towards automated cooperative driving. [Bengler et al., 2014, fig. 1]

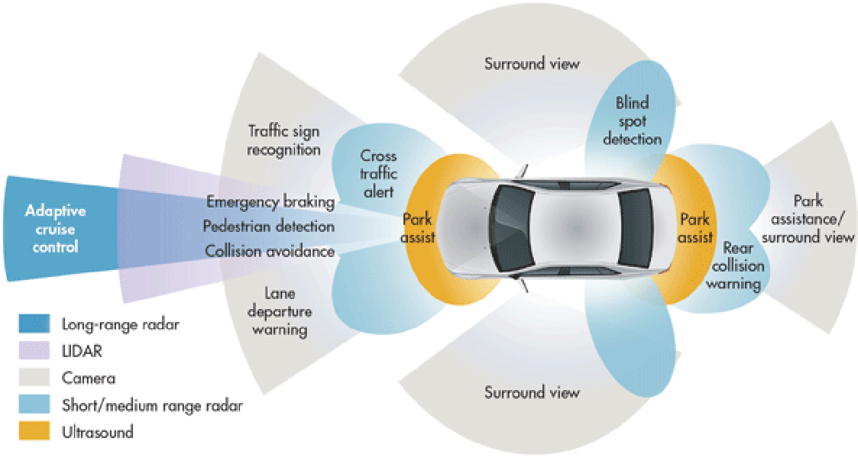

Figure 2.2: Advanced Driver Assistance Systems in an automobile. Berkeley Design Technology, Inc [1]

cameras provide visual material. Sensor fusion will be explained more in detail in section 2.3.1, while common sensors used in an automobile will be explained in subsection 2.2.

2.2 Sensors

This subsection deals with sensor components commonly used in cars for ADAS. Component types are separated in camera and distance sensors and their description will focus on systems that have an influence on this work.

2.2.1 Cameras

In general, cameras used in ADAS can be divided into visible light, 3D sensors and near and far infrared light. Kämpchen [2007, p. 10].Visible light cameras typically can deliver RGB and grayscale images and have a wide area of operations in the automobile industry [Liu, 2011, p. 5] and [Stüker, 2003, pp. 7–8]. Beside these models, there are other types which can be used:

- Mono camera
- Stereo camera or stereo camera systems
- RGB/IR camera
- Thermal camera
- Active 3D-camera
- Time-of-Flight camera

2.2.2 Distance Sensors

Usually, distance measurement in ADAS is performed for different ranges depending on the given task. Therefore, instruments used for distance measurement operate in a wide range of technologies. In the following, a brief overview of common hardware is given.

Radar

Radar systems are designed for short-range, mid-range and long-range detection and come with different opening angles. They are very robust against bad weather, dirt and mud [Sooyoung Choe et al., 2013, pp. 14–16], temperature changes or mechanical shocks [Stüker, 2003, p. 8]. A problem is the overlapping of many electromagnetic waves because it can cause measurement errors. Radars are the most used sensor system for ADAS [Bayless et al., 2014, p. 2]

Lidar

Laser sensors often have a higher precision of measurements than radar sensors. They can also cover wide areas and ranges, like radar. Disadvantages are that they are prone to dirt, dust and wet weather conditions [Liu, 2011, p. 7]. Laser class 1 is a requirement for lidar sensors because of safety reasons.

Ultrasound

These sensors have a significant shorter range than lidar and radar sensors. They are very sensitive to temperature, dust and steam because the air density influences the expansion of sound waves. In automobiles they are largely used in low-speed applications such as Park Assistance Systems. [Bengler et al., 2014, p. 7] and [Bayless et al., 2014, p. 6]

2.3 Software Methods for Person Detection

2.3.1 Sensor-Fusion

Sensor fusion is a method to combine sensors and their data. Kämpchen [2007, p. 14] states the objectives of sensor data fusion as follows:

- Improved state estimation accuracy.
- Increased object classification accuracy (higher detection rate, fewer false alarms).
- Improved robustness, for instance in bad weather conditions.
- Increased availability.
- Enlarged field of view.
- Enhanced level of detail of object description.

Depending on which level the fusion is done, three general distinctions are made [Stüker, 2003, pp. 6–7].

Raw-Level Fusion

This kind of fusion is only possible for sensors of the same type, for example when more ultrasound sensors are fused to have a wider acquisition field.

Feature-Level Fusion

In the next step, sensors of different types can be fused. Feature-Level Fusion is for example done to combine data from cameras and distance sensors, like lidar and camera [Liu, 2011, p. 9] and [Bui et al., 2014].

Decision-Level Fusion

The highest level of fusion connects decisions of sensors, for example when detecting whether an object is present or not. This method needs to be applied when closed sensor systems are used.

2.3.2 Person Recognition

As explained in Bui et al. [2014], algorithms for person recognition are generally very computationally intense and complex. Also, high-capacity graphics processors are needed for analysis in real-time. Base data is provided by cameras and sensors and is usually already fused when the detection begins. A very common combination is a camera with a lidar sensor as it is shown in Figure 2.3.

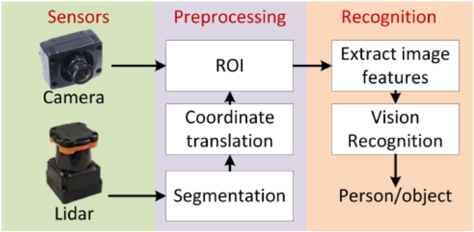

Figure 2.3: The Lidar-based sensor data fusion architecture. [Bui et al., 2014, fig. 4]

Some algorithms perform better than others, depending on the situation and the image type (RGB, Grayscale, Thermal). There are a lot of algorithms used for person detection and it would be beyond the scope to go in detail. However, the algorithms used in this project are the following:

- HoG person detector
- Blob detector
- KLT-feature-point-tracker

As summarized in Dollar et al. [2012, pp. 15–17] there are still some performance and runtime issues in person detection under real circumstances in typical city traffic. Sometimes, there are a lot of false positives detected and small and covered persons are often not recognised. Therefore, reliable object classification is a hard task to do.

2.4 Advanced Driver Assistance Systems in Construction Vehicles

As stated in Bengler et al. [2014, p. 8], ADAS could still be more effective in utility vehicles than in personal cars. Based on the information which is used in the automobile sector it is clear that such technology also can be used in construction vehicles. Some sensor properties are more important for automobiles than they are for construction vehicles.

Under normal circumstances, a construction vehicle would not need a long-range radar as it is not driving at the speed an automobile does on a highway. However, the characteristics of a construction vehicle are very different from those of an automobile. It is bigger, has much more mass, more blind spots and the direct field of vision could be covered by a shovel, constructional systems or dirt. Under these circumstances, the requirements to an assistance system are totally different. Especially in tunnels and underground construction, the hazard zone is much closer to the vehicle than at a construction site. The opening angles of the sensors have to be wider to cover more area around and next to the vehicle. Measuring distance for low-range has a higher priority than for long-range, in particular when the vehicle is not driving but working. Dirt, air moisture, temperature changes and lighting conditions are much more crucial for the sensors and cameras. They could be covered by dirt, fogged to temperature changes or blinded when the vehicle drives out of a tunnel. Environmental influence and pollution sensitivity of the sensor therefore could have a much higher impact than in usual traffic. This becomes even more fundamental when person recognition comes into play.

There are already systems for accident avoidance in construction vehicles on the market. All systems have in common, that they are primary designed for surface construction sites. Furthermore, only one system warns on pedestrians in low-range area.

Neptec ”Opal 360”[2]

The system is based on a lidar sensor which covers 360° of visual field. Software designs a complete 3D-model of the environment which makes object recognition and classification possible. In this model no sensor-fusion is used. The system is very robust against dust and weather conditions because of the wavelength used.

Indurad Radar Systems[3]

The company Indurad uses a selection of their radar-systems for different ranges and cameras with night vision. In combination with a ”Indurad Radar Processing Unit”, a collision warning system is implemented.

Brigade Electronic[4]

Brigade Electronic offers a wide spectrum of products which can be used in a Multi-Sensor-Security-System. Components are radar and ultrasound sensors and RGB and thermal cameras, some of them with 360° view. Construction vehicles are already successfully equiped with the Multi-Sensor-Security-System.

Arcure - BLAXTAIR[5]

With a suitable sensor fusion, applications of sensor system are more efficient. For short-range sensors like ultrasound for example, it would be possible to cover the whole near area of a vehicle with one raw-level fusion. Data and results are bundled, which also makes it easier to sort and interpret collected data.

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[2] http://www.neptec.com/

[3] http://www.indurad.com/

[4] http://brigade- electronics.com/

[5] http://www.arcure.net/

3 Parameters in Underground Construction

In order to implement a reasonable prototype of an ADAS for construction vehicles in underground environment, it is mandatory to understand general conditions in tunnelling. Therefore, environmental conditions and hazardous situations were also researched during the project. The following questions should be answered in this chapter. How are working processes structured? Why and when do accidents with physical injuries happen? What are common dangerous situations?

The points described in detail in chapter 4 have substantial influence on how the prototype and test plan are designed. Notably interesting for testing and evaluation are common danger situations because they occur frequently and have a high risk level for machines and mining staff in proximity of a tunnel. The environment also has an impact, especially for sensors and person recognition algorithms.

3.1 Environmental Conditions

On construction sites there are several environmental conditions and parameters which should be considered for the choice and placement of equipment. Due to the nature of tunnels, some points are notably important in underground construction. Statutory requirements can also make an impact, but for simplicity only Austrian legislation will be discussed. As final testing will be performed at BBT , the focus is on methods used at this construction site. Advancing methods influence the general tunnel condition most, therefore only blasting heading will be respected.

3.1.1 Light

It gets darker as one enters deeper into the tunnel, which makes lighting in any form necessary to make underground construction possible. While legislation for light exists, it only states that it is compulsory that it allows for the working place to be left quickly and safely. However, no exact values are stipulated in B-AStV [2002, §9]. In reality, it is common that there are areas which are lit up very well and others which are completely dark.

As shown in Figure 3.1 it became common over the past years to place lamps on the side walls in addition to the top lighting, in particular in working areas. Wether these lights are used or not depends on the construction site, mining companies and the task. Bergmann [2017] found out, that there are several tunnel sections which are very dark in spite of additional lighting. Usually, only road traffic occurs in such

Figure 3.1: Lighting in the exploration tunnel of BBT.

Figure 3.2: Usual front vehicle lighting for a wheel loader.

areas, but sometimes people are working in such sections. This can be dangerous because vehicle lighting and working lamps are the only lamps to light up the near surroundings and dark spots. An example of such a scenario can be seen in Figure 3.3.

From the vehicles perspective, there are some areas which are especially important for drivers and camera systems when driving and working. In particular, a quick and intense change of lighting conditions from bright to dark is a very critical situation. The human eye is affected by quick change of lighting conditions and so are stereo camera systems. The following spots are points of interests:

- The area behind the vehicle, usually lightened up very well, but often there is a blind spot.
- The area on the side of the vehicle which is lit with fixed lighting and/or some more of vehicle lighting, as demonstrated in Figure 3.3. This area is interesting especially for wheel loaders with articulated joints, like the experimental vehicle and excavators.
- The tunnel portal, where lighting conditions change quick and intense.

Beside fixed lamps there are many other sources of light. Examples are vehicle lightings, spotlights for areas, working lamps for equipment and headlamps for miners. As needed and usefull light is for workers, as negative it can be for person recognition. Vehicle lamps are very strong as shown in Figure 3.2. This can affect opposite traffic. Lighting causes shadows, which can make person recognition more difficult, especially for the stereo system. Warning vests can also cause problems due to their light reflective properties but also have positive properties for this task.

3.1.2 Temperature and Air Moisture

Air moisture and temperature go hand in hand. Air moisture usually is only a problem in higher locations in combination with water, but weather conditions can also have an influence, for example when a vehicle enters a warm tunnel in winter. Fogged and glazed windows, mirrors, cameras and sensors as well as condensed water

Figure 3.3: Road conditions in Gleinalmtunnel.

Figure 3.4: Road conditions in KAT3.

can be the consequences. The temperature typically encountered in underground construction are no problem for the components. The temperatures in tunnels vary depending on the geographic region and geologic factors.

3.1.3 Traffic Routes and Road Surface

Usually, there are many crosscuts, poor visibility areas and obstructions like containers on the side of the roads. B-AStV [2002, §2] provides some legislation for traffic routing, but it is very imprecise for construction sites. One of the main points in this legislation is to keep the way to emergency exits and the exits itself clear and to create safe ways for working staff. In many cases it is simply not implementable because of adverse conditions in tunnelling and mining.

Side caverns in the main tunnel are used for evasive manoeuvres, but their main purpose is for wheel loaders turns while mucking. Usually, vehicles head in backwards from the working face, loaded with broken ground and high speed, to turn and load a dump truck. This is a very frequent process, as it happens every time after blasting until no broken ground is left and the next blast can be set up. During mucking, the sight is normally very bad and caverns are among the main hazardous sections.

Rough and bumpy road surfaces are completely common on construction sites. Figures 3.3 and 3.4 show typical runways on underground construction sites. The surface has influence on the driving speed and therefore on braking distances. Rough road can also influence the performance of components because of kicks.

3.1.4 Dust and Dirt

Dirt and dust are present all the time and are main drivers for the pollution of windows, mirrors and ADAS. Again, there is no really clear legislative for construction sites and many things depend on the construction coordinator [BauKG, 1999]. As there are no automatic cleanup mechanisms while the machine is in service, the operator is responsible for fitness for service. This also applies to ADAS, where dirt can lead to misbehaviours.

In underground construction there is one specific periodic szenario which leads to a lot of dust and therefore to high stress levels for mining staff and machines. After an explosion, huge clouds of dust remain at the working face until it is soaked up by air siphoning or it has wandered out of the tunnel as explained by Bergmann [2017]. As described in subsection 3.1.3, mucking visibility is affected substantially but working goes on. This is a very dangerous situation — project partners defined it as the most dangerous scenario, where an ADAS can have a big impact on safety.

3.1.5 Speed Ranges

KFG [1967, §3] defines speed ranges on construction sites with the maximum speed of the vehicle type. In practice, ranges can span from walking speed up to 40 km/h or more. On underground construction sites usually, there can be different speed limits in place inside and outside the tunnel. When going underground, the speed limits often vary even more, depending on lighting and especially when people are working in a section. in proximity of the working face for example, a usual speed limit is 10 km/h, while for the rest of the tunnel 20 to 30 km/h is a common speed. Speed limits are set by the construction coordinator, as stated in BauKG [1999].

3.1.6 Construction Vehicle

All of the factors mentioned above directly and indirectly influence the construction vehicle, its on- board systems and driver. The vehicle itself also has properties which can have an impact on camera and sensor systems, for example by the means of vibrations, shapes and blind spot areas. These two parameters settle where the whole equipment can and should be placed. The location of cameras and sensors is essential for data collection. Badly placed components deliver bad data.

3.2 Accident Causes and Danger Situations

This section deals with the root causes of accidents with fatal injuries and high-risk situations. To that end, research and discussions with project partners in the Austrian construction industry were done by Klausecker [2015]. It is very important to understand under which circumstances accidents happen and to know critical situations in underground construction in order to build a fitting prototype.

3.2.1 Leading Accident Causes

Construction in general and underground construction in particular is a sector with a very high accident risk. Short distances between staff and heavy machines in tunnels are among the main reasons for incidents, that often result in fatal injuries.

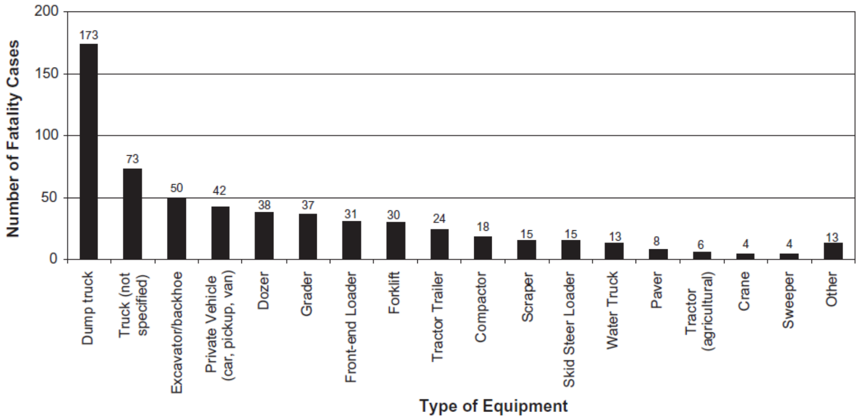


Figure 3.5: Frequency of the involvement of specific pieces of equipment in fatality cases in the United States from 1990 to 2007 (N=594) [Hinze and Teizer, 2011, fig. 2]

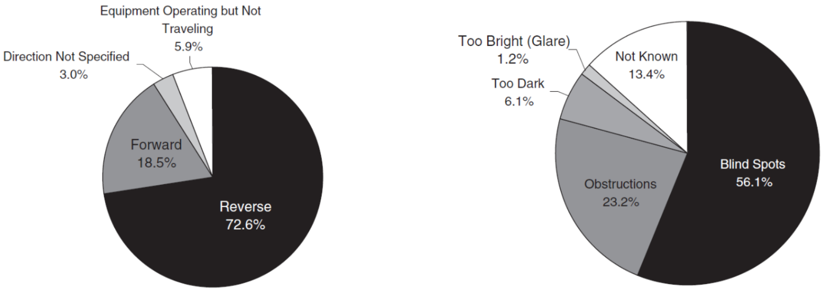
But Sifferlinger [2016] and MSHA [2015] point out that a high number of fatalities in tunnelling and mining worldwide could be avoided by implementing safety systems, that issue collision warning between machines and persons.

The primary causes for “contact with objects or equipment“ in construction sectors have been investigated over the past decades. Blind spots for machine operators have been identified as one of the primary reasons for struck-by accidents by Hinze and Teizer [2011]. Figure 3.6 illustrates visibility-related causes for accidents. Furthermore, Marks et al. [2013, p. 2] analysed data from OSHA [2009] and found out that up to 87% of visibilty-related fatalities were not predictable by neither the machine operator nor the worker. There are many technical aspects to address the blind-spot-problem. According to Su et al. [2015, p. 2], many studies were conducted in order to raise more awareness of this issue.

According to Hinze and Teizer [2011], dump trucks are the vehicles that are most involved in visibility- related accidents, followed by excavators and also wheel loaders. Figure 3.5 shows the relevant study results by Hinze and Teizer [2011]. In addition to that, Figure 3.6 demonstrates that most accidents happen when travelling in reverse.

> Dump trucks were involved in 31% of the struck-by cases that resulted from visibility-related conditions. Of these cases, 90% percent involved dump trucks traveling in reverse and this can probably be attributed to their large blind spot area (truck beds) as well as the frequency that trucks travel in reverse. [Hinze and Teizer, 2011, p. 6]

Leisering [2013] evaluated accidents involving injuries and fatalities in Germany from 2009 to 2012. It was detected that driveaways and swing-outs cause by far the highest numbers of injuries and fatal accidents. A more detailed analysis identifies



(a) Equipment movement direction

(b) Visibility/Awareness

Figure 3.6: (a) Nature of equipment movement at the time of accident occurrence in the United States from 1990 to 2007 (N=594). (b) Poor visibility/awareness as cause of accidents in the United States from 1990 to 2007 (N=82) [Hinze and Teizer, 2011, fig. 3 and 6].

dumpers, excavators and wheel loaders as machines that are involved the most, as Hinze and Teizer [2011] also found out. Many works and studies, for example Sifferlinger [2016], Su et al. [2015], Leisering [2013] and Thurston [2010], mention blind spots, obstructions and also darkness as the leading causes of struck-by accidents.

Klausecker [2015, pp. 28–30] defined a questionnaire to identify situations and activities which lead to accidents in tunnel construction in Austria. Discussions and interviews with project partners were conducted. The findings showed, that the vehicle groups most involved in accidents are wheel loaders and dumpers. Higher accident frequency also occurs when vehicles perform many changes of direction, reverse and exceed speed limits, mostly due to time pressure. Representatives from the construction industries also say that shift cycles have an influence on accident frequency as Klausecker [2015, p. 30] points out.

3.2.2 Danger Working Situations

Some areas and activities in tunnelling and mining are particularly very dangerous. Based on the questionnaire mentioned in 3.2.1, Klausecker [2015] investigated situations and activities with high accident risk on tunnel construction sites with project partners from the construction sector and AUVA [2017]. These situations will serve as orientation for the test plan design of situational tests in chapter 4.4.

Working Face

The main area is the heading face, which is usually very crowded and a lot of vehicles are parked or circulating. Some machines are used in standstill, but even so they take up some space, which reduces room for workers. Usually, materials and logistical equipment, like containers or cars, are also present near the heading face and can possibly cover persons. This causes obstructions for drivers and is

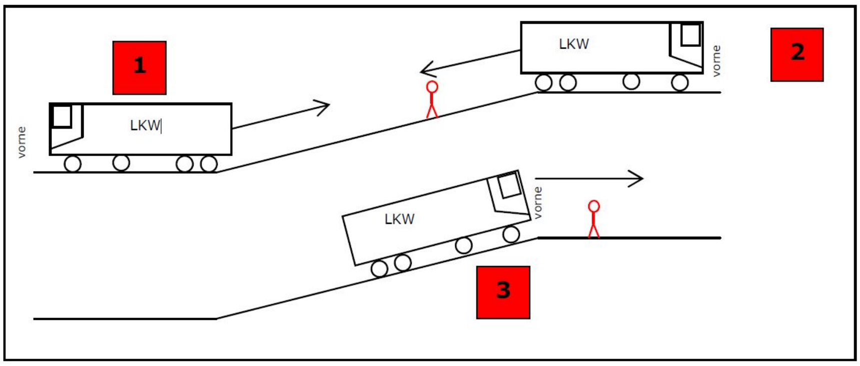


Figure 3.7: Demonstration of limiting in sight for the driver on a ramp. [Klausecker, 2015, fig. 24]

a source of hazard. Overall, there is a lot of accident potential in this particular working area.

Mucking out

Nearly all factors mentioned in 3.2.1 make mucking out one of the activities with highest risk level for this work. There is bad sight, travelling in reverse, many direction changes and tight space with the working staff on site. As Klausecker [2015] and project partners state, this activity presents by far the highest risk factor for tunnel construction.

For person detection, this scenario is challenging. There is much movement and people on site, while the sight of the cameras is influenced by dust, just as the drivers'. High speed and short distances between the vehicle and a possible collision object call for a fast calculation of the system, allowing operators to react in time.

Ramps

What makes ramps dangerous, is slope. It creates a larger blind spot, demonstrated in Figure 3.7, especially for the sight of dumper drivers. In Austria, driving backwards on ramps is often prohibited by construction coordinator, because of obvious safety issues [Klausecker, 2015, p. 29]. The risk of overlooking a person on the ramp in heavy construction vehicles is very high.

For the prototype person detection system, the difficulty lies in the difference in height between a person and the sensors, for example when a person is on a ramp, but the vehicle is still on flat ground. Person recognition may not be possible, because the person may not be in the vision field of the sensors.

Obstructions, Caverns and Equipment

The problem for drivers is that they do not know what is covered by obstructions in general. Individuals may be hidden, partially or fully, by any obstructions and may not hear a coming vehicle because of the noice level in tunnels. This is critical for vehicle operators when driving by, as a person can step on the driveway from behind a container, vehicle or equipment or out of a cavern. Finally, there are all the areas with poor insight for drivers like turns, caverns, crosscuts and all tunnel sections where persons can come out on slim roads.

When miners handle equipment or even do common things, like tying their laces, they are often not standing upright. This needs to be kept in mind for person detection. Obstructions caused by these elements can make it harder for drivers to identify persons, even when all safety equipment is worn by miners. Depending on degree of obstruction and/or the behaviour and movements of a person it can have a lower or higher impact on person recognition.

3.3 Summary

The environmental conditions discussed in section 3.1 show that a prototype needs proper design in order to live up to harsh conditions in tunnels. Sensitive hardware needs proper protection and dirt must be secured at all times. Hardware and software need to adapt to different lighting situations, reflections, speeds and road conditions as environmental parameters. Person detection algorithms also need to factor in variable obstructions, body movements and movement speeds of the mining staff while computing person recognition in real time.

As the studies and research findings presented in section 3.2 have shown, the biggest accident risk for vehicles are blind spots. These can be found around every vehicle depending on its shape. Typically, wheel loaders and dumpers have blind spots at the machines' rear end. Since those vehicles are frequently operated in reverse, blind spots are very dangerous. There are also specific situations, which are often repeated, that cause safety hazards. Mucking out and driving by obstructions are examples for such scenarios.

4 Experimental Setup

An ADAS prototype equipped with person recognition for underground construction should explicitly warn the driver when people are near construction vehicle. Therefore it is necessary to place cameras, sensors and other equipment in and on the experimental vehicle, which constitutes the complete prototype ADAS.

The equipment used should fit the environmental conditions discussed in section 3.1 and should minimise the risks mentioned in section 3.2. The goal is to cover blind spots and areas which are difficult to see for the driver in common situations and to make the ADAS as robust as possible.

4.1 Requirements

This subsection lists some terms and consitions, which should be taken into account when designing the prototype. All of the following points have an impact on the installation of the prototype as described in section 4.3. The final prototype should be tested under real conditions at the end.

Placement on the Experimental Vehicle

Sensors should be placed at the rear end of the vehicle and all tests should be designed for a backwards driving wheel loader. Other than that, the whole wheel loader can be used for equipment placement as long as the protection of equipment is sufficient and working is possible without restriction.

Build-In Equipment of the Experimental Vehicle

As defined by project partners, the original equipment of the wheel loader, such as integrated consoles or vehicles Controller Area Network (CAN) bus, should not be used for the prototype. Everything that is essential for person detection or other interfaces like the Human Machine Interface (HMI) should come from the application itself. Therefore, no vehicle data, for example speed or steer angle data, can be used for the prototype.

Cameras and Distance Sensors

It is mandatory to find the best suited components for an ADAS in underground construction. For this purpose, components used in automobile sector can be helpful. However, they are not necessarily suited for tunnelling, hence some changes and protection of used sensors may be needed. Sensors should also be tested on the environmental conditions mentioned in section 3.1, both in preliminary and final tests.

Different visual and distance sensors should be tested for comparison. This applies to preliminary tests as well as to final tests, which means that more than one visual and distance sensor should be used. This requires a setting is needed which holds all sensors and can be attached to and detached from the experimental vehicle in the easiest way possible. Sensor fusion should also be used and tested.

Human Machine Interface

In order to provide a visualisation for the driver a HMI is necessary. The most important part is to signal to the driver when a person is recognised. A HMI should be as simple as possible and should only present the most essential features. Additionally an evaluation should be made, aiming at establishing what signalisations drivers prefer and which utilities would fit best. Implementation examples can be:

- Acoustic signals
- Visual signalisation in traffic light colours on a rear view camera
- 360°multicolour LED string

Testing and Evaluation

Tests should be performed under the most real conditions possible. For this purpose, testing takes place at actual construction sites run by construction companies, including professional miners. The locations are Koralmtunnel (KAT3) and Brenner Base Tunnel (BBT). The final test with a complete test plan will be done at BBT. The complete test plan will be described in detail in chapter 4.4.

4.2 Preliminary Tests

The main goals of preliminary tests were the comparison of different sensor systems, the suitability under real conditions and the identification of the best locations for hardware on the experimental vehicle. In this section only a short overview of findings in preliminary tests will be given. Discussing the test results in great detail would exceed the scope and limits of this work.

4.2.1 Environmental Conditions

Once the preliminary tests of environmental conditions are done, the relevant results are described in section 3.1.

4.2.2 Sensors

Each sensor used was tested for usability in a laboratory under different environmental conditions. Additional try-out tests in Gleinalmtunnel, Götschkatunnel and Erzberg were also conducted and evaluated. Three camera systems and three distance measuring sensors were choosen to be built in the prototype. The working methods of sensors are described in detail in sections 2.2.1 and 2.2.2.

Table 4.1: Chosen cameras and their tested operating distances.

Camera	Range	Op. Distance [m]	Description
Active 3D Camera	Short	2.5-8	Used for 3D depth sensing
Stereo System	Short, Middle, Far	4-21	Two black and white cameras
IR Camera	Short, Middle, Far	5-20	Low resolution, small opening angle

Cameras

For middle and far ranges, a stereo system with two black and white cameras was chosen over RGB cameras. The RGB/IR camera (Axis 223M) has many positive properties because of the rendition of coloured images, but will not be used. The reason is its high vulnerability to motion blur, which is better handled by black and white cameras. This is a very important point when it comes to person recognition. This system will need additional protection against outer influences.

For the same range an infrared (IR) camera (FLIR SR 19) was tested. It has a tight opening angle but major benefits on distances to 30 metres and is immune to lighting effects. This camera is provided by Joanneum [2017] and is very robust against the underground environment.

An active 3D Camera (Asus Xtion PRO LIVE) has shown very good results on short ranges. Algorithms perform very well with 3D depth images and reliable person detection should be possible, as there is already a lot of functionality tested in the entertainment sectors. However, this is also a weak point. Used in the stereo system, this camera will also need extra protection.

A Time-of-Flight (TOF) camera (MESA Imaging SwissRanger SR4000) was also tested, but will not be used at this time. The main reason is its low resolution, which makes person recognition with this model nearly impossible.

In Table 4.1, an overview of the visual sensors used in the prototype, along with their operating distances is provided.

Distance Sensors

Tests have shown that radar sensors developed for the automobile sectors are only useable to a very limited extend in underground environment. With the tested long range radar (ARS30x) people can only be detected up to a distance of about 10 metres, but the main problem is the large number of false object detections. They are caused by side walls and even small road bumps. However, it was decided that this sensors will also be tested with the prototype. More detailed information should be gathered in order to possibly bypass this problem.

A 2D lidar sensor (Hokuyo UTM-30LX) is able to close this gap in middle and far ranges. Measurements with the lidar sensor were very accurate up to 30 metres. Negative aspects may be the sensitivity to dirt and dust and that measuring is only done at one height level.

Table 4.2: Chosen distance sensors and their tested operating distances.

Distance Sensor	Range	Op. Distance [m]	Description
Ultrasound	Short	0-5	Can be used in synchronised mode
Radar	Short, Middle, Far	2-10	Many false positives
Lidar	Short, Middle, Far	0-30	Very precise and robust

Three synchronised ultrasound sensors are used for the area closest to the vehicle. Ultrasound sensors and electronics were built by ViF [2017] to fulfill the requirements concerning dirt, dust and waterproofness. The sensors worked as expected in preliminary tests and will nicely complement the data delivered by the active 3D camera.

Table 4.2 shows data of distance measuring sensors and their working distances.

4.2.3 Experimental Vehicle

One of the main goals for preliminary tests was to find the appropriate spots on the wheel loader for placing the equipment. Geometry, blind spots and the surrounding environment have to be considered. Tests indicated that the best place for sensor placement is the rear end of the vehicle. That is why it was defined as requirement in section 4.1. This area is a blind spot and a lot of accidents happen when backing up. Installing the equipment on the back of the vehicle, sensors have the same height as people and they are one “unit“ with the vehicle because they now define the end of the wheel loader. This would not be the case with an installation on the cabin. The higher position would require a lot of sensor angle adjustment. In addition, sensors would be positioned in the middle of the vehicle which would limit the operating distances. Short range sensors in particular would have to reduce their working distances by 50%.

Vehicle vibrations in specific frequency spectrums can cause problems for sensors. Therefore, swinging in common working processes was measured and analysed. It was found that the only working situations with problematic frequency values are loading and beating out the shovel. This problem can be solved with proper isolation for sensors.

4.2.4 Summary

Testing has shown that the best place for sensors is the rear end of the vehicle. This position simplifies some implementation aspects, but in first instance it is placed in an area with high danger potential, which is good for testing under real circumstances.

Chosen sensors can be combined very well and cover the safety zones behind the vehicle. Especially the lidar sensor will be a corner post for position calculation. Tables 4.1 and 4.2 show, that there are overlappings in operating distances of diffe-

Figure 4.1: Wheel loader Typ L576 by Liebherr [2017].

rent sensors. The area in near (0-5m) and middle (5-15m) range behind the vehicle is usually the most dangerous area. Avoiding gaps in working distances of combined sensors brings the best results for sensor fusion and person recognition.

4.3 Installation

This section deals with implementation aspects of the prototype on the experimental vehicle. The structure of hardware and most important components will be discussed.

4.3.1 Experimental Vehicle

For the implementation of the prototype, a wheel loader, as shown in Figure 4.1, is provided by the company Liebherr [2017]. This construction vehicle is commonly used on underground construction sites. Therefore it is well suited for research under realistic conditions.

4.3.2 Architecture

The whole prototype systems consists of four major parts, which are installed at seperate spots on the wheel loader.

Hardware Platform

Figure 4.2 shows a summary of the hardware used for the prototype and how it is connected. The wireless routers and a notebook, shown in the bottom left corner, are only used for testing purposes in order to gain remote access to the computer while driving and are not mandatory for the system.

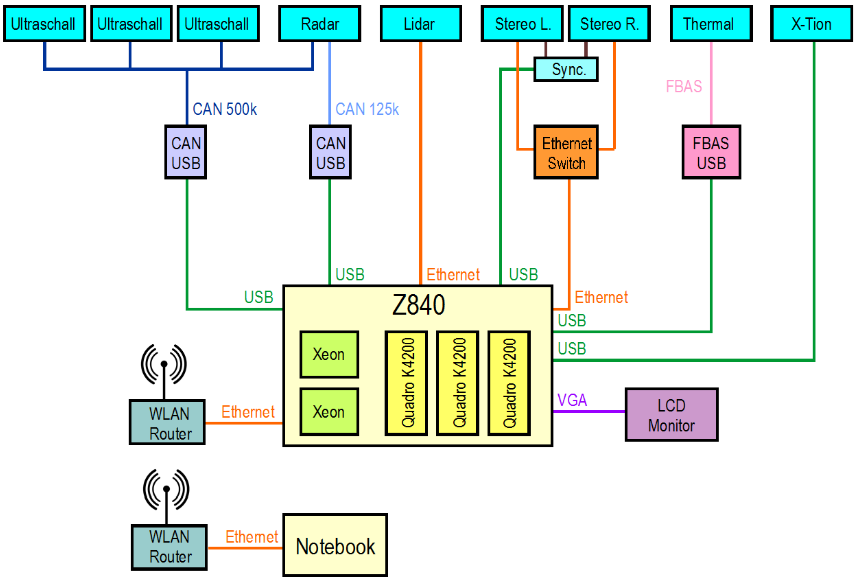


Figure 4.2: Hardware topology for the prototype [ViF, 2017].

The core unit is a high performance workstation “HP Z840“ with hardware that fits the requirements for person detection and is connected to an Uninterrupted Power Supply Unit (UPS). It runs the main application, called “ModuleGUI“ developed by Joanneum [2017]. It is responsible for data processing and hence for person recognition and for deploying the results to the driver’s monitor, the HMI. All sensors are connected to the workstation by wire. Sensors send their data via USB or Ethernet to the processing unit and need a power supply of 12 volts. Some sensors require 230 volts and therefore have extra wires connected to a UPS.

All sensors are placed on a console as demonstrated in Figure 4.3. It can also be seen that stereo system and Xtion are built into a case. As demonstrated out in section 4.2.2, this components need extra protection against conditions in tunnels.The whole console can be mounted on and dismounted from the experimental vehicle very quickly because it is installed instead of the fender, which is fixed by screws. All sensor cables are bundled and run to the processing unit or power supplies.

Processing Unit

Workstation and periphery are installed in the right ballast weight of the experimental vehicle. This is the only place that provides enough space and protection. Absorption elements and coverings are also installed for more protection against kicks, dust and dirt.

HMI-Interface

In order to make handling for drivers as simple and straightforward as possible, an ordinary HMI is implemented. It consists of a standard LCD monitor which is

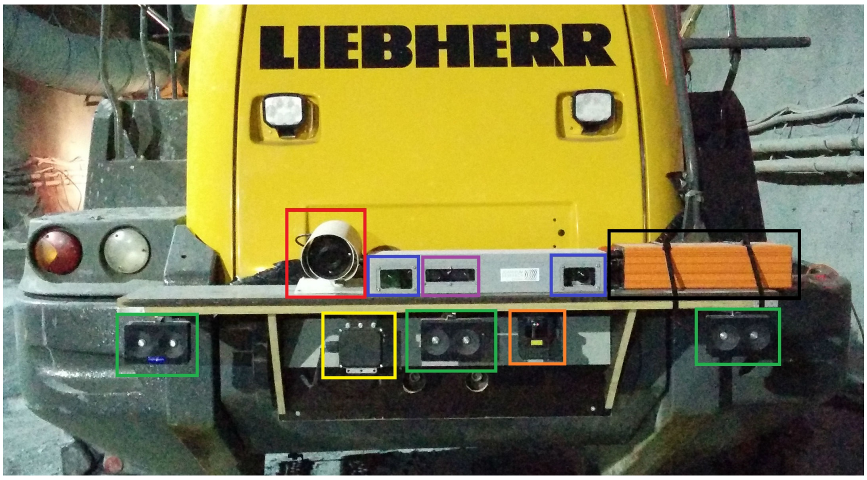


Figure 4.3: Console with all sensors installed on the experimental vehicle instead of the fender. From left to right. Top: Red: Thermal camera, Blue: Stereo system, Purple: Active 3D Camera, Black: Voltage Converter, Bottom: Green: Ultrasound, Yellow: Radar, Orange: Lidar

placed at the right bottom of the front window inside the cabin. With a cover to minimise monitor light, only a small live stream from one of the stereo cameras is shown to vehicle operators. A coloured frame around the videostream signalises to the driver in red if persons are recognised and in green when no persons are detected. A simple example illustrates this functionality in Figures 4.4 and 4.5.

Power Supply

In order to make it possible to drive for longer times without charging, the UPS is supplied with battery power of the wheel loader. The batteries are connected to a voltage converter which is placed on the console outside of the ballast weight for the reasons of heat avoidance. Figure 4.3 shows the exact location. The UPS is

Figure 4.4: Example of HMI, no persons recognised.

Figure 4.5: Example of HMI, with a person detected.

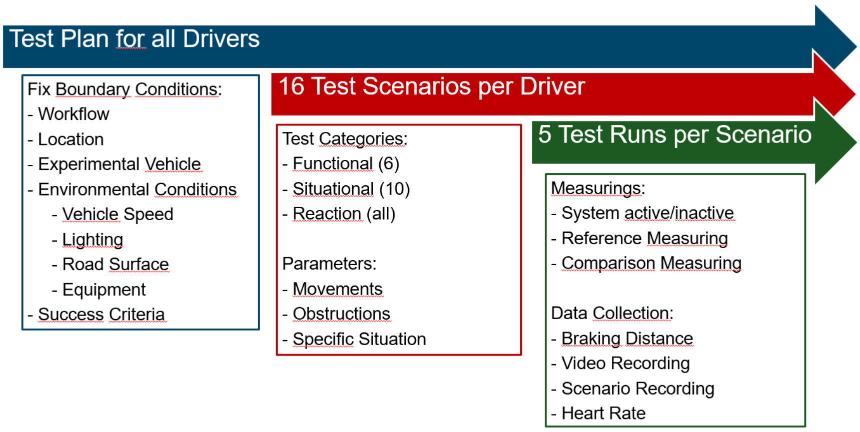


Figure 4.6: Test plan for final tests in BBT.

supplied with that voltage and is the source of power for all components and the processing unit.

4.4 Test Plan Design

This section deals with test structure and scenarios in detail and provides an overview of the final testing location in BBT. Findings from previous chapters and sections serve as the base for designing test scenarios. Moreover, data collection for subsequent evaluation will be explained.

4.4.1 Test Structure

The test plan is designed for any driver driving the experimental vehicle in use and the installation described in section 4.3. There are boundary conditions and different scenarios, described in detail in subsections 4.4.2 and 4.4.3. Each scenario is completed five times by every driver. Figure 4.6 illustrates the complete test structure.

4.4.2 Test Scenarios

The tests are divided into 16 scenarios in different test categories for each driver, which cover different situations. Each scenario is explored in five test runs. Out of all test runs, two runs are performed without and three runs are performed with the prototype system active to analyse drivers' behaviours. The first run with or without the system respectively serves as reference for the other runs, which are comparison measurements.

In Table 4.3 all scenarios are listed. Scenarios include a backwards driving wheel loader and people actively moving. Only scenario 8, when a person steps out on the road from behind a side obstruction, is an exception. The driver does not know when a person will step out and a few no action runs are performed in order to randomise the overall test setting. For scenario evaluation, only test runs where a person walked out on the road are analysed.

Table 4.3: Overview of test scenarios for final tests at Brenner Basetunnel. Legend for Type: F: Functional, S: Situational, R: Reaction

#	Type	Location	Description
1	F/R	1	Walking on the road or road side
2	F/R	1	Sitting near the road
3	F/R	1	Obscured torso
4	F/R	1	Obscured legs
5	F/R	1	Operational activities
6	F/R	1	Crossing the road
7	S/R	1	Looking behind a side obstruction
8	S/R	1	Stepping out on the road from behind a side obstruction in dangerously close distance
9	S/R	1	Standing in the back light of another vehicle
10	S/R	1	Walking in the back light of another vehicle
11	S/R	1	Turning into cavern
12	S/R	1	Turning into cavern to load a dumper
13	S/R	2	Driving up a ramp
14	S/R	2	Driving down a ramp
15	S/R	3	Driving into the tunnel
16	S/R	3	Driving out of the tunnel

4.4.3 Boundary Conditions

For final tests in BBT there is a fixed setting with different drivers but with the same experimental vehicle and prototype installation. In order to create a objective testing environment, boundary conditions are determined and remain the same for each test run.

Testing Locations

The contract section Wolf 2 at BBT near Steinach am Brenner is operated by the construction company Swietelsky[1]. It covers some logistic tunnels and a four kilometre access tunnel that leads to a part of the exploration tunnel. This tunnel is built twelve metres under and between the two main rail tunnels and has a smaller width compared to main tunnels [BBT, 2017]. After thorough inspection, three tunnel sections are chosen as testing locations.

The first area, location 1, is where most of the tests are done. It is a big cavern where the access tunnel ends and the exploration tunnel of this contract section begins. Figure 4.7 shows a picture of the whole cavern. The working face is about 800 metres away at the time of testing.

This location is very well suited for testing because of a transition from the entry portal into the main tunnel and a container in the near area. The wheel loader can head into the tunnel and drive out backwards again. On its way the vehicle passes

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[1] https://www.swietelsky.com/

Figure 4.7: Cavern and begin of exploration tunnel used for test scenarios 1-12

both the tunnel entry portal and the container, which can be ideally used for many scenarios. This area also represents a crosscut, has tight and wide roads and a side cavern. In addition to that, lighting and road surface conditions are completely real and will barely change due the fact that the construction site is out of service at the time of testing. For mucking out scenarios, loose ground is available and can be used.

For testing scenarios 13 and 14, which are simulate hazardous situations involving ramps, a dump disposal site is selected at location 2. The area is near the crosscut of the access and evacuation tunnels and is one of a few intermediate disposal sites. Wheel loaders create ramps to carry up piles of broken ground for unloading in order to save space. This ramp has sufficient slope but is very short and is not ideal for testing, but no better alternatives are given in the tunnel.

Location 3 is the entry portal of a tunnel which is used for the evacuation of broken ground into the Padastertal dump. Test scenarios 15 and 16, which cover tunnel portals, are set in this section. In comparison to the main entry portal of the access tunnel, this portal is not lit up very well, because usually vehicles only drive out of this tunnel. However, all other requirements for this test are fulfilled.

Drivers and Experimental Vehicle

As already mentioned, the experimental vehicle and installation stay the same for every driver and all tests. In total, four vehicle operators run the test program. Three experienced drivers are provided by the construction companies Swietelsky[2], STRABAG[3] and Hinteregger[4], which are also project partners. Another driver, unexperienced in tunnelling, comes from company Liebherr [2017].

Before running the scenarios, every driver is instructed in test plan, prototype system and especially HMI specifications. Also, a brief introduction exploring how each situation is processed is given before setting up all data collection mediums. If test runs are performed with an activated system, drivers are instructed to rely on the person detection system as much as possible. When all test runs are completed, drivers give feedback on how everything worked out for them.

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[2] https://www.swietelsky.com/

[3] http://www.strabag.at/

[4] http://www.hinteregger.co.at/

Environmental Conditions

Every driver has to go through the same situations because during of testing, the construction site is out of service. Therefore, no advancing of the tunnel is done and no other workers or vehicles are present. In the following, the most important environmental conditions for testing and their states for the final tests are stated:

- Vehicle speed: Is set to a constant speed of 25 km/h, which is a usual average speed. Drivers should keep that speed as constant as possible, as there is no connection to vehicle's CAN bus.
- Lighting: Tests are run in a normal working section. Therefore, fixed tunnel lighting is guaranteed. Vehicle lighting is also as usual, which means full vehicle lighting during working underground.
- Road surface: Roads are as expected in a tunnel. That means bumpy, wet and muddy in some areas. As there is no more traffic in testing areas, road conditions can be assumed to be the same for every driver.
- Dust and dirt: Although dust is also swirled up by driving vehicles, it is not possible to test the system in common conditions, because the tunnel is not advanced in time of testing. There is no blasting and with that, there is less dust and dirt in the air.
- Equipment: All persons, drivers and people to detect, wear the usual prescribed safety equipment. It consists of boots, warning vest and a helmet.

Success Criteria

In order to evaluate every test run for success or failure simple success criteria are set. There are criteria for test runs with the prototype system activated or inactivated because the recognition of persons differs.

A test run is a success, with or without active system, if the driver or the system successfully detects one or more persons in the dangerous zone near the vehicle. In addition to that, the driver has to react in order to avoid a hazard or accident. In tests, this means bringing the vehicle to stillstand, in urgent cases with an emergency brake. Even if it was possible in some scenarios, evasive manoeuvres should not be made to not falsify the data.

If any of the above points fails, the test fails. For evaluation, data is also examined more closely. It is for example analysed whether or not the person detection was successful and whether or not the time for provoking a machine stillstand was sufficient.

4.4.4 Test Categories

When testing the prototype, not only single situations and parameter sets are tested, but also the interplay of the complete system. Drivers should run and test the designed prototype and give feedback about how the concept worked out for them. For simplicity and organisational reasons, test scenarios are divided into three different types.

Functional Tests

This kind of tests has its focus on single parameters of environmental conditions or a hazardous situation. Also reliability, usability and robustness of each single sensor and the prototype as a whole are tested in different scenarios. Another core issue is the quality of person recognition for one specific situation, as every scenario features only one parameter, like horizontal obstruction of a person or body posture or movement. Furthermore, component tests serve as a practical introduction to the system and test plan for the driver.

Situational Tests

Based on the findings from section 3.2, common working and hazardous situations in underground construction are tested under the most real conditions possible. Tests are performed as close to usual speeds when in business operation mode. Also surprise moments for drivers are included in test runs to trigger reactions. These scenarios primarily aim at testing and gathering information about the following aspects:

- Combination of optical and distance sensors
- Interplay of hardware and software
- Robustness of person detection in working situations
- Usability of the HMI
- Rating of the installation on the experimental vehicle
- Feedback of vehicle operators to implement in working situations

Reaction Tests

This test type is listed for the sake of completeness because every test is basically a reaction test. The drivers' heart rate is measured during the whole test for subsequent analysis, but is evaluated separately. These tests aim at analysing the drivers' responses in stressful situations. In fact situational tests often provoke pressure on the driver in order to trigger reactions.

4.4.5 Data Collection

For subsequent evaluation some data is gathered. This subsection provides an overview about what data is collected and how. All recording components are set up to the same time, ensuring that data is brought into a meaningful relation in order to be evaluated.

Scenario Recording

Each scenario is recorded with a built-in recorder of the “ModuleGUI“ software. With these recordings, the test run can be simulated anytime with just the processing unit. This allows for a detailed analysis of each scenario.

Video Recording

In order to capture the drivers' reactions, their HMI handling and workflows while driving, an ordinary video camera is placed inside the vehicle's cabin. This allows for a comparison with specific situations from test runs. During some runs, a camera is placed outside on the cabin with rear view permitting to record situations from the driver's perspective.

Heart Rate Measurement

The drivers heart rates are recorded throughout the entire test. This is done with a heart rate and oxygen sensor from an e-health sensor platform kit provided by Cooking Hacks[5]. The heart rate sensor was chosen over an Electrocardiogram (ECG) sensor mainly because it is easier to handle. This data is sufficient enough for analysis. The current heart rate is measured and saved every second.

The heart rate sensor is placed on the driver's index finger with additional protection, in order to prevent the sensor of falling off. This is because the right hand is used for the joystick to handle the shovel and to switch between the vehicle's forward and backward driving mode.

Distance Measurement

Detection distances of sensors are computed by “ModuleGUI“ and can be identified with data provided by scenario recording. Required data, which can not be provided by “ModuleGUI“, like the braking distance, is measured with a digital distance measuring sensor and by the distance markers placed in the tunnel. While data collected by the means of the distance measuring sensor is accurate, the markers' data may be vague but is used as little as possible. A sample usage for markers is the moment a person steps on the road outside a cavern, for example when the vehicle passes the 20 metre marker.

4.4.6 Evaluation Sheet

For better understanding in chapter 5, the structure of the used evaluation sheet is explained in this subsection. All distances measured during runs of each driver are recorded on this sheet. Furthermore, some calculations are done to gather more information about each scenario.

Data for each Driver

Table 4.4 shows an example of data measured per driver in all test runs. The distances recorded include the recognition distance and the braking distance in metres. The recognition distance is the distance from the rear of the experimental vehicle to a detected person, when the person is recognised by the system. The braking distance indicates the way the wheel loader needed for bringing the vehicle to a

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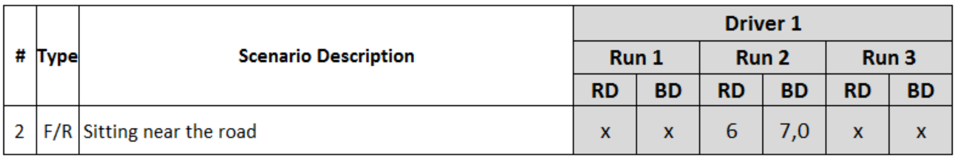
[5] https://www.cooking-hacks.com/

halt from the point of initiating the braking process. The letter “x“ indicates that this test run is not successful.

Table 4.4: Example of the evaluation sheet for each test driver and every test scenario. Legend: RD: Person recognition distance, BD: Braking distance, x: Test run failed. All distances measured in metres.

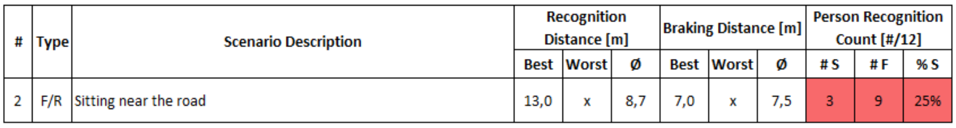


#	Type	Scenario Description	Driver 1					
			Run 1		Run 2		Run 3	
			RD	BD	RD	BD	RD	BD
2	F/R	Sitting near the road	x	x	6	7,0	x	x

Summarized Data

In order to provide a complete evaluation, data of all drivers is summarized. An example of the structure of summarized data is given in Table 4.5. Measured distances are separated in best, worst and average values. Moreover the single test runs are broken down in numbers, respecting success criteria in section 4.4.3. The letter “x“ indicates that this test run is not successful.

Table 4.5: Example of the evaluation sheet for summarized data for each scenario. Legend: x: Test run failed, S: Successful test run, F: Failed test run. All distances measured in metres.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
2	F/R	Sitting near the road	13,0	x	8,7	7,0	x	7,5	3	9	25%

5 Evaluation

In this chapter, data from all test runs is evaluated by test category. For this purpose, mainly aggregated data is used, but in some cases data close-ups from different drivers are examined. As all figures in this chapter are details from the complete evaluation sheet, the complete sheet is provided in chapter 7 in Tables 7.2 and 7.1.

It was found that test runs with an inactive person recognition system delivered nearly equal results for all drivers in all test scenarios. For this reason test sections only contain test runs with an active system. The test runs with driving on sight are covered in section 5.3.

This chapter also deals with the feedback given by drivers regarding the idea of such a system in general and the prototype system as it is integrated in the experimental vehicle. In the end, the limitations in the test scenarios are discussed.

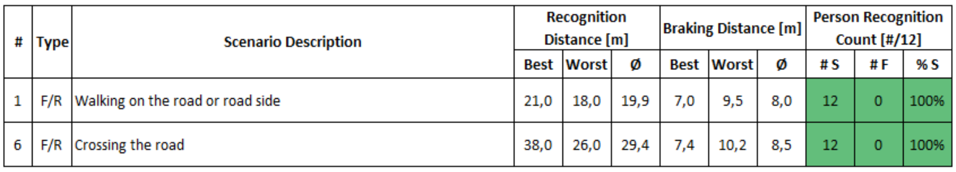
5.1 Functional Tests

This section deals with the results of functional tests for the system. Scenarios are designed for single or multiple components of the person recognition system by range as described in subsection 4.2.2. Due to the reasons stated in the same subsection, the only component which is not examined in detail is the radar sensor.

5.1.1 Persons in Motion

These scenarios are designed to introduce drivers to the system. Regarding tunnelling, these scenarios cover basically every person walking or standing in unobstructed view for the driver. Such situations are primarily suited for long-range components.

Table 5.1: Evaluation sheet for scenarios with persons in motion.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
1	F/R	Walking on the road or road side	21,0	18,0	19,9	7,0	9,5	8,0	12	0	100%
6	F/R	Crossing the road	38,0	26,0	29,4	7,4	10,2	8,5	12	0	100%

Scenarios 1 and 6

Preliminary tests on a smaller scale have shown that persons can be recognised very successful while moving. This circumstance applies in a larger scale as well.

The results of this scenarios are displayed in Table 5.1. It can be seen that person recognition was successful in all test runs.

Among the explanations is the fact that walking happens in an upright position and the fact that people are moving. A lateral position of the body to the cameras can impede, not in this all-clear situation with no obstructions.

The initial detection was deliberately in all cases by long range systems. When the area of other range systems is reached, systems also recognised the person successfully. Scenario 6 has the best average recognition distance out of all test runs, due to the circumstance that there was clear sight without any obstructions and/or occlusions.

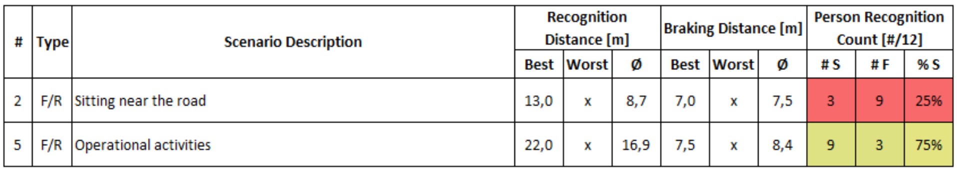
Summary

Although these scenarios are simple in their structure, the following sections will also demonstrate that movement in general, a body standing in frontal position to the camera systems and an upright posture are very important parameters for a successful person recognition.

5.1.2 Body Postures

This subsection covers the different body postures and how they are recognised by the system. Moving the body into different positions is a natural behaviour, especially when working. There is an unlimited number of possibilities, which can not be completely covered. The two situations tested reflect typical work patterns. The results are shown in Table 5.2.

Table 5.2: Evaluation sheet for scenarios with different body postures.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
2	F/R	Sitting near the road	13,0	x	8,7	7,0	x	7,5	3	9	25%
5	F/R	Operational activities	22,0	x	16,9	7,5	x	8,4	9	3	75%

Scenario 2

When a person is sitting, the application was able to recognise the person in only 3 out of 12 test runs. The person is taken for an object and is therefore not recognisable. When a detection occurred, it happened most likely in short to mid-range by the means of stereo system and ultrasound sensors. It should also be pointed out that the lidar sensor did not even recognise that there was something in the first place. It was scanning above the body, because of the low position of the person.

This scenario has the worst results in matters of person recognition out of all scenarios. The problem with such a situation is that it can happen quite frequently, maybe not exactly with a sitting but with a kneeling worker, while he connects something or picks up something for example. Kneeling or sitting person is very small compared to an upright position and can be overlooked very easily. When driving at the defined speed for test runs, stopping in time is often not possible because detection happens too late. The time to bring the vehicle to standstill in such a short distance is simply not enough, even if a person was successfully identified.

Scenario 5

This scenario has much in common with scenarios mentioned in 5.1.1. When persons are doing work patterns, like shovelling or carrying something, person recognition is more successful than in scenario 2. But it depends substantially on the work that is done. If the body of the person is turned sidewards and/or is deeply inclined, detection is harder and often not possible.

Most of the times, long and mid-range systems were able to identify the person, even if the the person was standing sideways to the camera systems. Movement while working and sometimes taking an upright body position have a positive effect on person recognition.

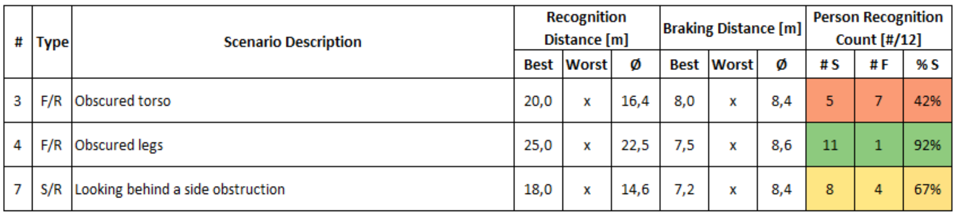
Summary

Different body positions make it harder for the system to successfully recognise persons. The results in Table 5.2 underline again that movement and straight body postures are favouring person detection.

5.1.3 Body Occlusions

Situations with body occlusions occur frequently. A person can be occluded by tools, vehicles, containers, material or similar objects. These test runs are designed for all components, as occlusions can happen at all times in every distance involving any body part. Especially scenario 7 is a common and dangerous situation, because usually the intention is to step on the driveway. Table 5.3 shows the results for each scenario.

Table 5.3: Evaluation sheet for scenarios with different body occlusions.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
3	F/R	Obscured torso	20,0	x	16,4	8,0	x	8,4	5	7	42%
4	F/R	Obscured legs	25,0	x	22,5	7,5	x	8,6	11	1	92%
7	S/R	Looking behind a side obstruction	18,0	x	14,6	7,2	x	8,4	8	4	67%

Scenario 3

In these test runs, the upper body was occluded in a way that only the legs of the body were visible. Carrying a wooden board, which is widely used on constructions sites, is an example of upper body occlusion.

The persons were moving around during the run, which facilitated for person recognition. Regardless, this situation has the worst results out of all test runs in this scenario category. As Table 5.3 shows, only 5 out of 12 runs were successful.

But there is a positive aspect as well. Although the success rate is low, detection was completed by long and mid-range components. This circumstance allowed drivers to react in time and to avoid possible hazards, if a person was recognised. Lastly, that were a lot of false detections in these test runs.

Scenario 4

This scenario involved the occlusion of the lower part of the body, like in Figure 5.1, however, person recognition was much better in comparison to scenario 3. Occlusions of this type can occur often, because there are a lot of obstructions on a construction side, which are about waist-high.

In 11 out of 12 runs person detection was successful, as displayed in Table 5.1. Identification of persons was done by long and mid- range components on an average recognition distance of 22.5 metres. This is the second best average recognition distance out of all scenarios.

The test runs in this scenario indicated that person detection can work very well with occluded people, as long as the upper body is visible for the camera systems.

Figure 5.1: Example of scenario 4 with an occlusion of the lower part of the body.

Scenario 7

The last scenario in this category covers vertical occlusions of a body, which is also a common case. Often, people are standing near vehicles, tools, containers or in caverns and there is a large possibility that they are partially covered by them.

For these test runs, the detection rate was in between the other two scenarios for occlusions with 8 successful person recognitions out of 12. The system either identified the person with long and mid- range components or not at all. It depends mainly on the actual vertical occlusion of the body. Less vertical occlusion leads to better results in person recognition at very good distances, while greater occlusion of the body could sometimes not be detected at all. The breakpoint is approximately in the middle of the body.

Figure 5.2: Test run for scenario 7 with views of the outside camera on the left and stereo system on the right.

Summary

Scenarios 3 and 4 have indicated that person detection works better when the torso is visible. Like in the scenarios before, movement had an impact, most notably when the torso is occluded. In case of vertical occlusions, the system works reliably when approximately half of the body is visible for the camera systems.

It should be highlighted that in all scenarios long and mid-range components detected persons, if a person was identified successful. This would make a big impact on braking distances in a real life situations. Furthermore, it seems that the active 3D camera and ultrasound do not get in working range, because there are no recognitions on short distances. This may be caused by the safety distance the wheel loader has to maintain to the test person.

5.2 Situational Tests

This part of the evaluation covers situational tests. In these scenarios, working situations from underground construction are tested under most real conditions possible. Scenarios are focusing on the most common operating procedures because working processes are very diverse. They are also designed for hazardous situations, mentioned in section 3.2. Therefore, all components of the person recognition system should be used. Like in section 5.1, the radar sensor will not be respected.

5.2.1 Stepping out on the Road

A situation situation involving a person suddenly stepping out on a driveway can occur in various forms in tunnelling, as well as in normal road traffic. In the following, a brief overview of such possibilities is given, in order to better understand working procedures and the environment in underground construction, which this scenario is designed for.

Introduction

In a tunnel, the space for movement is very restricted. Therefore there is not much room, if at all, for evasion manoeuvres. A complete stop of the vehicle is required in most cases to avoid a possible accident. In addition to that, there is often a short shock moment, which is directly influencing the braking distance.

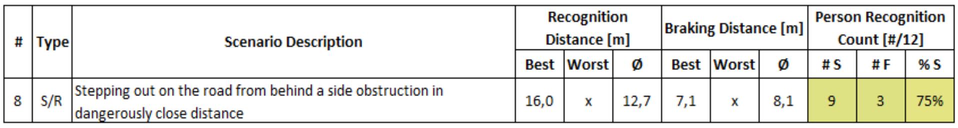
Mucking is one of the working processes featuring the hardest conditions for this type of situations. After blasting, there is a lot of dust, which produces poor sight for the drivers. While the mining personnel is moving around to prepare the next blasting, wheel loaders, dumb trucks and maybe other vehicles are driving in the area to take away broken ground from the heading face . At this point it should be noted that sight conditions while testing are far better than in usual conditions because the tunnel is not advanced during testing. There are no blastings, other vehicles or work that produce dust.

Usually every miner knows, where standing or walking is permitted and where vehicles are moving. This applies also to drivers. They usually know where people are standing or where they are headed to for the only reason of avoiding an accident. They have awareness of the situation. Most of the times accidents occur when people are at locations where they are not supposed to be or when they are not paying attention to the surroundings.

Because of this, this scenario is designed in a way that the drivers do not know when the person is stepping on the road. There are three different distances at which people walk out on the driveway. These distances are at 10, 15 and 25 metres. The drivers do not know in which test run someone is stepping on the road at which distance, or if nothing will happen. This scenario is a build-up from functional tests. There are occlusions in combination with body postures and movement. The critical factor in this scenario is the time, starting at the point in time when a person is detected by the system until vehicle standstill. When the scenario was designed it was clear that a stepping-out- distance of 10 metres may not be successful all the time.

The execution of this scenario takes place near a cavern. The test person is stepping

Table 5.4: Evaluation sheet for the scenario when a person steps out on the road out of a cavern in dangerous distance to a driving-by vehicle.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
8	S/R	Stepping out on the road from behind a side obstruction in dangerously close distance	16,0	x	12,7	7,1	x	8,1	9	3	75%

on the road when the vehicle passes markers for the defined distance. In this tunnel section, the driveway is getting wider. For security reasons, the person steps out on one road side and stays there, while the vehicle is driving as far away from the person as possible. The procedure of such a test run is illustrated in Figure 5.3 with a view from the stereo system and the thermal camera.

Figure 5.4 shows the results of scenario 8. Because of the hazard potential of such a situation, the braking distances will be examined in greater detail in the following section.

Scenario 8

Results displayed in Figure 5.4 point out 9 succeeded test runs out of 12 for this scenario. Regarding the success criteria in section 4.4.3, a test fails when an accident can not be avoided. This is the only scenario where person recognition was performed successfully back to back, but stopping the vehicle in time failed.

First, the gathered data will be split up according to different distances, at which the person stepped out on the road. Subsequently, measured braking distances and person detection distances are examined in detail for each driver.

Test runs involving 25 and 15 metres distance to the vehicle delivered perfect results. The system was able to detect the person and it was possible to bring the vehicle to standstill. As stated in subsection 5.1.3, vertical occlusions of a body can be detected very well by the system when about half of the body is visible. When the person was fully visible, the person was detected as well.

The issues brought up above also apply to a stepping-out-distance of 10 metres. Although person recognition was successful in every run, it was only possible to stop the vehicle once to avoid an accident. As pointed out in section 5.3, driving on sight in fact avoided the accident. All drivers saw the person in the moment they walked on the road, independent of the distance at which they stepped out. Halting was always possible. When driving with an active person recognition system, drivers should rely on the system to the largest possible extend. The system needs some time to clearly detect a person and to notify the driver, which causes a delay. This reduces the stopping distance too much and an accident can no longer be avoided.

A deeper look at the numbers in Table 5.5 reveals that in might in fact be just this delay that is responsible for failings in this test runs. Even though this accident

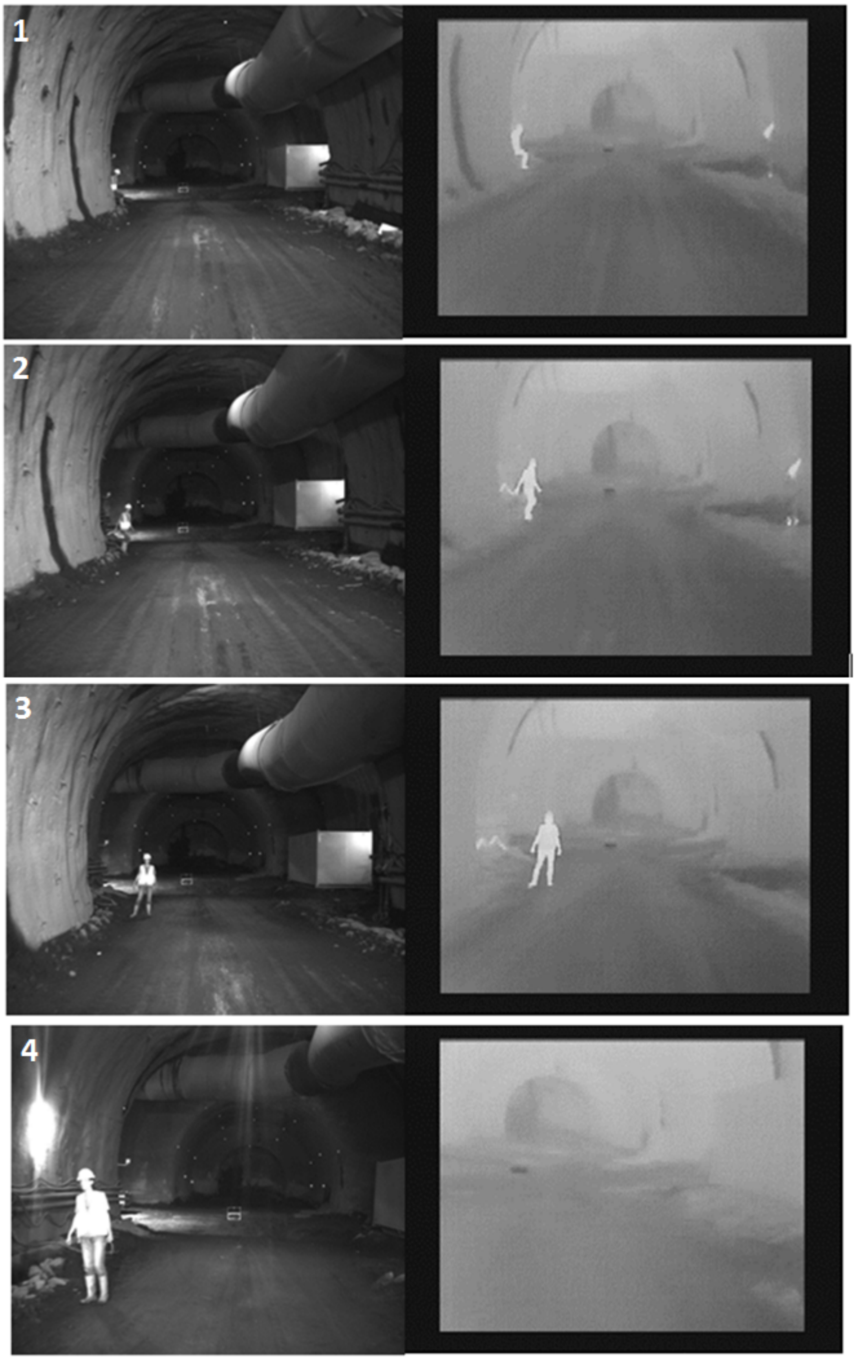
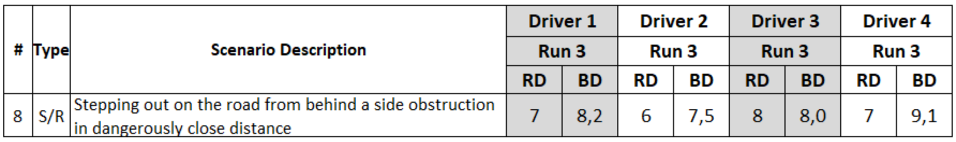


Figure 5.3: Test run process for scenario 8 (1-4). The sequence shows a person stepping out on the road, when the vehicle is 25 metres away (1) until it stops (4). The images show views from a stereo camera on the left and a thermal camera on the right side.

Table 5.5: Braking and recognition distances for test run 3 of scenario 8 for all drivers. The test person steps out on the road when the vehicle is 10 metres away.



#	Type	Scenario Description	Driver 1		Driver 2		Driver 3		Driver 4	
			Run 3		Run 3		Run 3		Run 3	
			RD	BD	RD	BD	RD	BD	RD	BD
8	S/R	Stepping out on the road from behind a side obstruction in dangerously close distance	7	8,2	6	7,5	8	8,0	7	9,1

may not have been fatal, experienced drivers would have only needed 1.2 and 1.5 metres more to completely avoid an accident, while the inexperienced driver would have needed 2.1 metres. The delay of the system cannot be measured accurately, because it depends on numerous factors of the system and the environment. Under those circumstances the delay could be narrowed down to 1 to 2 seconds. This timespan could be enough for the driver to react and stop the vehicle before a collision.

Summary

This scenario supports the results of the functional test from section 5.1. This applies especially to long and mid-range situations, but also in scenarios with shorter distances, when it was also possible to successfully detect the person in all test runs.

Tests have also shown that the system has limits. This is not true in particular in terms of person recognition, which worked properly, but for the time this process needs to enforce a decision. In this scenario for short distances, driving by sight is clearly up on driving by system in the current state, when it comes to accident avoidance.

5.2.2 Backlight Conditions

Everyone knows how it is to drive with backlight in normal road traffic. The situation is the same, but there are more lights and the lights are much stronger. An example of a usual vehicle lighting of a wheel loader is provided in subsection 3.1.1 with Figure 3.2.

Introduction

By regulation, vehicles must have vehicle lighting on, when driving in a tunnel. In case of the experimental vehicle this means, that there are respectively two spotlighs and two flood lights on the front and back, which are constantly turned on and are very strong. These lights illuminate front and back areas in a large area. There are also other vehicles, for example dump trucks and pick-up trucks. Bigger dump trucks, like the ones used at BBT, also have spot lights and flood lights on front and back. Each lamp of a vehicle lighting in normal mode is like a travelling

Figure 5.4: Test setup for scenarios 9 and 10, with a pick-up truck with turned on travelling lights as source of backlight. There is a person standing between the vehicle lights.

light for a common car. In addition, most of the time machines or working places are additionally lightened by flood lights.

Strong lighting usually causes no problems at all when the vehicle is driving by itself. The driver's sight is impacted in the presence of opposing traffic, in bigger caverns where vehicles are standing or turning and when works like mucking are done. As stated before, dust is present most of the time when a tunnel is advanced. For the driver's vision this means similar conditions like driving in fog. Driving on sight is also impeded for drivers when persons stand in backlight. Figure 5.4 demonstrates an example from a test run.

Scenarios in this category are designed for real working situations, but it should be mentioned beforehand that a driver usually will drive carefully when they see a vehicle with lighting on standing around. This commonly means that people are in this area. It was decided to use a pick-up truck with travelling lights turned on as a source of backlight, which can also be seen in Figure 5.4. To test the sensor systems, the driver is slowly driving further to the vehicle after the common stop of an initial detection.

As far as person recognition is concerned, lighting is very challenging for camera

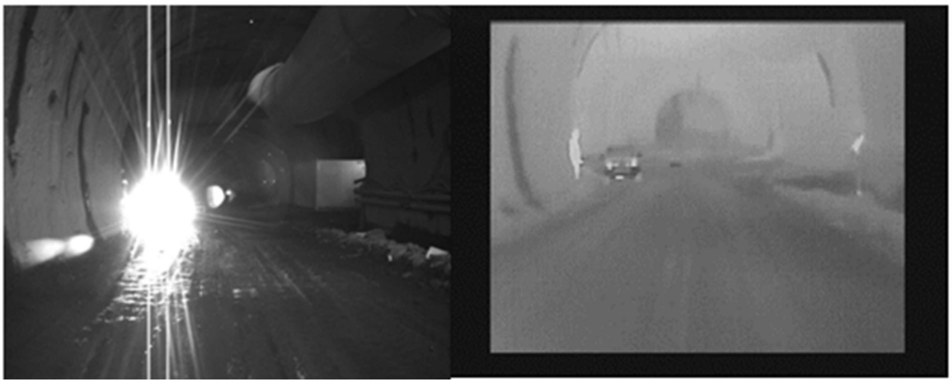
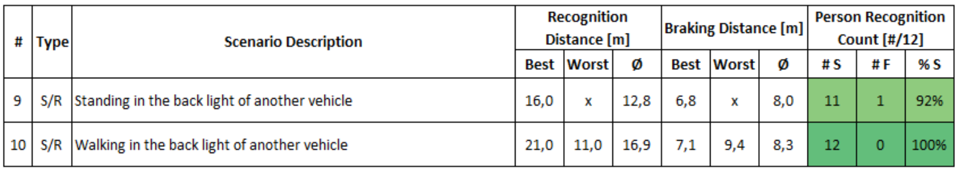


Figure 5.5: Comparison of stereo with thermal cameras for scenarios 9 and 10, where people stand in backlight of another vehicle.

Table 5.6: Evaluation sheet for scenarios when a person is in the backlight of another vehicle.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
9	S/R	Standing in the back light of another vehicle	16,0	x	12,8	6,8	x	8,0	11	1	92%
10	S/R	Walking in the back light of another vehicle	21,0	11,0	16,9	7,1	9,4	8,3	12	0	100%

systems. As mentioned before in subsection 3.1.1, stereo cameras can be affected by lighting conditions just as the human eye. But as demonstrated in Figure 5.5, this is a situation where the thermal camera comes in very handy, because it is not influenced by lighting at all. Furthermore, results of this scenarios are presented in Table 5.6.

Scenario 9

With 11 out of 12 successful runs, the person recognition system performed well in this scenario. The thermal camera in combination with lidar sensor were able to recognise the person at an average distance of 16 metres. With a distance of 5 to 8 metres to the pick-up, it was also possible for the stereo system to detect the person standing between the lights.

Although the success rate is very high, there were a lot false detections in the test runs with the stereo system. In addition to side and head lamps, there is a backlight situation which makes it even harder for stereo cameras to deliver good quality images for person recognition. When the person is standing still, even drivers were only capable of clearly identifying the person within a distance of about 20 to 25 metres, but not before.

It is not completely clear why one single test run failed. Like in other test runs, there were many false detections and the road in this specific area is very bumpy. The person was sometimes detected by single components, but not by enough components to guarantee a clear person recognition. Most likely, it was a combination of all unlucky factors playing in that caused the test run to fail.

Scenario 10

The second scenario for this category, when the test person is moving in front of vehicle lights, performed similarly. The IR camera and the lidar sensor were able again to recognise a test person on a long range. With an average recognition distance of 21 metres it scored even better than the scenario before. When the experimental vehicle was coming into the stereo system's range, it also detected the person right away. Unlike scenario 9, drivers clearly recognised a person in front of the car, because of movement of the test person in front of the pick-up truck.

Once more, many false occurrences were recorded, but the stereo system was able to detect the test person, because it was moving in front of the lights. The movement alone was not enough for the sensors, but when the person hid one of the vehicle lights with his body, recognition succeeded immediately.

Summary

The test runs in this situation made clear what was already observed before. Lighting in general causes a lot of false detections. These additional difficulties make it very challenging for the stereo system to successfully detect persons which are not moving. Even so, if there is movement in a situation, all systems are able to perform very well in this scenario.

The combination of the thermal camera with the lidar sensor has again proven its strengths. Especially in long and mid-range distances, this system works very accurately and reliably. In addition, lighting conditions in this scenario are favourable for a thermal system.

In terms of person detection with driving on sight, tests have shown that also drivers may see persons only on approachment, if the person is standing still in backlight. As pointed out in the introduction, drivers tend to operate very carefully when they are passing vehicles with lighting turned on. Nevertheless, due to good success rates in such situations, the system has proven that it can be very valuable in this type of scenario.

5.2.3 Caverns

Caverns are built while advancing a tunnel, especially when a tunnel is not very wide. They are used for different operations. Caverns in the area where advancing of the tunnel is executed, are usually used for evasive manoeuvres and turning points during mucking, but also as storage areas and as a compound site for containers. Other caverns, which are established further away from the heading face, are

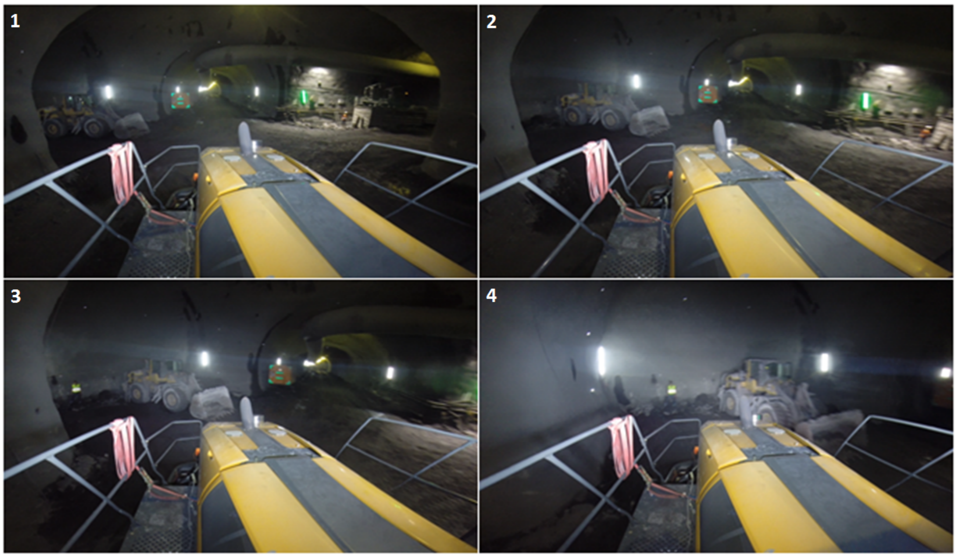


Figure 5.6: Driving into a cavern with view of the driver (1-4).

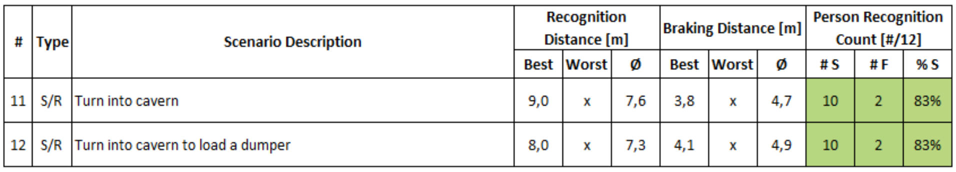
usually used as storage sites for tools and broken ground. This scenario primarily involves caverns at the heading face, in particular in relation with the process of mucking.

Introduction

The operation of mucking takes place as follows: After blasting, a wheel loader drives up to the heading face to load up excavated material. The vehicle drives backwards to the next cavern, where a dump truck is waiting with the cargo area headed towards the working face. The wheel loader performs a so called ”Y-turn”. It drives backwards into the cavern from the heading face and drives out in forward direction towards the tunnel portal in order to load the dumper. Another ”Y-turn” is performed to head back to the working face. This work is done as fast as possible. When most of the broken ground is gone, the next blast is already prepared and construction work is done, while mucking is finished. An example of a drive into a cavern is provided in Figure 5.6.

It is obvious from the figure, that a lot of things are going on during this work. While vehicles are driving around, people are also working and walking in the area. As this work is done after blasting, there is a high dust concentration and bad sight for all miners. Loading and unloading excavated material is very loud and causes dust in specific areas. Overall, there are a lot of danger zones, but under normal circumstances everyone knows where these are and people stay out of them. But many accidents happen when someone is at a location where he is not supposed to be. Caverns are particularly dangerous, because the driver is not able to look around the corner when driving there usually very fast. Moreover, due to the lack of space, drivers often back up until the fender of the wheel loader hits the back

Table 5.7: Evaluation sheet for scenarios when the vehicle drives backwards into a cavern.



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
11	S/R	Turn into cavern	9,0	x	7,6	3,8	x	4,7	10	2	83%
12	S/R	Turn into cavern to load a dumper	8,0	x	7,3	4,1	x	4,9	10	2	83%

wall of a cavern. This makes accidents in many cases fatal.

All test runs are executed in the area at the beginning of the exploration tunnel, shown in Figure 4.7. There is enough room for accelerating the vehicle and a cavern with about 11 metres depth. Both scenarios in this category basically have the same structure, performing a turn back into a cavern. The difference between them is that in one scenario a mucking operation is simulated. That means that the wheel loader's shovel is loaded. This brings more weight to the front of the vehicle, which causes the wheel loader to swing and slip more. However, only the drive into the cavern will be performed in the context of the scenario, because this is the only relevant part for person recognition. For security reasons, all drivers are instructed to drive into the cavern as fast as possible, but at a speed that allows them to halt before they reach the back wall. This is necessary, because it is not possible to work with a dummy and a test person has to stand at the back of the cavern.

Because of a cavern depth of 11 metres, a reasonable use of the thermal camera is not possible. This is the only test in which cameras need to deal with a horizontal movement. Therefore, motion blur is more likely to happen, which has negative effects on person recognition. As the vehicle turns into the cavern, the person comes into camera vision very late. An example of the view of a stereo camera can be seen in Figure 5.7. The time frame for successful person recognition and for stopping the wheel loader is very small compared to other scenarios. The results for this scenarios are shown in Table 5.7.

Scenario 11

Test runs were successful in 10 out of 12 runs, which is displayed in Table 5.7. In all successful test runs, person detection was performed at a distance between 7 and 9 metres to the test persons. That means that recognition was able nearly at the same time the test person came into camera vision. Because the vehicle drives slower than in other scenarios, the braking distance is also shorter. As displayed in Figure 5.7, motion blur did not cause problems at the driven speeds. It should also be mentioned that there were hardly any false detections in these test runs. This is due to the fact that there were no other light sources beside the vehicle's.

It is nearly impossible to do each test run at the same speed in this scenario. Therefore a variation in speed cannot be completely avoided. According to their own

Figure 5.7: Driving into a cavern with view of a stereo camera. The person comes into camera vision at a distance of 9 metres (1-4).

statements, drivers who drove faster failed the test runs. Driving faster also makes the vehicle slip and bounce more, which may be the main reason for failed person recognitions.

Scenario 12

Test runs with a loaded shovel did not show any noticeable differences in terms of person recognition compared to scenario 11. Due to the higher weight of the vehicle, the braking distance tends to be slightly higher, which can be seen in Table 7.2. The tests have also proven that at least at this vehicle speeds, it makes no difference if the wheel loader is loaded or not.

Summary

One of the main outcomes from these scenarios is that a horizontal movement for the cameras is not much of a problem, as was expected before. Motion blur occurs, but only to a very low degree. Stereo cameras, lidar and ultrasound sensors performed very well together, but too high speed can be a problem for person recognition. Drivers stated, that they were driving into the cavern with 60 to 70 percent of their usual speed. As caverns in the tube are usually less deep and vehicles are driving in faster, the time for person detection and halting the vehicle is also shorter. Moreover it was confirmed that lights are mostly responsible for the high number of false detections.

5.2.4 Ramps

For these scenarios it was not possible to gather significant data for a detailed evaluation. At BBT, no ramp with enough length and slope could be found to meet the needed criteria required for a meaningful test run. However, test runs were performed with given possibilities and tests for driving up a ramp where executed.

Introduction

Ramps or ramp situations can be built everywhere in underground construction. A usual place for such slopes are intermediate storages for broken ground. Depending on the place in a tunnel, they vary in size and height. They are built by driving up the ramp and unloading material, which causes the slope.

For the person recognition system used, there are two scenarios that have high hazard potential. Figure 3.7 demonstrates both situations. Both situations occur when entering or leaving a ramp. In either case, the problem is a blind spot caused by the slope. A person standing in a hazardous area may not be visible to the driver and any component of the person detection system and can therefore not be recognised.

Scenario 13

Test runs have shown that person recognition is possible like in other scenarios, if the person is in vision of the cameras. In this case, the whole ramp was in vision

Figure 5.8: Test run for driving up a ramp, with view of a stereo camera.

all the time, like shown in Figure 5.8. The vision was never obstructed, even when the wheel loader was entering the ramp. As soon as a person got within the range of person detection, it was recognised.

As the system uses a 2D-lidar sensor, this was the only component not be able to detect the person, until the vehicle completely entered the ramp. This sensor is only scanning at one height. While the vehicle has not entered the ramp completely, this sensor constantly scans the ground.

Summary

Although it was not possible to make tests in real ramp situations, it was found that person recognition works as usual if a person is in vision for sensors. It should also be pointed out, that entering and leaving a ramp, where the wheel loader gets a small hit and bounces when driving at appropriate speed, does not impact person detection. But the lidar sensor is not working until the vehicle entered the ramp completely.

5.2.5 Tunnel Portals

It was decided not to run this tests as intended. The reasons behind this are safety issues. Components were getting within person recognition range very late and the test person was exposed to the hazardous area, while vision for the driver was also very bad.

It was possible to gather data for this scenarios but a detailed evaluation cannot be done because there is too little data available. This applies in particular to scenario 15, driving into a tunnel. Usually, wheel loaders do not drive in and out of a tunnel frequently, but dump trucks and other vehicles do and this is why such situations are also tested. In general, these scenarios leave many questions unanswered and further testing with different conditions can generate more significant data to examine.

Introduction

The area around a tunnel portal often serves as storage site and parking area. This applies to the outside and inside areas of a tunnel portal. It therefore can be the case that people are working or walking in this zone. Measured on the basis of vision for drivers and cameras system, driving into a tunnel is the situation with the highest hazard potential, because of changing lighting conditions, especially in the daytime.

Both scenarios take place at the tunnel portal of the excavation tunnel to Padastertal. This portal is not lit up very well in comparison with the main entry portal, which makes person detection more challenging. The difficult part for the person recognition system for these scenarios is the change of lighting conditions during daytime. They cause a short blindness for vehicle operators and the stereo system as well. A bad lightened tunnel portal during daytime, is probably the worst case, because human eyes and the camera need more time to adjust.

Scenario 15

Test runs have confirmed that driving into a tunnel is a risky situation. In order to obtain significant evaluation data, the test person needs to be in a danger zone, right after the entry point of the tunnel. Because of the high safety risk it was decided not to run this tests as intended. Nevertheless, some functional test at a slow speed were done instead and observations will be discussed in detail in the following.

Figure 5.9 demonstrates the view from stereo and thermal cameras, shortly before the vehicle enters the tunnel, but with the person standing more far away from the portal. As it can be seen in the image provided by the stereo system, the entry point is like a black wall, only a few lights in the background can be recognised. The driver's view is very similar. It is hardly possible to see if there is something in the near area in the tunnel, despite strong vehicle lighting and the test person wearing a warning vest. Images delivered by the thermal camera are very good, as this system is not influenced by lighting.

Figure 5.9: Test run for driving into a tunnel, with views from a stereo system on the left and thermal camera on the right. The person is approximately 30 metres away.

Under these conditions, distance is influencing person recognition more than in other scenarios. In addition, vehicles typically enter a tunnel at a higher speed than the speed used in these scenarios. Mid and short range systems do not get within the range for a detection, or only get in range, when it is too late to avoid an accident. The thermal camera delivers good images to the HMI and the lidar sensor makes detections as well, but components get within the range of person recognition very late. A reliable person recognition can not be done with the current state of the system under these conditions.

However, functional tests with different speeds revealed that all components work as intended only a few metres after the vehicle entered the tunnel. Stereo cameras have adjusted their vision at this point and are able to identify people. Observations have also shown that the driven speed has no noticeable impact on the time the camera needs to adjust its vision.

Scenario 16

Driving out a tunnel is no problem at all. The vision of the drivers and sensors is not influenced by changing lighting conditions from dark to bright. Person recognition works like in other scenarios.

Summary

Test runs have shown that person recognition is not reliable and hardly possible when lighting conditions change from bright to dark, like when entering a tunnel. Components do not get within the range of person recognition or get in range too late. But images provided to the HMI by the IR camera can assist the driver in such situations. Lighting changes from dark to bright on the other hand are working just as planned.

5.3 Reaction Tests

This section covers everything that might influence a driver's reaction. Apart from that, driving with and without the system will get a closer look. To that end, interviews were made with drivers after test runs.

First, an overview of general behaviours while running test scenarios is given. Then, measured heart rates are examined. This section concludes with a look into braking distances, because they are influenced by the driver's reaction.

5.3.1 Driver Reactions and Behaviour

First it should be stated that there was nearly no difference between experienced and unexperienced drivers, where ”unexperienced” means in terms of underground construction and not in driving a wheel loader. From an observational point of view it can be stated, the unexperienced driver ran the tests more cautiously but at the same speed and under the same conditions as experienced miners. This driver said that this was due to the fact that he had almost no know-how in driving a wheel loader in underground construction sites, which seems reasonable. Furthermore, there are no outliers in evaluation results that would suggest that a test has failed because of inexperience. Heart rate measurings, explored in detail in subsection 5.3.2, do not give information for differences on performings between experienced and inexperienced vehicle operators either. However, a slightly longer average braking distance compared to experienced drivers could be measured, which will be explored in subsection 5.3.3. Due to the circumstances mentioned above, the factor ”experience” will be neglected in this part of the evaluation.

Because of the nature of the test runs, drivers are know that something will happen. However, the premise was to make the tests as surprising as possible when the scenario conditions allowed it and as long as safety was ensured. When driving with the person recognition system activated, drivers were instructed to rely on the system as much as possible and not on driving on sight. That means that a driver himself may see a person stepping on the road, but he will not do anything until the system clearly detects the person or there is an imminent danger. In interviews, the drivers stated a few issues, which are essential to avoid accidents. Those are as follows:

- Calm and careful driving
- Permanent environment monitoring
- Knowing the positions of other miners, especially near the vehicle and while mucking
- Knowing the placement of caverns and other obstructions
- Immediate switching to brake-ready driving on conspicuities

These points were the essential issues that could be observed during test runs. All drivers were aware of the situation at all times. When driving on sight, persons were recognised immediately at all times. The only exception is scenario 15, entering a tunnel. Therefore danger situations did not even occur and accidents were avoided. Especially in scenario 8, stepping out on the road from behind a side obstruction, was handled very well by driving on sight. With a controlled emergency brake, drivers always stopped the wheel loader in time. Very noticeable is the fact that this happened very carefully and as mentioned in subsection 5.3.2, without any signs of shock. All this suggests that all drivers knew exactly what to do and how they have to work with their equipment in these conditions.

Running tests with an active person recognition system has only one major aspect worth mentioned. With the problem of false detections, notifications for detected persons changed a lot on the HMI. As the drivers were asked to rely as much as possible on the system, this means that there were moments where the driver was uncertain if a person was recognised correctly. Especially for scenarios, which are favouring the IR camera, a detection may be possible in a long range and therefore can be a correct identification. Because of the problem with false detections, it was observed that drivers were very alert and cautious while driving. When the HMI communicated a detection, regardless if correct or not, all drivers took the foot off the accelerator, let the vehicle roll and went in brake- ready mode. This is a long learned behaviour which demonstrates foresight and aware driving.

5.3.2 Heart Rate

The evaluation of this part will be simplified, due to the fact that no major distinctive feature could be found. The heart rate was measured during all test runs for each driver. This includes driving with and without the person recognition system activated in all scenarios. The goal was to investigate how drivers react in certain situations, to find out if shock moments occur in specific scenarios and how the drivers handle test runs in general.

It could be clearly detected that all drivers were calm during testing. As Figure 5.10 shows, there were no peaks or indicators in measurings that would suggest nervousness, panickiness or uncertainty. Recordings do not show any shock moments either. Measurings for each driver show a usual heart rate progress in their frequency over the whole time the test runs lasted.

Results from heart measurings strengthen the points mentioned in subsection 5.3.1. Drivers stayed calm during performing test runs and were not disconcerted easily. They always expected something to happen and were therefore driving with a lot foresight and awareness to be prepared for the unexpected.

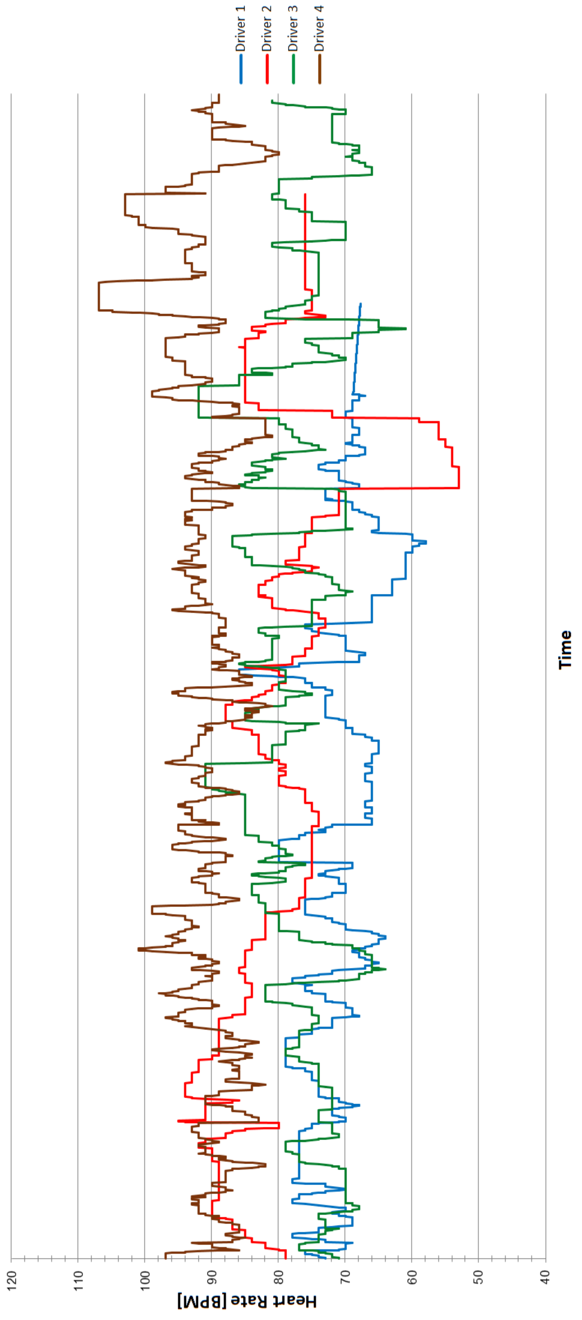


Figure 5.10: Heart rate measurings of all drivers during all test runs.

5.3.3 Braking Distances

Table 7.1 and 7.2 point out that average braking distances in general are very short. Experienced and unexperienced drivers stop the vehicle under any circumstances in a very controlled and fast manner, with an emergency brake if necessary. This is in particular true in scenario 8, when a person walks on the road unexpectedly, at a distance of 10 metres without a person detection system being activated. Cases with an active person recognition system indicate that initiating the braking process takes longer than without system active. Consultation with drivers revealed that this happens because of the delay, which is caused by the process of person recognition. As instructed, they wait until a person is clearly identified by the system, even if they have already seen the test person.

There is no noticeable variation in braking distances overall, but it could be noted that braking distances of the unexperienced driver are sometimes slightly longer. This results most likely from the fact that the driver lacks experience in driving a wheel loader under the given circumstances. Moreover, experienced drivers stated that they may be able to stop the vehicle within an even shorter distance in emergency situations and when they are allowed to make evasive manoeuvres. Therefore, the difference in braking distances between experienced and inexperienced drivers might be even more substantial, because of varying degree of expert knowledge.

5.4 Driver Feedback

This section deals with the feedback given by drivers after test scenarios were run. The feedback was given in the form of a questionnaire. The answers of all drivers are summarised in subsection 5.4.1. Ideas for improvement and weaknesses of the system, in particular the HMI, were also discussed and will be explored in subsection 5.4.2.

5.4.1 Assistance System

Every person was separately interviewed directly after the test runs. Before launching an open discussion about the topic, a questionnaire with ten questions was completed. In the following section, the statements of all drivers are summarized.

1. What are positive aspects of the system?

All drivers stated that the idea to design and introduce a person detection system is a good way to go. The system in its current state does have faults, but it would support work very well. They also mentioned that they would like to work with a person recognition system. Another point stated by all respondents, was the simplicity of the HMI.

2. What are negative aspects of the system?

All operators mentioned that driving backwards by vision is a hard task, because the monitor is installed in the front but the driver is looking over his shoulder most of the time. An improvisation for test runs may be acceptable, but for a possible real-life operation this is absolutely not satisfying. Also, the monitor should be built in directly into vehicle consoles, since every information is usually provided there. Another issue brought up by all drivers, is the number of false detections. Without this problem solved, none of the drivers would rely on the system and would prefer driving by sight. One driver criticised the delay of the video stream. Ideas for improvement were also given and will be explored in greater detail in question 6.

3. Is driving better with a person recognition system or by vision?

It was said that driving by vision is currently common practice, because no such system is usually built in by default. Some vehicles, especially dump-trucks, have reverse cameras, but person detection would help a lot in specific situations. Drivers agree that a mix of both is the way to go. There are some situations, in which this system would be very helpful. Examples are a driving off while mucking because of the bad sight and entering a cavern or tunnel portal for better overview. One driver proposed special functionality for certain scenarios, like a panorama image when driving off.

4. Do you feel you can rely on the system?

In its current state, no one would completely rely on the system mostly because of false detections, which make it hard for the operator to rate a situation. Misjudgement is a possible result of this behaviour, which can lead to accidents. Therefore driving by vision is prefered by all drivers, when it comes to driving in the tunnel. But also all drivers mentioned that they would use it for drive off, in order to get an additional overview.

5. How helpful was the person recognition system?

All miners saw the biggest benefit of person detection in poorly visible areas, blind spots and in situations with bad vision. Two drivers mentioned the positive aspect of a reverse camera, which is a very important tool and used frequently when already built in. Although there is a delay in the current system state, it helped when driving off and moving in poor visibility areas. In addition to that, all drivers agreed that it helped a lot that the HMI was easy to use.

6. How can the system be improved?

A few points were already mentioned in questions before. The following list is a compilation of the most important ideas for improvements, mentioned by one or more drivers:

- Driving backwards: Information must be accessible for the driver when looking over his shoulder while travelling in reverse.
- False detections: The number of occurrences needs to be reduced in order to increase the system reliability.
- HMI: This point will be explained in subsection 5.4.2.
- Live stream delay: Must be minimised as much as possible.
- Reverse camera: The system should be useable as reverse camera.
- System integration: The whole system needs to be integrated to the vehicle, because of working conditions in tunnelling.
- System crashes: Drivers understand that this can happen with a prototype system. This issue shall be examined in greater detail in section 5.5

7. What are weaknesses of the system?

Drivers mentioned all points stated in question 6.

8. Would such a system help in everyday situations?

All drivers agreed that this is the case. The person detection system helps especially to get an overview of the current situation. The possibility to recognise persons is an essential safety aspect. In addition to that, two drivers also brought up what was already said in question 3: Such a system would be most beneficial when driving off or when entering areas with bad sight, and in situations with dusty conditions.

9. Can you think of situations that would be handled differently with a person recognition system instead of driving by vision?

Three drivers mentioned mucking as a potential scenario, due to bad sight and danger potential. A turn into a cavern before loading a dump truck was mentioned by one person, while all agreed that driving off is the most likely situation.

10. Are there any situations in which the system did not help at all?

No driver could think of a situation, in which the person detection system is completely ”useless”. All positive and negative points mentioned in questions above indicate that the system has room for improvement, but is suited to assist vehicle operators at any time.

5.4.2 HMI-Interface

After the questionnaire an open discussion about the HMI was done with each driver. Strengths, weaknesses and potential improvements should be found out. In the following statements of all drivers are summarized.

Live Stream

Two drivers did not consider the live stream feature to be absolutely indispensable for person recognition, although it allows for better view due to the presence of a rear camera. Other options for HMI structure are mentioned in the next point.

All drivers agreed that the delay in the live stream was not that bad, but should be minimised as much as possible. The main reason is that a delay can make the difference between an almost-accident and an accident, as was shown in scenario 8 in section 5.2.1.

Positioning and Notifications

As already stated in section 5.4, one of the main problems is driving backwards, because the driver is not looking forward, where the HMI is located. Several approaches are mentioned. The main focus lies on a console integration for the monitor in combination with colour indicators on different spots in the cabin for notifications. Colours indicate in traffic-light-stlye if there is a person or not. Indicating the distance to detected persons is not mandatory, because in most situations a warning would be enough. Installation spots recommended by the drivers are the bottom area of the front area and side posts on the back. Positioning of indicators is argued by the drivers as follows: When driving forward, the focus is on the shovel, which is located in the bottom area from the view of the driver most of the time. When travelling in reverse, drivers check the area around the vehicle and then drive back by looking over one shoulder. In both cases, indicators would be in the drivers' field of vision.

Acoustic Signals

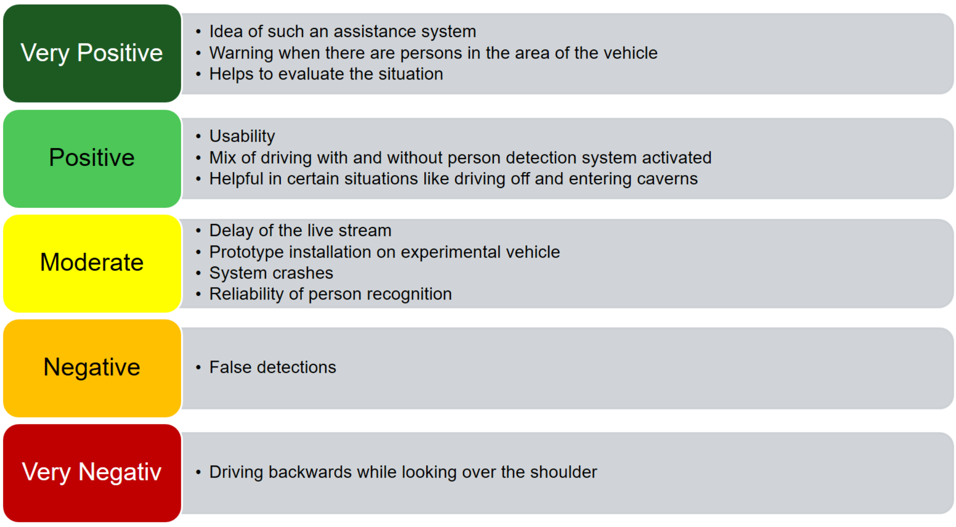
This point was addressed separately by one of the drivers, because he would find it helpful. However, the acoustic signal has to be different and unique among all the other sounds the vehicle can make. Other drivers see acoustic signals critical and consider them disturbing. They also point out that noises on a construction site are very loud most of the time. Often, such signals cannot be heard because of that and are ignored at some point. It is also possible that workersrely on such a signal and are less attentive as a consequence.

5.4.3 Summary

Discussions with the drivers revealed some interesting points. The idea of a person recognition system was well received and rated as useful by drivers. It is clear that a prototype system needs some improvements to be able to work properly, but it should also be designed in a way that operators want to work with it. Otherwise, it would not be used. It was stated that a mix of driving by sight and by system would be a good way to go. It might also help if such a system had some special functionality for situations where assistance is needed the most. Table 5.8 shows a summary of all points mentioned in the questionnaire.

The structure of HMI was satisfying for the prototype. As the main points of improvement a complete integration in the vehicle's console and colour indicators on the front window and side posts of the vehicle cabin were mentioned. With such an installation everything needed would be in the field of vision for the driver. It was also pointed out that a reverse camera would definitely be a nice thing to have, but

Table 5.8: Overview of points mentioned as feedback from drivers about the person detection system.



Very Positive	• Idea of such an assistance system • Warning when there are persons in the area of the vehicle • Helps to evaluate the situation
Positive	• Usability • Mix of driving with and without person detection system activated • Helpful in certain situations like driving off and entering caverns
Moderate	• Delay of the live stream • Prototype installation on experimental vehicle • System crashes • Reliability of person recognition
Negative	• False detections
Very Negativ	• Driving backwards while looking over the shoulder

also that it is not necessarily needed for warnings when persons are in proximity of a vehicle. Acoustic signals for a person detection can be an option, but as stated by drivers, this is an addition to the suggestion mentioned above.

5.5 Prototype System

In this section, single components and combinations of sensors are discussed. Information of sensors were gathered in preliminary tests and final tests at BBT. Prototype setup and installation are evaluated and how the used constellation worked out in underground conditions. Finally, test results for person recognition are evaluated and ideas for improvement are explained from the drivers' perspective and from observations made during testing.

At this point it should be highlighted that the focus of this work lies in the evaluation of the complete prototype and its service for person recognition and safety in underground construction and not in providing a detailed evaluation of single components of this system or person recognition algorithms. These aspects are covered by other project partners that worked on this project.

5.5.1 Cameras

Cameras provide images used in person detection algorithms for different ranges as explained in subsection 4.2.2. In the following, overall and situation-specific performances of each vision sensor are discussed.

IR Camera

Most scenarios in final tests are designed for long and mid-range person detections. Therefore, thermal and stereo cameras are mainly responsible for providing images for person recognition. The thermal camera has done a very good job. Often, person recognition was possible on very long distances. Another positive feature is the insensitivity to light, which is very helpful in scenarios with backlight and a lot of light. This is the reason why in such situations, person identification was possible for middle and long ranges. Thermal camera and lidar sensor are working together very well and are a strong, reliable combination for middle and long range person recognition. Furthermore it can be confirmed that this system is very robust against the underground environment. There are no signs that the camera delivered bad images because of dust or dirt.

Apart from the high cost of a thermal camera, there are a few other downsides as well. Low resolution limits the area of vision, which can be a problem if the distance between sensor and person gets shorter. This is not a huge problem, as the stereo system is closing this gap. Another thing is that long operation time can cause blindness. This happens due to the operation mode of an IR system by adapting its temperature to outer temperatures. During final tests, only a slight worsening in image quality has been experienced, but the system only was in service for a day at once.

Stereo Camera System

The main job of this system is to cover areas in ranges between the IR camera and the active 3D camera. Furthermore, images from stereo cameras were shown in the live stream on the HMI. In general, a high number of person recognitions occurred in the range of this camera system. In most scenarios, it delivered good images to person detection algorithms. Motion blur, which can be a problem with systems like that, was no problem at all, which proves that not using a RGB camera was the right decision. Environmental conditions did not influence this system at all because it was kept in a protection case.

Tests have also shown that there are certain situations which reveal some negative aspects of this system. The worst case for this component are situations with backlight, followed by scenarios with a lot of light in general. This gap can be closed by the thermal camera because of its immunity to light effects, if the distance is not too short. Overall, the system performed very well in most situations and can be used as a reverse camera.

Active 3D Camera

Test runs in BBT have not used this camera very much and most results for evaluating this component have been provided by preliminary tests. Often, this system was not challenged at all, because thermal and especially stereo cameras already have recognised a person and therefore the vehicle was stopped. This is a good thing in most cases, but also showed that at the tests in BBT did not challenge the system enough in areas in proximity to the vehicle. Though, it performed very well in combination with ultrasound distance sensors (as planned), when persons were close to the vehicle, in particular during preliminary tests. Dust, dirt and other environmental influences had no impact on this camera. It was also kept in a protection case like the stereo system.

It has to be stated however, that an active 3D system in combination with ultrasound sensors is used exclusively in situations involving manoeuvres that affect the immediate surroundings of the vehicle, such as parking, driving off as well as in situations with poor driver vision and in order to cover blind spots. As operators mentioned, driving off is a situation in which such a system could offer much assistance. Furthermore, blind spots are usually located in the immediate surroundings of a wheel loader. All these reasons make it a requirement to use a short range system, even if there were not many situations in final tests needing it.

5.5.2 Distance Sensors

Distance sensors have an assisting role for person recognition. Apart from the stereo system, no other camera is able to provide distance information. Only in combination with fused data from cameras and distance sensors person detection is possible.

Lidar

This sensor is a very powerful tool. It works very accurately and reliably and helped a lot in person detection in nearly every situation. With its very wide range covering the point of installation up to 30 metres in a circle, the sensor covers the largest area out of all distance and camera sensors. It is helpful in short distance situations but excells in mid to long range scenarios in combination with thermal and stereo cameras.

As the component is installed outdoors without any further protection, it was suspected that it will be heavily impacted by dust and dirt. Apart from that, lidar sensors are not very robust against outer influences.This was, however, not case, at least not in the conditions it was tested. After four days of driving, the sensor still worked as intended. While most dust is caused on vehicles back and therefore directly hits all sensors, not the same conditions are given while testing because no advancing of the tunnel was done during the test runs. Therefore, environmental conditions are not the same as in real life. in order to examine outer influences on this sensor, further tests in live working environments are needed.

One of negative aspects of this component is its price, which is very high. Due to the fact that this model scans in only one dimension and not in 3D, is not very well suited for situations involving ramps. Another problem might be that this sensor is installed in a height of approximately 1.20 metres. It basically does not cover anything that is located below this level, which can be a person kneeling or sitting behind the vehicle in a worst-case scenario. The last point worth noting is that this sensor gets very warm as the operation time advances. Sometimes it had to be plugged out for a few minutes to cool down.

Radar

Like already mentioned in section 4.2.2, this sensors caused a lot of false occurrences during preliminary tests. It is unclear if these are generated by the radar model used, in underground construction in general or by the software implementation. However, until final testing, the problem remains unchanged as well as in preliminary tests. It was tried to improve the situation from the software perspective, but as no solution could be found it was decided not to use this sensor in final test runs at BBT in order to not falsify data.

A radar sensor can be a valuable asset for a person detection system. As stated in 2.4, it has already successfully entered into operation, albeit not for person detection itself. Hence, there is a solution to bypass this problem. With the given resources, it was not possible to do more testing or development in this area.

Ultrasound

Because no proper components were found on the market, this sensors were self-built in order to resist the environment on tunnel construction sites. Ultrasound is working very well with the active 3D camera, as both have the same short operating range.

Like the active 3D system, this distance sensor could not show its full potential in tests at BBT. In preliminary tests, results were very promising. The sensors worked reliably most of the time, too. The issues mentioned about operational areas for the active 3D system in section 5.5.1, apply to this system as well. The system's strengths lie in covering blind spots in close proximity to the vehicle and when driving off, which are the main reasons why this component is a must-have.

5.5.3 System Setup

Based on observations and driver feedback, the installation of the person recognition system was all right for a prototype system. There was enough space to place all components on the vehicle, without influencing the vehicle's infrastructure or working processes during test runs. It was also possible to quickly install and uninstall the whole system on the experimental vehicle. It was also a good decision to place all sensors on the vehicle's back instead near the vehicle's center. As test results show, most person detections occurred in a range of approximately 10 to 20 metres. By placing sensors more in the middle of the experimental vehicle, at least 5 to 7 metres would have been lost.

There are some downsides regarding the hardware platform placement. A vehicle's balance weight is a good location to place it, but the heat output of the hardware itself and of the engine is very high. Most workstation system crashes can be traced back to overheating. The temperature of other hardware placed there, like UPS and switches, was also very high most of the time. Furthermore, the dust concentration in the wheel loaders balance weight was extremely high, though there was some protection for this. Longer time in service may result in broken components because of dust and heat. Protection against vibrations and kicks due to road conditions can also be improved.

If further testing in this prototype constellation should be done, an idea for improvement is a closable console for the entire hardware platform, which can be directly placed in the balance weight. This would result in better protection for hardware against kicks and dust as as against heat from the engine. Also, additional ventilation can be built in in order to channel warm air away from the components. The second solution would be to find a complete new location for hardware components.

5.5.4 Environmental Conditions

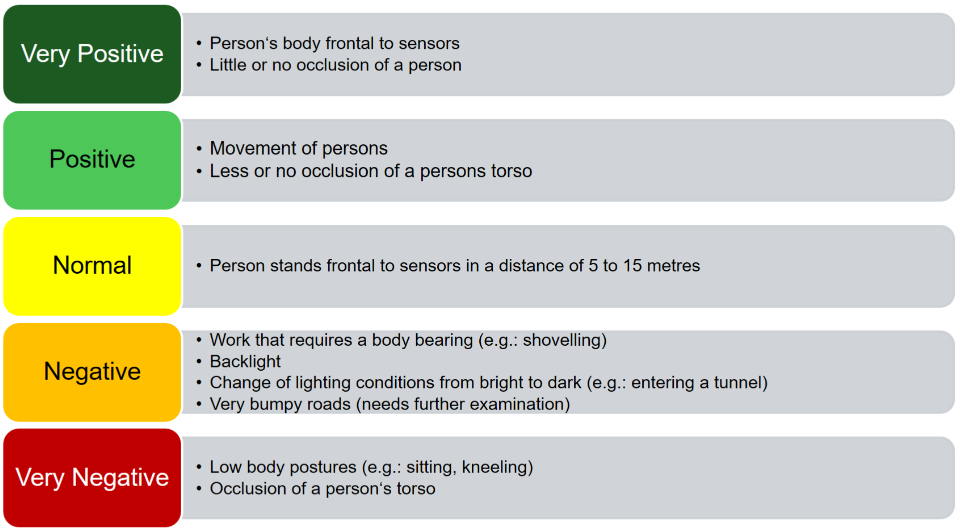
Two things should be stated with respect to environmental conditions. As already mentioned, no advancing of the tunnel was done during testing. Therefore, dust concentration was at its minimum level for testing in BBT. During testing, no worsening of person recognition because of dust could be observed, testing taking only place over the course of four days, however, without blasting happening. In order to find out how the system is working in real life, further tests need to be executed.

Road conditions is another factor that needs to be discussed. During preliminary testing, the road surface was usually very flat and only a little bit bumpy. This was different at BBT. Roads were very bumpy, like expected on a construction site. There is not enough data available in order to make a clear statement, but road conditions may have a bigger influence on person recognition than assumed. To get things straight concerning the impact on person detection, much more testing and investigation is necessary.

5.5.5 Person Recognition

Figure 7.1 shows all test results. In total, there were 144 possibilities for successful tests in all test runs including all drivers. Out of that, test runs were successful 112 times and failed 32 times. Hence, the overall success rate is 78%. Table 5.9 lists situations and circumstances that either facilitate person recognition or make it harder. Rating is based on a common best case, when a person is standing frontal to sensors in a distance of 5 to 15 metres. This statements are based on test results and observations from BBT.

Table 5.9: Situations and circumstances that either help person recognition or make it harder.



Very Positive	• Person's body frontal to sensors • Little or no occlusion of a person
Positive	• Movement of persons • Less or no occlusion of a persons torso
Normal	• Person stands frontal to sensors in a distance of 5 to 15 metres
Negative	• Work that requires a body bearing (e.g.: shovelling) • Backlight • Change of lighting conditions from bright to dark (e.g.: entering a tunnel) • Very bumpy roads (needs further examination)
Very Negative	• Low body postures (e.g.: sitting, kneeling) • Occlusion of a person's torso

6 Conclusions

This work was carried out with the object of finding out if real time person recognition in underground construction is possible. This could help improve the overall safety on construction sites and in specific situations with high accident risk. For this purpose a prototype system with multiple cameras, distance sensors, hardware platform and HMI was installed on a wheel loader. A test plan was designed and executed under the most real conditions possible.

Results showed, that person detection in underground conditions is possible, but there is also a lot room for improvement. The system gives good support in situations with a high accident risk such as entering caverns, driving off and when the sight is bad. It was also shown that person recognition works very situational. A person which is standing upright, frontal to sensors is more likely to be detected than a person sitting or kneeling. Movement in general helps to detect persons as well. An occlusion of the torso makes it much harder for the system to identify people, while an occlusion of legs does not have a big impact. Furthermore, backlight and a low position of the person's body also hinder person recognition. Usability for drivers was good for a prototype, as well as reliability on person detection.

While performing test runs it was observed that drivers are handling the wheel loader very cautiously, calmly and carefully, even when driving at high speeds. They are aware that accidents can happen at any time. They are monitoring the environment and know where obstructions can happen and where other miners are located. If a situation gets conspicuous they switch to brake-ready driving immediately or initiate an emergency break if necessary. As heart rate monitoring has shown, there was no moments of shock in any test run, which confirms points mentioned above. This is in particular true when driving on vision, like drivers currently operate, but also with person recognition system active.

Most times, the person recognition system was able to detect people at longer distances and an emergency brake was not needed since the vehicle was stopped as fast and controlled as possible. However, for the defined test run speed of 25 km/h, the stopping distances are very short. In most test scenarios, halting may be possible even at a higher vehicle speed. It remains questionable if sensors are still able to provide good data for person recognition algorithms at significant higher speeds, because the wheel loader will bounce a lot more. Some outline tests performed at higher speeds have shown that it is very situational if tests succeed or not. There is a tendency, that person detection fails more often at speeds exceeding 30 km/h in the current state of the system.

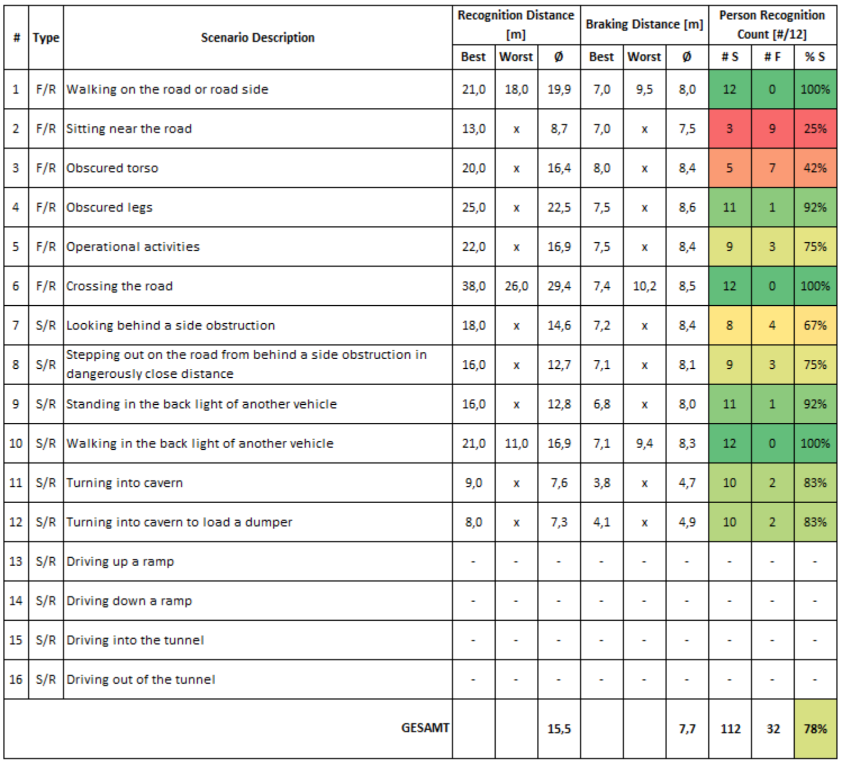
The sensors worked as expected and delivered good data to person detection algorithms. The only exception is the radar sensor. It requires more testing with different models or adaptations in person recognition algorithms to solve the problem of false detections. The combination of thermal and stereo cameras with a lidar sensor for distance measuring is very well suited. It can be even more effective with a 3D lidar sensor. Although this sensor is very expensive, it might close gaps in many situations and can be an overall improvement. It is very likely that long operation times cause blindness for thermal cameras. Beside this fact, they are very expensive and have a low resolution. The IR camera was helpful in long range situations and when a lot of light is involved. Nevertheless, future person detection systems might advance more, if the system focuses on a stereo camera and lidar based sensor combination for mid and long range situations and ultrasound for short range scenarios.

Furthermore, concepts for a better vehicle integration need to be worked out to increase safety for components and possibly overall performance. This applies in particular to HMI and the hardware platform, which was fine for a prototype, but can be improved.

In general, it needs to be noted that a lot more of hardware and software based testing in real conditions is required to make the person detection system suitable for daily use. Especially the pollution of sensors due to of dust and dirt and longer operation times of the whole system should be examined more in detail. The preliminary and final tests performed gave good indications, but the sample is too small to provide solid results.

Although the person recognition system in its current state has its weaknesses, it could be a very useful addition to the safety system in underground construction, once improved. As pointed out by the drivers participating in the tests, such a system could be particularly valuable in situations with high accident potential, and might even be able to avoid accidents.

7 Appendix



#	Type	Scenario Description	Recognition Distance [m]			Braking Distance [m]			Person Recognition Count [#/12]		
			Best	Worst	Ø	Best	Worst	Ø	# S	# F	% S
1	F/R	Walking on the road or road side	21,0	18,0	19,9	7,0	9,5	8,0	12	0	100%
2	F/R	Sitting near the road	13,0	x	8,7	7,0	x	7,5	3	9	25%
3	F/R	Obscured torso	20,0	x	16,4	8,0	x	8,4	5	7	42%
4	F/R	Obscured legs	25,0	x	22,5	7,5	x	8,6	11	1	92%
5	F/R	Operational activities	22,0	x	16,9	7,5	x	8,4	9	3	75%
6	F/R	Crossing the road	38,0	26,0	29,4	7,4	10,2	8,5	12	0	100%
7	S/R	Looking behind a side obstruction	18,0	x	14,6	7,2	x	8,4	8	4	67%
8	S/R	Stepping out on the road from behind a side obstruction in dangerously close distance	16,0	x	12,7	7,1	x	8,1	9	3	75%
9	S/R	Standing in the back light of another vehicle	16,0	x	12,8	6,8	x	8,0	11	1	92%
10	S/R	Walking in the back light of another vehicle	21,0	11,0	16,9	7,1	9,4	8,3	12	0	100%
11	S/R	Turning into cavern	9,0	x	7,6	3,8	x	4,7	10	2	83%
12	S/R	Turning into cavern to load a dumper	8,0	x	7,3	4,1	x	4,9	10	2	83%
13	S/R	Driving up a ramp	-	-	-	-	-	-	-	-	-
14	S/R	Driving down a ramp	-	-	-	-	-	-	-	-	-
15	S/R	Driving into the tunnel	-	-	-	-	-	-	-	-	-
16	S/R	Driving out of the tunnel	-	-	-	-	-	-	-	-	-
		GESAMT			**15,5**			**7,7**	**112**	**32**	**78%**

Table 7.1: Summarized data for final tests in BBT for all test scenarios.

#	Type	Scenario Description	Driver 1						Driver 2						Driver 3						Driver 4					
			Run 1		Run 2		Run 3		Run 1		Run 2		Run 3		Run 1		Run 2		Run 3		Run 1		Run 2		Run 3	
			RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD	RD	BD
1	F/R	Walking on the road or road side	21	8,0	19	7,0	21	8,5	18	7,5	21	8,0	21	8,0	20	7,0	19	8,0	20	7,5	19	9,0	19	9,5	21	8,5
2	F/R	Sitting near the road	x	x	6	7,0	x	x	x	x	x	x	7	7,0	x	x	x	x	x	x	x	x	x	x	13	8,5
3	F/R	Obscured torso	x	x	18	8,0	x	x	x	x	x	x	16	8,0	x	x	x	x	11	9,0	20	8,0	x	x	17	9,0
4	F/R	Obscured legs	22	8,5	25	8,5	24	8,0	22	8,5	24	8,0	24	8,5	25	7,5	x	x	25	8,0	18	10,5	17	9,5	21	9,5
5	F/R	Operational activities	15	8,5	x	x	13	8,5	14	7,5	x	x	15	8,0	x	x	21	8,5	18	8,0	22	9,0	18	9,5	16	8,5
6	F/R	Crossing the road	32	8,0	28	7,6	29	8,7	29	8,1	26	7,4	30	8,4	28	8,2	38	7,9	27	8,9	27	9,2	31	10,2	28	8,9
7	S/R	Looking behind a side obstruction	18	8,2	15	7,8	x	x	16	8,9	x	x	10	7,2	15	9,1	x	x	16	8,5	15	8,9	x	x	12	8,2
8	S/R	Stepping out on the road from behind a side obstruction in dangerously close distance	15	7,9	13	8,6	x	x	14	8,7	9	7,1	x	x	16	7,2	12	7,9	8	8,0	16	9,2	11	8,6	x	x
9	S/R	Standing in the back light of another vehicle	12	7,9	14	8,3	11	8,1	11	7,5	15	7,5	16	8,8	14	6,8	12	8,6	x	x	12	7,2	11	7,5	13	9,4
10	S/R	Walking in the back light of another vehicle	21	8,2	18	8,9	19	8,0	19	8,5	16	9,2	13	7,2	18	7,1	19	8,4	18	8,0	11	8,3	18	9,4	13	8,9
11	S/R	Turning into cavern	7	4,5	8	4,8	x	x	9	4,7	7	3,8	7	4,2	8	5,2	7	4,8	x	x	7	4,9	8	5,1	8	5,4
12	S/R	Turning into cavern to load a dumper	8	5,1	x	x	7	4,7	6	5,4	8	4,3	x	x	8	5,4	8	4,4	7	4,1	7	5,8	8	5,1	6	4,7

Table 7.2: Measured data from final tests in BBT for all test scenarios for every driver.

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