GRADUATION REPORT

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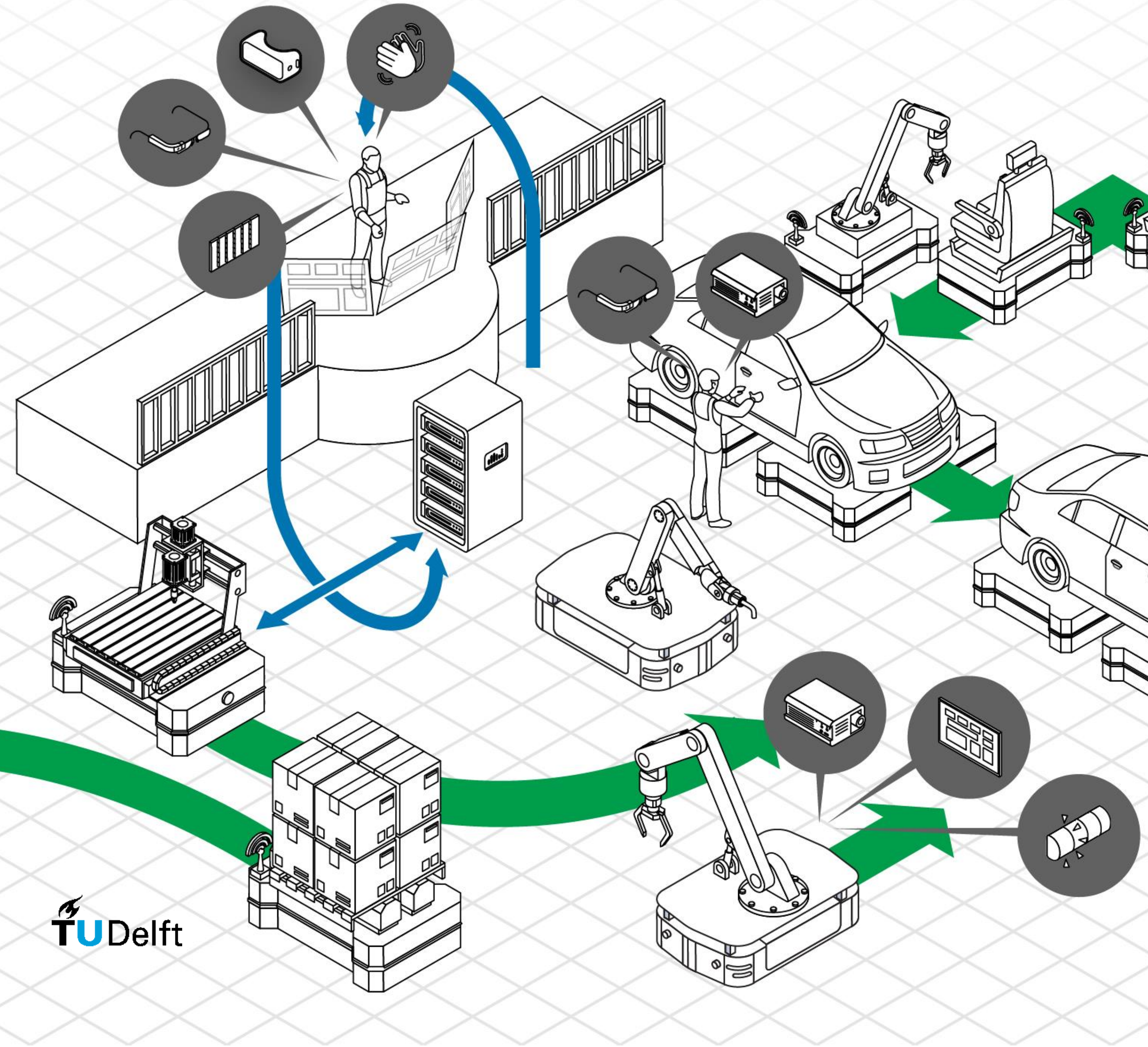
EXPLORATIVE STUDY FOR APPLICATION OF **SPATIAL AUGMENTED REALITY** ON FACTORY **AUTOMATED GROUND VEHICLES**



TU Delft

The document at hand is the final report of a graduation assignment at the faculty of Industrial Design Engineering at the Delft University of Technology by Martijn Verbeij. The graduation assignment is performed in cooperation with the Smart Factory department of Magna Steyr, located in Graz, Austria, and is under the supervision of dr. Doris Aschenbrenner as chair of the graduation committee and dr. Zoltán Rusák as mentor.

Executive summary

Context & Problem

The development of human industry can be divided into separate 'revolutions'. The first one brought mechanical innovation, the second introduced electrical power into the factory, while the third revolved around the use of computers and automation. We are now at the brink of a 4th industrial revolution: improving factories by applying smart sensors, artificial intelligence, and other emerging technologies. One of these emerging technologies are called AGVs: Autonomous Ground Vehicles. these are fully automated driverless vehicles that can transport goods and machinery. The newest generation AGVs moves efficiently and flexibly without guiding rails or fixed paths.

All of these extra ingredients are causing the factory to become more complex and less transparent in the face of high demands for safety and efficiency. Humans and their robotic colleagues are in dire need of enhanced methods for information exchange. Augmented Reality (AR) is an excellent tool to provide this exchange because of its inert ability to curate visual information and untangle complexity. The goal is to improve situation awareness and safety in the factory.

Analysis

The Magna Steyr factory in Graz was visited so to better understand the context. Literature research provided the necessary insights into the state of the art of the smart factory and AGVs as well as the human factors involved.

Design & iteration

To work towards the design of a solution an explorative approach was first adopted by matching different AR methodologies to different roles within the factory. This created a matrix of possible solutions. The following idea was selected: to place a projector on top of the AGV to provide visual cues to the factory worker by projecting the spatial intention of the robot directly on the factory floor. An iterative approach was now adopted to develop a solution that could be mounted on top of an AGV.

Validation

In order to validate the presumed positive effect of placing spatial cues in front of the AGV, a between-groups study was conducted. Because of COVID-19 restrictions, physical lab research was not possible. Instead, a questionnaire research was devised in which a test group and a control group were shown videos of an AGV approaching the participant. The test group videos included projected arrows while the control group videos included no indication of the direction the AGV would take. Multiple realistic scenarios were tested to measure the response of the participants. Apart from the response of the participants, the experienced task load and situation awareness were also measured.

Results & conclusion

It was concluded that the projection of arrows in front of an AGV improves the perceived safety of workers as well as their assessment of the robot's future actions. Participants that were shown the projected arrows had a far greater chance of executing the desired response toward the robot. Improvement with regards to the situation awareness was measured in some, but not all scenarios. Additional research and design opportunities are identified and presented in chapters 12 and 13.

This project proposes a framework for future AR projects in the smart factory environment and also provides insights into the merits of using (spatial) augmented reality to facilitate communication between robots and people in the smart factory context. It shows that the use of Spatial Augmented Reality can make factories safer and more efficient, paving the way for more industries to adopt AGV systems and take the next step toward the factory 4.0 paradigm.

Introduction

Automated Ground Vehicles (AGVs) are autonomously functioning vehicles often used in factory context for transport and logistics. The new generation of AGVs will not just follow static guides but will be versatile, flexibly adapting to a more and more dynamic factory environment. The dialogue between machine and men needs to be properly facilitated, otherwise the AGVs are perceived as unpredictable by human factory workers, decreasing the trust and value of the AGVs contribution to the manufacturing process.

Additionally, supervisors run the risk of losing the overview of the swarm of AGVs. The supervisory operator is currently using desktop applications to read out the sensor data from vehicles and associated hardware. Multiple screens are used to display information. The information should provide insight into the current, past, and future actions of the AGV's, which is plentiful and complex.

Augmented Reality (AR) technologies allow for the mediation of visual information. It can supplement, emphasize, and contextualize information that is already visually present. This provides a good opportunity to untangle the complexity for both the factory floor worker and the supervisory operator. Within this project, special attention is given to the opportunities of Spatial Augmented Reality (SAR). SAR aims to create augmented layers of information utilizing only hardware that is external to the user. This methodology offers many advantages in terms of ergonomics and cooperative use.

The goal of the assignment is defined as:

This project will identify (Spatial) Augmented Reality solutions, that are suited to facilitate the interaction with AGVs (automated ground vehicles) in a smart factory setting. The focus is to identify problems experienced by factory supervisors such as information overload or lack of oversight and to design an AR user interface solution, that will increase situation awareness.

In a broader perspective lessons from this project may be applied to other Cyber-Physical Systems (CPS) that wish to apply AR solutions to improve situation awareness.

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Part 1

Analysis

Chapter 1

Analysis plan

1.1. Structure of the Analysis part

The analysis part of this report is quite extensive. Hopefully, this short chapter can explain the structure and help you find what you are looking for.

This chapter, chapter 1, outlines the analysis plan of the project; it defines a scope and the resources required for the analysis. Chapter 2 outlines the stakeholders and their position within the project. In chapter 3 the fundamentals of the relevant fields of research are provided. Chapter 4 describes the contextual inquiry that was performed to understand the current industry state and the challenges the client is facing. Chapter 5 combines the information found in chapters 2, 3, and 4 to go deeper into the relevant research fields and show the status of the industry.

In chapter 6 we reflect on the insights that were found and derive requirements for further specification of the project scope. The three variable factors (Industry state, application context and technological framework) are used to create a three-dimensional chart (This is further explained in chapter 1.2, 'Scope'). Every combination of these three factors leads to a 'solution space'. A solution space consists of a problem (defined by the industry state and application context) and a solution (technological framework). If a technological framework can be used to solve the problem, then the solution space is fertile for AR-based innovations and can be further investigated.
Finally, a solution space is selected based on the requirements in chapter 7.

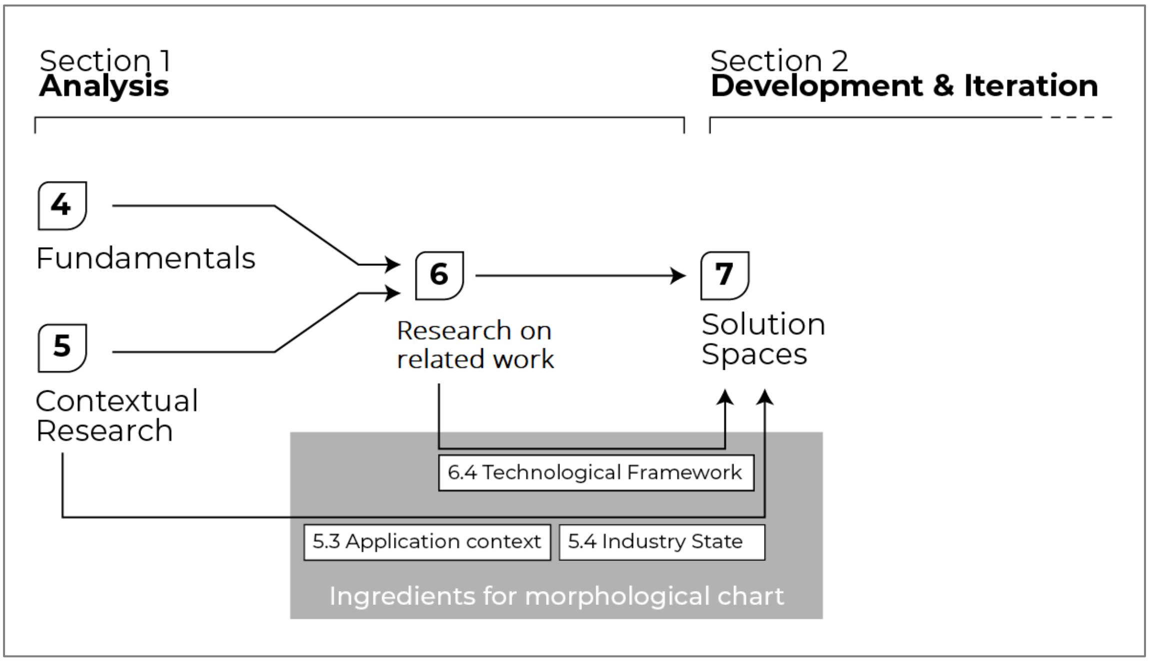


Image 1: A diagram showing the progression of information in the analysis part of this report.

1.2. Scope

The project scope consists of two sets of factors. First, we define a fixed set of factors which have been defined from the beginning, and secondly, a variable set of three key factors that are defined based on the outcome of the analysis research. Let's discuss the variable factors first.

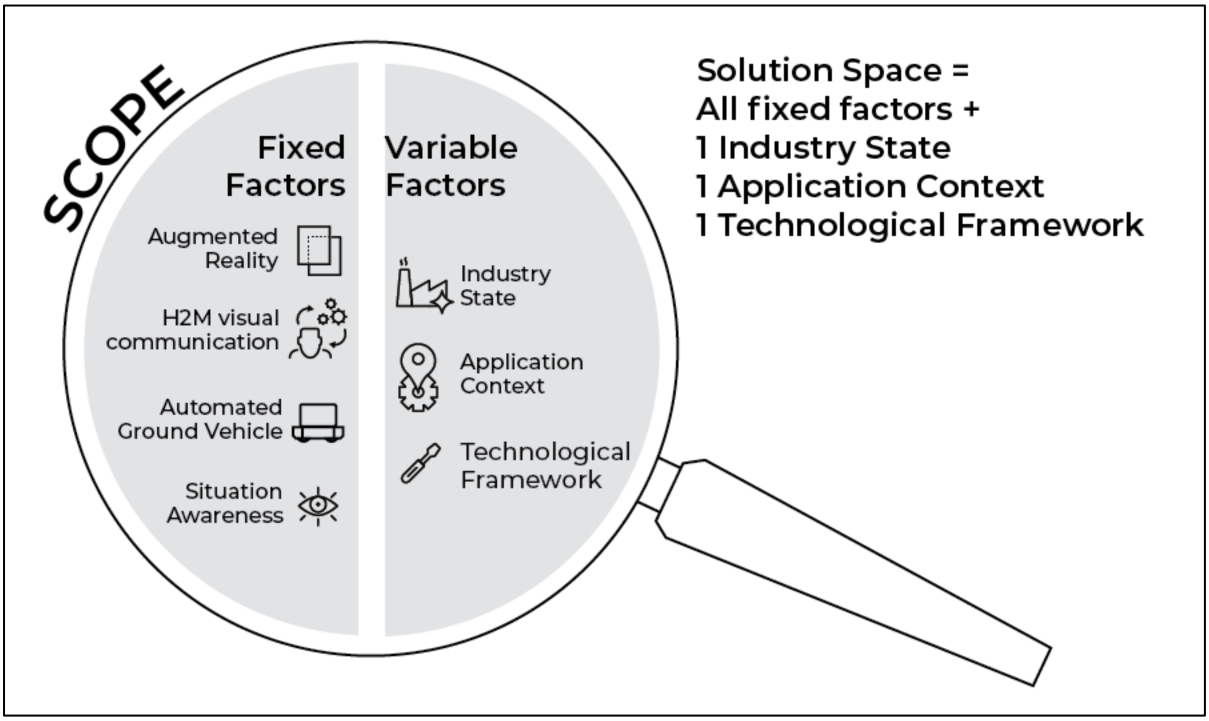


Image 2: The scope consists of fixed factors (set from the beginning) and variable factors (to be decided on in the analysis part of this report).

Variable factors

The scope of the project is defined by three key factors:
1. **The industry state.** How 'advanced' is the factory? It describes how far technological advancements such as AR, AI and AGV automation are integrated into the manufacturing process.
2. **The application context.** Where in the factory do we apply the solution? Who is experiencing the problem? This is a specific context of use in which it is suspected that use cases for Augmented Reality solutions can be found.
3. **The technological framework.** What kind of Augmented Reality are we applying? There are different approaches to achieving Augmented Reality, which are defined by their technological means.

Industry state

Three industry states are defined: current, intermediate and future. The current state describes the current situation in the Magna factory. The intermediate state is presumed reachable within 10 years and the future state is presumed reachable within 20 years. The measure of the integration of factory 4.0 technologies greatly influences the type of AR innovations that would be suitable for the factory. The industry states are illustrated in chapter 4.3. It is important to realize that the industry state as it is discussed in this report concerns the Magna factory specifically. If the same is to be applied to other companies or other industries an analysis is needed to divide the progression of that factory in a meaningful manner.

Application context
Four application contexts were selected. They will be researched to obtain a generic overview of the processes and functions that are fulfilled within that context. All contexts contain human-robot interactions. A more elaborate description of the four application cases can be found in chapter 4.4.

Technological framework
Four different approaches to creating augmented reality are distinguished. see chapter 5.4.

Apart from these three key factors, the direction of the project is influenced by the stakeholders (see chapter 2).

A specific industry state and application context will need to be selected to create a proper, narrow scope for the project. The technological frameworks will be selected based on the combination of industry state and application context.

Fixed Factors

The following scope-defining factors were set when the assignment was written

Augmented Reality: the project will involve the application of augmented reality to solve the problems encountered.

Human-to-Machine and Machine-to-Human visual communication: Within the complex system of an automotive factory many types of communication take place. This project focuses on the visual communication between humans and machines. Other senses may be included such as auditory or tactile communication. This is briefly touched upon in chapter 12, design opportunities.

Automated Ground Vehicles: the project works toward improving the interaction with AGVs and not with other machinery or robots.

Situation awareness: The goal of the project is to provide a means to improve situation awareness within the chosen application context.

1.3. Research Questions

The questions formulated here are not research questions in the traditional sense but are used to guide the analysis phase.

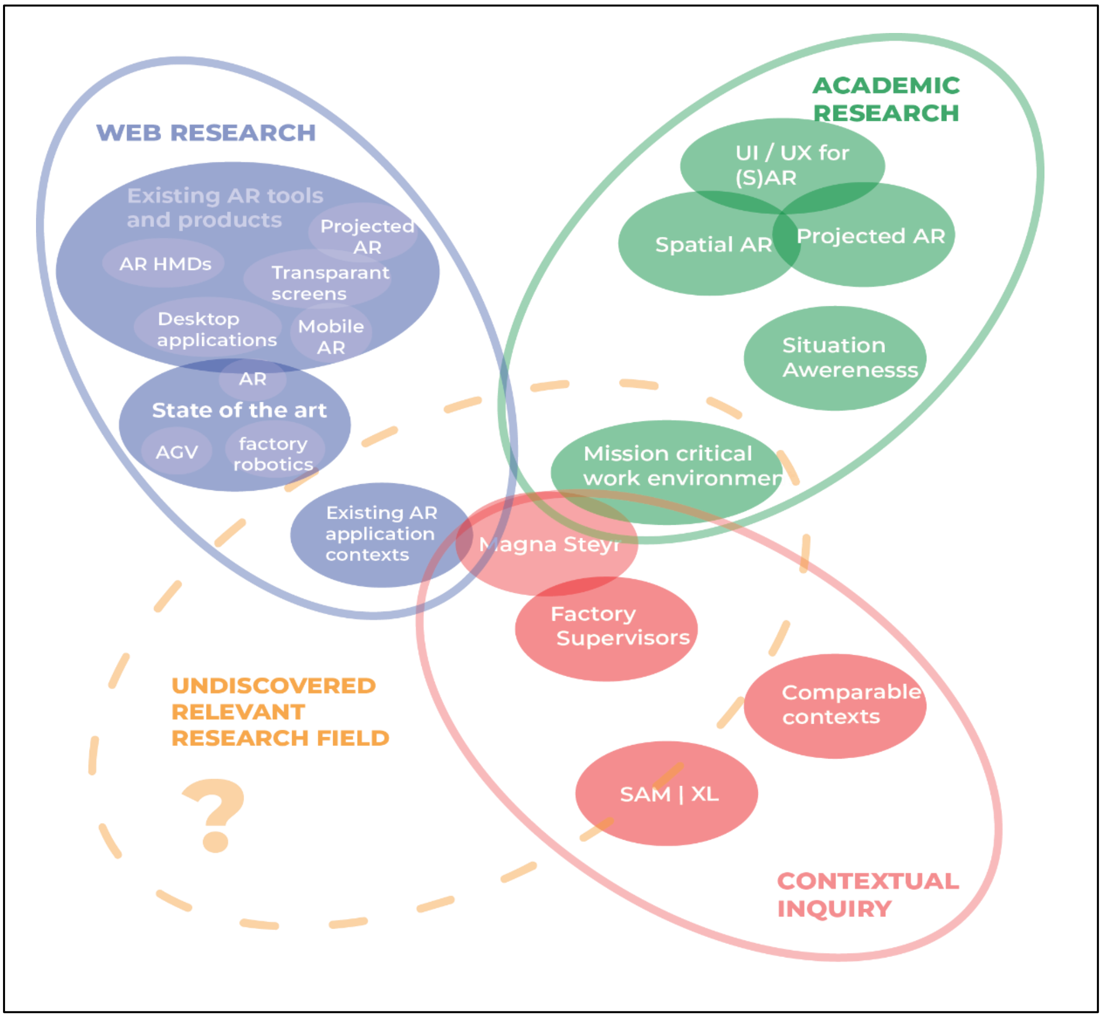


Image 3: The three areas of academic research and the topics they contain.

Web research

- What are definitions for SAR / AR / MR / AGVs / Swarm robotics / Situation Awareness?
- What is currently possible and impossible with the technologies mentioned above and what will soon be possible?
- What are the current applications of AR in a (smart) factory context or within a comparable context?

Contextual inquiry

- How is the work process structured regarding control of the AGVs?
- How far are Industry 4.0 developments integrated into the current Magna manufacturing sets and what are the plans for integrating more in the future?
- What hardware and software are being used in the application contexts?
- Which problems occur in the process of controlling the AGVs?
- What is the distribution of responsibilities regarding the AGVs?
- How is situation awareness regarding AGVs obtained in the current context of use?

- What type of tasks are currently given to AGVs and what tasks does the client envision for them in the future?
- What problems occur at all levels of interaction with the AGVs?
- Basic information about Magna as a company including their future vision and mission.

Academic research

- What are the current possibilities and limitations of AR through HMDs or other technological means?
- What are the human factors relevant for human-to-AGV interaction? how are they measured? how are they improved?
- How do you measure and improve situation awareness?
- What else is published regarding projected AR and Spatial AR? (explorative research)

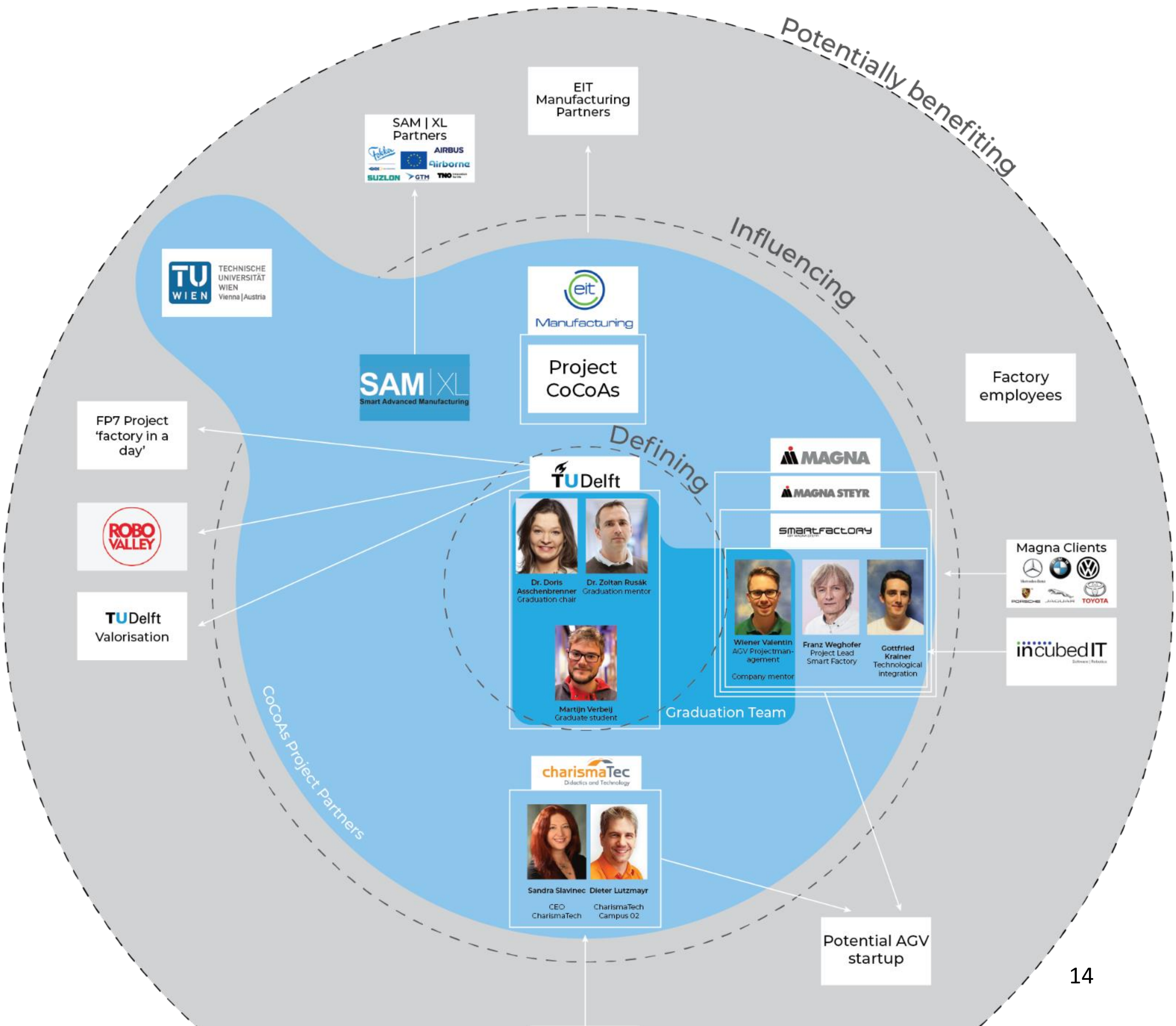
Stakeholders

The stakeholder map as seen in image 4 divides all involved parties in three 'circles of influence'.

This model puts more emphasis on the amount of influence stakeholders have on the direction of the project than a traditional stakeholder map, which shows all parties affected by the outcome of the project and how they will potentially be affected.

The Stakeholder map is divided into three 'rings': *defining, influencing*, and '*potentially benefiting'*. People and entities within the inner ring are *defining* for the direction of the project, this is the graduate student and his graduation team exclusively.
The middle ring (*influencing*) are all in contact with the graduation team and can directly influence the direction by contributing resources and feedback. the most important of these is the client, Magna. All others are part of the CoCoAs project consortium. The outer ring consists of institutions that can *potentially benefit* from developments within the project. Their preferences and activities may be considered when making design decisions, but they do not directly influence the direction of the project.

Image 4: the Stakeholder map is divided in three 'rings' indicating different amounts of influence on the project.



Chapter 3

Fundamentals

The assignment goal is defined as follows:
*This project will identify **(Spatial) Augmented Reality** solutions, that are suited to facilitate the interaction with **AGVs (Automated Ground Vehicle)** in a **smart factory** setting. The focus is to identify problems experienced by factory supervisors such as information overload or lack of oversight and to design an AR user interface solution, that will increase **situation awareness**.*

Specific terms used in this description require a common shared definition and background information. The purpose of this chapter is to provide that.

3.1 Industry 4.0 and the smart factory

In literature, the development of human industry is often divided by pointing at distinct 'revolutions'. [1] [2][3]. The first industrial revolution was started at the end of the 18th century and saw the emergence of the mechanization of industrial processes.
The second industrial revolution was driven by the availability of electricity as well as the optimization of factory processes using the organizational models of innovators like Ford and Taylor.
The third industrial revolution is considered to have started with the widespread use of electronic components during the 1970s. This allowed for automation within the factory walls.
Although these developments are often referred to as 'revolutions', in reality the process contains gradual change spread out over the duration of multiple decades.

These days many people believe we are at the start of a fourth industrial revolution. The term 'Industry 4.0' originated from a governmental high-tech strategy started by Germany in 2011 [4]. These days the term is used everywhere in the industrial landscape when talking about the integration of emerging technologies into the manufacturing process.

According to Wang & Wan [5], the industry 4.0 entails horizontal integration through value networks, vertical integration and networked manufacturing systems, and end-to-end digital integration of engineering across the entire value chain. To this end 'industry 4.0' is an often-used term when talking about the integration of modern IT solutions in the manufacturing field including but not limited to: Internet of Things, artificial intelligence, and Augmented and Virtual Reality. This interpretation will be chosen for this report.

Industry 4.0 is first and foremost a vision for an industrial company. Not only may this vision differ strongly from company to company, but the steps toward it as well. It can be stated that a shared aspect is the purpose of improving the manufactured value, safety, and efficiency of the factory.

Many futuristic visions published by companies include a strong focus on flexible and versatile transport automation [6][7]. The versatile use of AGVs in the factory context allows for high-level automation and facilitates the integration of other process innovations.

Internet of Things & the Digital Twin

Wang et al. describe four distinguishing characteristics for Industry 4.0: high interconnection, dynamic reconfiguration, mass data, and deep integration [1]. The ‘high interconnection’ and ‘mass data’ are well illustrated by the ‘Internet of Things’ (IoT). Within the industrial context, IoT refers to a trend in which more and more objects are being incorporated as part of the factory network. This means elements are outfitted with the sensors and connectivity to report local data to a centralized system. This is creating a strong upward trend for the sensor density in factories.
When the entire physical state of a factory can be accessed, we can speak of a ‘Digital Twin’ of the factory. This information about the real world can be used to benefit a variety of factory processes, for example by creating information-rich augmentation layers and overlay them more efficiently to create effective augmented reality.

Image 5: an example of a digital factory by Siemens [8]. *AGV locations, assembly lines states, and the positioning of every robot arm are included.*

The higher density of sensors also allows hardware to report more accurately and in a more centralized manner on its state. When this information is processed in large quantities accurate predictions can be made about the state of the hardware and they may receive maintenance before malfunctions occur. This is referenced to as ‘predictive maintenance’.

Cobotics

Another step toward higher levels of automation is the concept of ‘cobots’, a contraction of ‘cooperation’ and ‘robotics’ [9]. Many application efforts are currently focused on creating safe coexistence between robots and humans. In the current industrial context, humans and robots are often already working alongside each other but tasks are usually divided between them. In the immediate future robots and humans will interact in a shared work process (collaboration)[10]. In the past, some tasks could exclusively be done by humans because of the subtleties of the required motion or the required short feedback loop. Thanks to the dynamic between human and cobot we can start to ‘teach’ these tasks to robots. Because of the short feedback loop and connectivity with other robots (motions and error margins can be shared instantly with robots performing the same task), higher efficiency can be achieved.

It is important to remember that all these developments and more are unfolding simultaneously. Most companies will attempt to apply a selection of them to their production chain and during the integration of such technologies, they will influence each other as well. The most successful businesses will be the ones that succeed at selecting the most relevant technologies and successfully integrate them into their existing manufacturing process.

One development that belongs in this list are Automated Ground Vehicles (AGV's) because this is specifically a focus of this project, we will discuss them in greater detail here.

3.2 Automated Ground Vehicles

For this project we will use the following definition:
An AGV is a term encompassing all driving transport systems that are capable of functioning without driver operation. [11]

In the discourse surrounding AGVs, the first two letters of the acronym are contested. The 'A' meaning either 'Automated' or 'Autonomous' and the G meaning either 'Guided' or 'Ground'. Although there is a discussion to be had about the different meanings of these words, the result is that 4 terms are used that are almost always referencing the same phenomenon. Within the context of this project AGV will mean: 'Automated Ground Vehicle'. 'Autonomous' is rejected because it can be argued that a machine is not autonomous if centrally controlled, like most AGVs. The term 'Guided' is rejected because it might suggest the AGVs are guided by external physical elements such as painted or magnetic lines. Early AGV systems functioned in this way but as we will discuss later this is no longer the case for the vehicles considered for this project.

Especially in the area of supply and disposal in storage and production areas (both of which are present in an automotive manufacturing plant), AGVs have been found to reduce the damage to inventory, make production scheduling more flexible, and reduce staffing needs [12].
Thanks in part to this, the AGV market is growing fast. Bloomberg estimates the current AGV market to be worth 2 billion dollar (2019) and expects it to achieve a value of 2.9 billion dollar by 2024 [13].

Image 6: AGVs exist in many shapes and sizes and are designed for a broad variety of applications. (top left: Automated pallet truck by Jungheinrich, top right: Ridgeback by Clearpath Robotics, bottom left: WEASEL by SSI Schaefer, bottom right: KATE by Götting KG).

Currently, the most often occurring use for AGVs in the factory context is to have them function as autonomous forklifts. Moving pallets within the workplace. In the context of the Magna factory, most of this transport is currently done by human-operated forklifts that are eligible to be replaced by AGVs. Currently, AGVs in the Magna factories are used for short transport tasks such as transporting a car-seat from one side of an assembly line to the other.

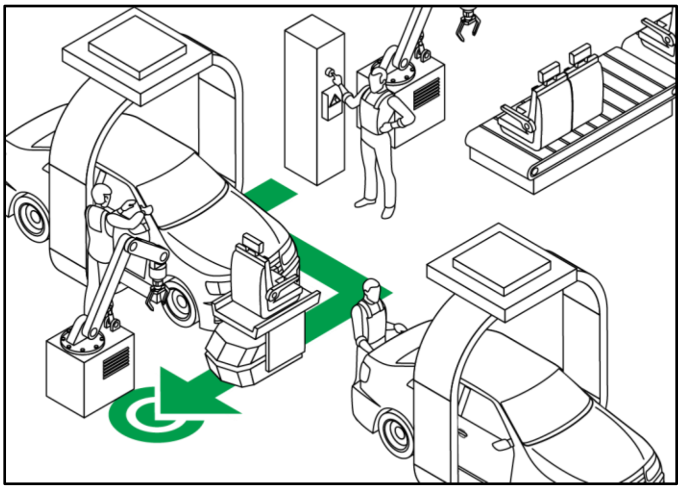


Image 7: An illustration showing an AGV transport car seats to the other side of the assembly line. This strategy was chosen because the alternative was to build an elaborate and costly transport-line over the main assembly line.

There is a great variety between different AGV systems, which for example differ in their mode of localization and navigation. The systems governing the AGVs differ in the way that they schedule the AGVs and in the amount of autonomy the system has compared to the amount of control exerted by human operators. Image 8 gives an overview of these different aspects and how they relate to each other. They are further discussed in the following paragraphs.

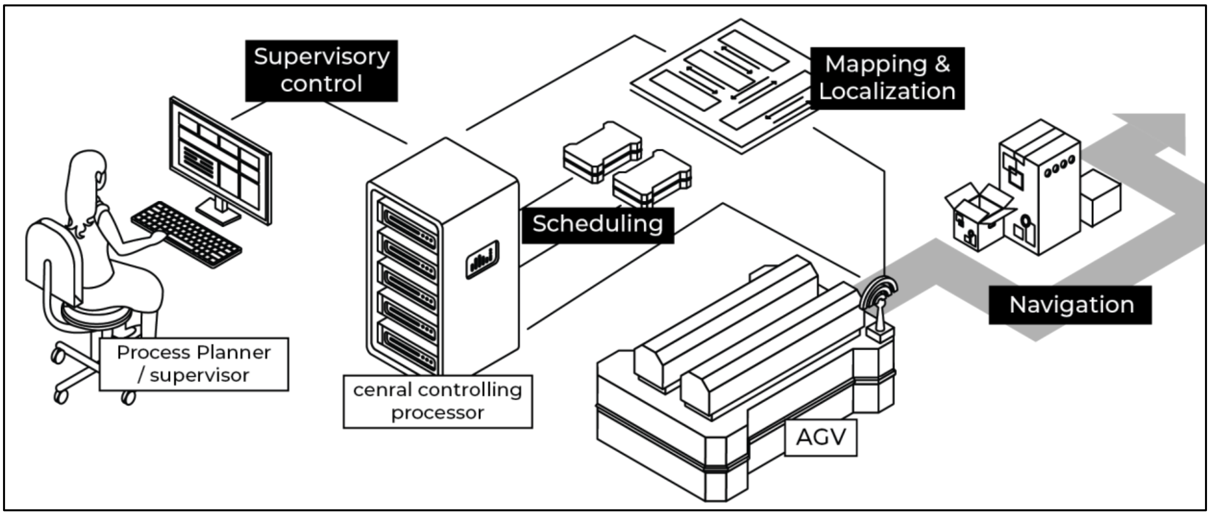


Image 8: Mapping is the creation of a shared map that can be used by the AGVs. Localization is determining where on the map the AGV is and which way it is oriented. Navigation is the AGVs ability to use the map to move to a different location. The central processor provides scheduling by giving the AGV their tasks. This continuous process is supervised and influenced by the process planner who exerts supervisory control to supplement the autonomy of the system.

Localization

Localization is the AGVs ability to define its physical position within the working area. Older 'guided' AGV systems provide magnetic or painted lines for the AGVs to follow. The vehicle might follow the line until the goal position is reached, requiring no localization. Another method is the use of QR codes placed in fixed positions in the working area. The codes (sometimes called AR-tags) are read and interpreted by cameras mounted on the AGV [14]. Localization can also be achieved the other way around, by placing AR tags on the AGVs and using cameras that cover the entire workplace area [15]. Sometimes multiple methods may be applied to achieve a higher accuracy of the localization. Because AGVs often use an industrial WIFI connection for data transfer, WIFI can be used as a supplemental localization technique [16]. The current industry standard for localization is the 'SLAM technique' which takes care of the localization as well as the mapping and is covered in the next paragraph.

Image 9: An AGV system that uses painted navigation lines. Source: Movexx.com.

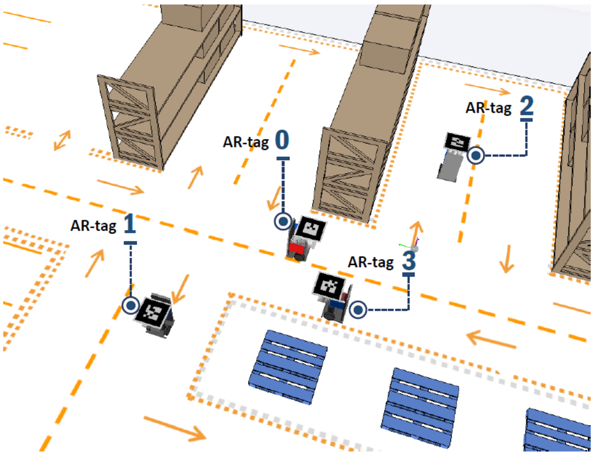


Image 10: AGV system using AR-tags for localization. image is taken from [14].

Mapping

The SLAM-technique (Simultaneous Localization and Mapping) creates a shared real-time approximation of the factory floor that is used to plan the routes for all AGVs [17]. A commonly used hardware for this application is a LIDAR sensor. These emit laser light in a 360-degree field around the sensor. The light is reflected by the surrounding objects and registered by the LIDAR sensor upon return. Using the angle of incidence and the time the light has traveled the sensor can approximate the location of the surface the beam was reflected from. By combining thousands of these measurements in a map the entire surrounding environment can be mapped in real-time.

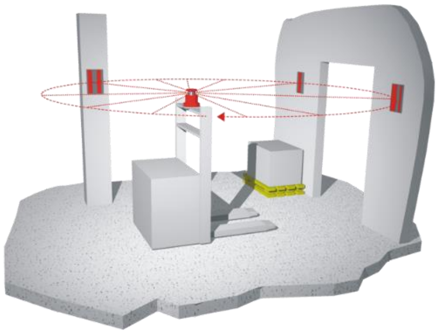


Image 11: Example of a LIDAR sensor in action. the sensor in the head rotates to capture measurements in all directions. Image is taken from [18].

Image 12: Thousands of SLAM measurements together form a map. For AGVs a 2D map is sufficient but a 3d map is also possible. The map contains both static points (such as walls and permanent obstructions) as well as temporary points such as humans or other AGVs. Image adapted from [19].

All AGVs contribute to the shared map and use it for localization and navigation. Every scan of an object improves the accuracy of the map. This method however does pose a 'chicken and egg' problem because the method of localization is dependent on the map and the method of mapping is dependent on localization (the position and orientation of the AGV). Multiple mathematical approaches exist for dealing with this problem, but analysis of this lies beyond the scope of this project. It is enough to know these methods exist and have been proved to create dynamic multi-robot systems that are accurate enough for industrial applications.
Additional information provided to the system can help make the SLAM problem easier to solve (such as pre-existing maps and secondary localization techniques like WIFI localization).

Planning and Scheduling

Once the AGVs have a map and know where on this map they are positioned they can be given tasks to perform.

Rigorous research has been done to mathematically define optimal paths and schedules for AGVs [20]. Current path planners are typically used to determine paths that minimize time or length, which does usually not include the social desirability of the path as a factor [21]. Machine learning may be applied to optimize for social desirability of the path without harming the production process. Considering the isolated environment of a factory, employees may be trained to give AGVs priority over their own movement.

AGV scheduling can even go further and let AGVs function as a swarm that actively works together to meet production goals. AGVs could be coupled together to achieve tasks that would not be possible with a single machine. Another example of advanced planning is to have the AGV schedule replace a faulty or low-battery AGV with another unoccupied AGV before downtime occurs, effectively increasing the redundancy and reliability of the system.

Navigation

When AGVs are tasked with going from A to B and are given the path they should ride to reach their destination we can talk about AGV navigation.

A simple model AGV will simply follow magnetic or painted lines on the floor for the AGV to follow. An AGV would simply follow this line until it reaches its destination (indicated in a similar way by using magnetics or visuals cues on the floor) unless an unexpected object would enter the safety area surveyed by the AGV his sensors, in which case the AGV would make an emergency stop.

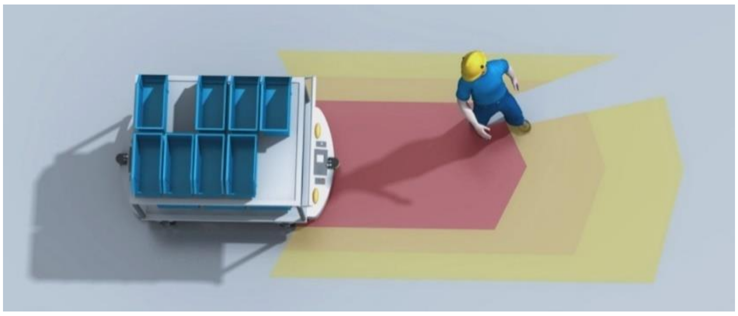


Image 13: AGVs typically define separate spatial zones around and in front of the machine. Behavioral consequences are tied to the occurrence of objects being measured in these zones. The first zone, for example, may prompt the AGV to slow down while zones closer to the AGV trigger an emergency stop. The zones are often programmed to scale up with the speed of the AGV. Image adapted from [22].

However, it is far more efficient if an AGV can avoid obstacles and adapt its route accordingly. When demands for the versatility of production processes grow fixed-path AGVs are no longer an optimal solution for warehouses and factories [23]. 'Natural' navigation methods (AGV systems in which the AGVs perceive the world in a similar fashion as humans do [24]) are becoming more mainstream in the AGV market. A SLAM driven AGV system is an excellent example of this.

Supervisory control & autonomy

Industrial contexts such as an automotive manufacturing plant use 'supervisory control' to control individual processes and control loops within the environment. Sheridan defines supervisory control as follows: "supervisory control means that one or more human operators are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors to the controlled process or task environment." [25]. Within this definition, there is still a spectrum of possibilities ranging from complete control of the human over the system or complete autonomy held by the machine. For defining the position on that spectrum Sheridan developed a 10-level scale as indicated in image 14.

1	The computer offers no assistance, human must do it all.
2	The computer offers a complete set of action alternatives, and
3	narrows the selection down to a few, or
4	suggests one, and
5	executes that suggestion if the human approves, or
6	allows the human a restricted time to veto before automatic execution, or
7	executes automatically, then necessarily informs the human, or
8	informs him after execution only if he asks, or
9	informs him after execution if it, the computer, decides to.
10	The computer decides everything and acts autonomously, ignoring the human.

Image 14: Sheridan's model for defining levels of autonomy. ranging from 1 (total control by the human supervisor) to 10 (total autonomy of the computer). Image adapted from [26].

As the development toward industry 4.0 progresses it is expected that the supervisory control will move toward the higher end of Sheridan's scale because the growing complexity is too much for human operators to handle without help.

When the highest level of autonomy is reached, warehouses and distribution centers can be turned into 'dark factories', the concept of a factory with no human involvement and therefore no need for lighting. The automotive industry however requires very specific assembly tasks that so far have proven difficult or expensive to automate. Therefore the human presence inside an automotive factory will be a defining factor for automation for the coming decades.

The development of solutions in the areas of navigation and AGV scheduling is influential for the industry of AGVs itself. It is, however, outside the scope of this project to develop solutions that optimize AGV scheduling, navigation, mapping or localization. Technical problems that still exist within these fields are assumed solved or solvable to allow this project to focus on the Human-to-AGV interaction.

3.3 Situation Awareness

Situation awareness (SA) is defined by Endsley as the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status [27].

One of the most adopted theoretical frameworks for situation awareness is Endsley's model [27]. The model works in three steps (or levels) leading up to a decision and its execution. The first level concerns the *perception* of the monitored elements (these can, for example, be objects, events and people). The second level is called *comprehension* and requires that the individual can create cognitive connections between the separated elements and understand how they interact and create causality. The third and final level of situation awareness allows the individual to *project* what it has learned on the first 2 levels on future situations. The individual obtains a predictive capability over the situation.

Apart from this, there are individual factors, environmental, and task factors that influence all steps of the process including the decision and the performance with which it is executed. Examples of individual factors are the experience, goals and knowledge of the individual. Examples of environmental factors are the complexity, dynamics and transparency of the system as described in [3]. Examples of task factors are the workload of the task as well as its complexity and structure. Because of the number of influential factors, Van Doorn argues a holistic approach is required when measuring and assessing situation awareness [28].

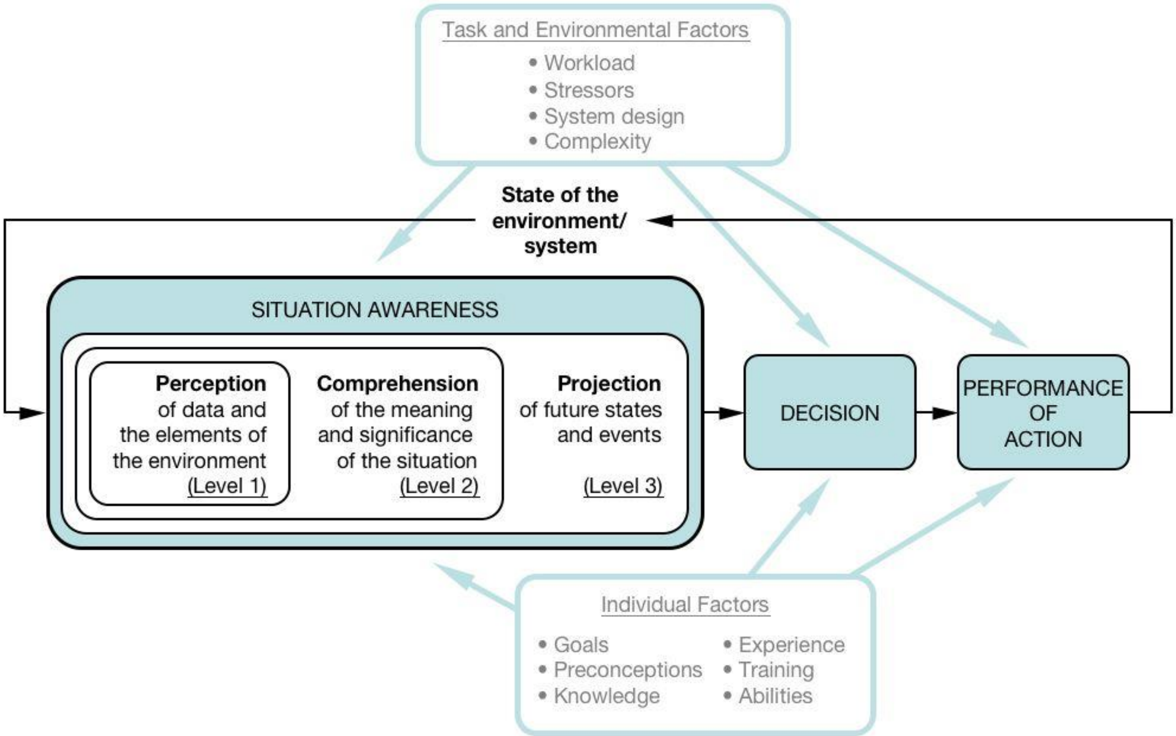


Image 15: A diagram showing Endsley's model for Situation Awareness [13].

In some situations, errors made by manufacturing operators can result in large damages, expensive loss of progress, and health risks ranging from injury to loss of life (environments where this is the case are called 'mission-critical'). In the United States of America, 61 robot-related workplace fatalities were reported between 1992 and 2015 [29]. Especially in these environments improving the situation awareness is critical for preventing incidents and correcting errors where they arise [2]. The cause of human errors can be attributed to three main problem factors: the degree of complexity, dynamics, and lack of transparency within the system [3].

Moving toward the factory 4.0 paradigm will likely result in operators having more responsibilities [30] and having to survey a cyber-physical system that is increasingly complex, dynamic, and non-transparent. These problem fields lead to a higher mental workload resulting in lower task performance. Because of this development situation awareness is the main metric used to measure the success of designed interventions in this project.

Measuring situation awareness

There are multiple standardized methods for measuring situation awareness:
SAGAT (Situation Awareness Global Assessment Technique) provides an objective measure of SA based on queries during freezes in a simulation, this is referred to as a freeze probe technique [31]. The main advantage of SAGAT is that it allows an objective, unbiased index of SA that assesses operator SA across a wide range of elements that are important for SA in a particular system. [32]
SART (Situational Awareness Rating Technique) [33] is a different measuring technique that provides an assessment of the SA provided by some system based on an operators' subjective opinion. The main advantages of SART are that it is easy to use and can be administered in a wide range of task types [32]. The choice of a measurement method will depend on the mode of testing that is used at the end of the project.

3.4 Communication

Human-Robot Spatial Interaction (HRSI)

Moshayedi et al. note in a review paper concerning novel AGV challenges that the interaction between human and AGV is considered one of the greatest roadblocks for a successful AGV installation, with the trust in the AGV being the most important factor [34].
Human-Robot Spatial Interaction (HRSI), is the study of joint movement of robots and humans through space and the social signals governing these interactions [35]. This is a more specific study area that falls within the study of Human-to-Robot communication as briefly discussed in chapter 3.4 and deals exclusively with multi-agent systems. Within HRSI a goal is to improve the predictability and legibility of mobile robots. Many researchers outline the importance of legibility especially for navigating robots such as AGVs [35]–[37]. Within the context we can define three categories of communication: Human-to-Human, Machine-to-machine, and Machine-to-Human. In modern industrial applications, communication is often bi-directional. Machines and humans communicate with each other and will iterate and adapt in accordance with each other's input.

This project will primarily concern itself with Machine-to-Human communication. This is the type of communication that should be optimized in order to increase situation awareness.

Depending on the context three different categories of communication from a machine such as an AGV toward the human operator can be defined: Legacy, Status, and Intention. Put in simpler words these communications are the past actions, current status, and future intentions respectively.

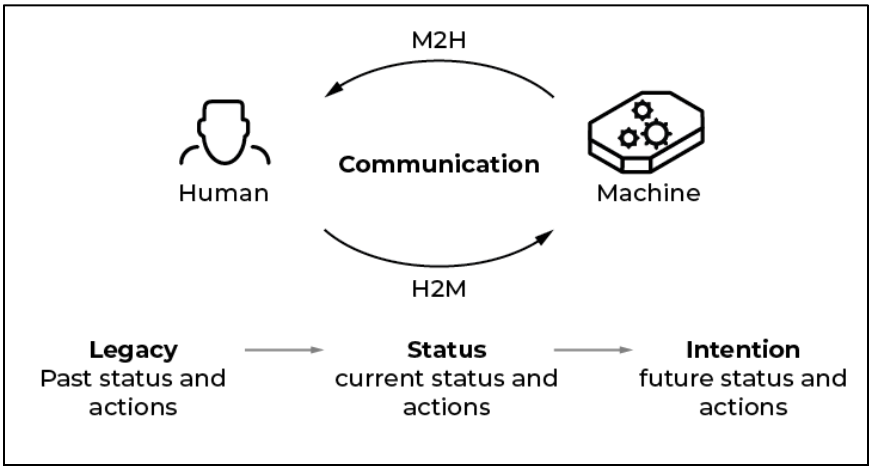


Image 16: Diagram depicting the types of communication between humans and machines. In this project, the type of information is primarily spatial and the mode of communication is primarily visual.

Legacy communication

Perhaps the least relevant for the industrial context of use is the communication of the past actions of the AGV. It does, however, allow the interacting user to backtrack perceived problems and error behavior of the machine. With sufficient training, this may increase the likelihood for the individual user to reach the 'projection' level of situation awareness.

Status communication

Status communication comes in two shapes in this context. Firstly, the machine reports all data of its sensors in a continuous stream to the centralized processing unit. This includes positions, temperatures, and forces. From this information, it automatically can be deduced whether the machine is having problems or whether certain performance values are falling outside of the acceptable boundaries. When the reported values are used to determine whether parts of the machine are approaching these boundaries repairs can be automatically planned to intervene before the machine fails. This is called predictive maintenance. It is mainly a machine-to-machine type of communication where only after reaching certain conditions humans are notified about the required maintenance steps to be taken to guarantee smooth planned production.

The other way in which machines report on their status is between machine and human. This happens mostly directly on the factory floor where workers and operators might need to assess the machines' status and current task directly. This can be done using lights, screens or voice generation.

Intention communication

An important factor for achieving situation awareness and higher perceived safety is the communication of intent. If an AGV can successfully communicate its intent, comprehension, and projection (levels 2 and 3 of Endsley's model) can more easily be achieved.

This works in two ways. The user will also need to communicate its navigational intent to the AGV. This can be done by interpreting the head pose [38] or by tracking the eye movement [39], [40].

Apart from navigation other types of intent also need to be communicated between humans and machines such as the spatial positioning of a robot arm [41]. As the amount of automation and flexibility grows within the factory, we will need more intention communication between machines and humans.

3.5 Augmented Reality

The Virtuality Continuum

Milgram and Kishino define a spectrum of visual display techniques that they group as 'Mixed reality' [42] and which they group as a subset of Virtual Reality displays.

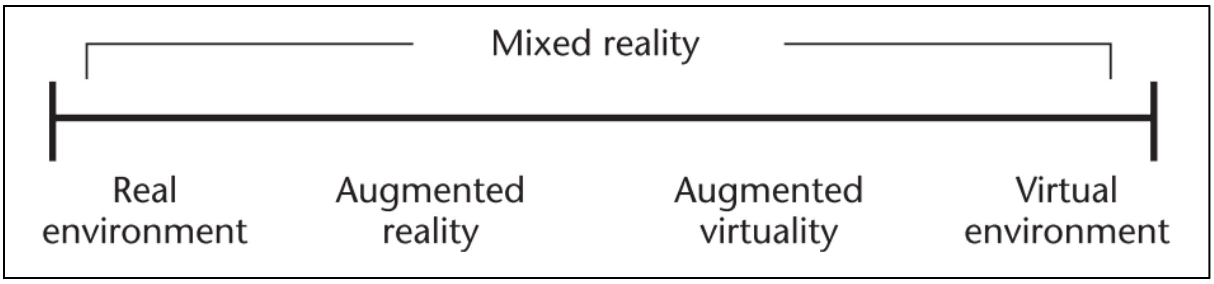


Image 17: a visualization of the mixed reality landscape. Adapted from Milgram and Kishino [42].

Let's talk about the spectrum and the four categories defined within image 17 with the exception of the real environment since that would concern our unenhanced real world.

A virtual reality environment attempts to suppress all senses of the subject in order to make room for new sensory input that is virtually created. The subject is therefore closed off from the real world. Popular examples are virtual reality glasses such as the Oculus Rift and HTC Vive. These types of solutions often cover the visual and auditory senses. Haptic gloves can be used to create a virtual haptic sensation and there are even solutions for creating olfactory sensations e.g. smells.

Image 18: In virtual reality, senses are blocked off in order to be replaced. In this picture we see a man use an HTC Vive for visual VR, a headset for auditory VR and HapTX haptic gloves for haptic VR.

Augmented virtuality is equal to a virtual environment that is enhanced and supplemented by virtually placing real-world objects inside of it or using other real-world factors.

Augmented Reality

According to Azuma [43] a (visual) AR system should:

- Combine real and virtual objects
- Run interactively and in real-time
- Register and align the real and virtual objects

In the context of this project, we are primarily discussing Augmented Reality. There are different ways of augmenting virtual layers on the real world. Subsets of this modality are spatial augmented reality, recorded augmented reality, and see-through augmented reality (which in turn includes head-mounted displays). The four types considered for this project are discussed in more detail in chapter 5.4.

When objects are removed or replaced in the real environment this can additionally be called *mediated* or *diminished* reality. If this is done carefully and in a contextually adaptive manner it can be deployed to lower perceived complexity.

Image 19: The physical equivalent of a "diminished reality". The TV remote has all buttons that are not needed covered with tape to minimize confusion and misuse. Image source: Reddit.

Spatial Augmented Reality

In their book about Mixed reality experiences Meschini et al. [44] define Spatial augmented reality as *"augmentations of real-world objects and scenes without the use of special displays such as monitors, head-mounted displays or hand-held devices'. SAR makes use of digital projectors to display graphical information onto physical objects"*
This definition ties SAR specifically to the use of digital projectors and prescribes that any other medium cannot create a SAR.

For the purpose of this project, we will slightly broaden this definition. We define SAR as *the use of augmented layers of visual information that use the same spatial distribution as the real world*. This definition would include projects such as The Shaderlamps project [45] see (image 20)., in which a hand-held device is used to project on objects. This would fall outside the original definition provided by Meschini et al, while it could easily be argued that this is an excellent example of the spatial variation of AR.

Image 20: This 2001 project called Shaderlamps [45], [46] *explored a variety of tabletop applications to apply colors and textures to real-life objects using projectors.*

Image 21: Projections can be used to illuminate shelves and products in storerooms. guiding employees to a specific product, giving alerts when supply is low and providing improved situation awareness in general. Image source: Alexander Isreb on Pexels (Creative Commons).

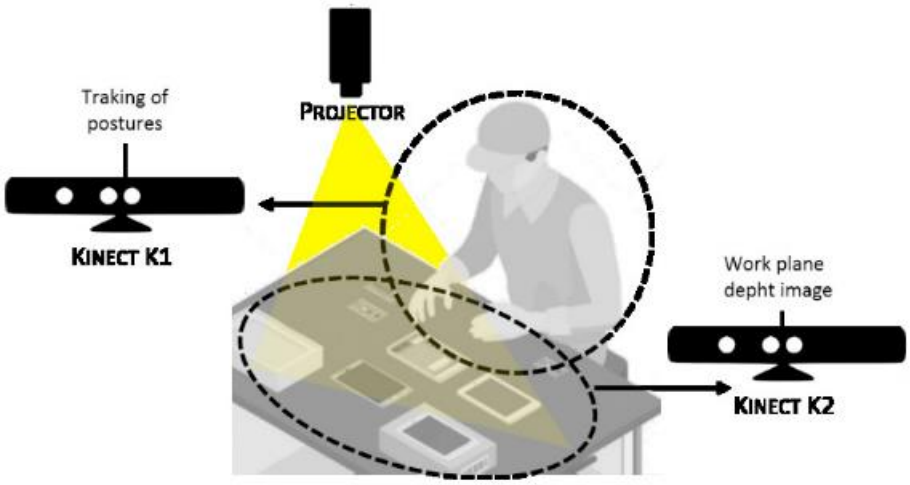


Image 22: Multiple academic groups are researching possibilities to use spatial augmented reality to aid in repair, maintenance, and assembly tasks. This is an example from Mengoni et al. [47] *using a projector and depth sensors (Microsoft Kinect) to aid in the assembly of a phone.*

Only when this is done in collaboration with cameras and other sensors we can speak of real augmented reality because the information becomes interactive and updates in real-time, fulfilling the second requirement set by Azuma et al. (*an AR system should run interactively and in real-time)* [43]

Because multiple people can observe the same augmented information in the real world without the need for installations that measure the human observer (transparent screen) or hardware mounted to the human observer (HMD) this approach has been found well suited for collaborative applications. More specific applications of Spatial Augmented Reality are outlined in chapter 5.3 where we shall discuss it in relation to AGVs and situation awareness.

Technological challenges and limitations

While VR headsets have proven to induce a troublesome amount of motion sickness and dizziness in some individuals, research indicates that this may be less the case for AR headsets [48] because most of the visual context used for orientation is maintained. However, research still needs to be done toward the potential health risks of elongated AR headset use.

Applying spatial augmented reality can only be done for selective spaces. Illuminating entire factories with projections is (and will probably remain) too costly, both in terms of installation and maintenance. One way to minimize the hardware cost is to consider which contexts are best suited for enrichment with spatial augmented reality solutions. Another way is to make the projection move with the user (for example the shaderlamps project in image 20 or by attaching the projector to an AGV)

Although Azuma et al. describe that all senses can be augmented [43], Mangold estimates that 85-90% of information processing by humans is done by the visual system [49].
Therefore we prioritize visual augmentation while keeping in mind that auditory and haptic augmentation are promising additions to support and enrich a visual augmented experience.

3.6 Key insights (fundamentals)

The following list contains the most important insights that are relevant for the project:

- The development of AGVs is a prime driver for other industry 4.0 innovations.
- There are certain prerequisites for an industrial smart AGV network:
  - The factory needs a high sensor density approaching the level on which a digital twin of the factory can be made.
  - There needs to be a state of cooperation between industrial robotics and human workers. This in turn requires a multitude of innovations to streamline and optimize the interactions between them. This project aims to contribute in this regard.
- The road to Industry 4.0 is vastly different from industry to industry and from company to company. For Magna smart adaptive transport systems are pivotal to prepare for a market that is becoming more and more demanding in terms of speed and customizability.
- This project focusses on the optimization of the visual communication of spatial information between human and machine. Other challenges in the AGV industry such as planning, scheduling, navigation, and localization are left out of focus.
  The communication is divided into 3 parts: legacy (past), status (current), and intention (future).
- For this project we consider the AGVs to use LiDAR sensor for the SLAM method.
- Within the AGV system, the balance between autonomy and supervisory control will shift more toward autonomy as we move to more futuristic industry states.
- Endsley's model and definition are used to define situation awareness.
- The decision of a SA measurement method depends on the type of evaluation chosen for the later stages of the project. SAGAT can be used in user simulations while SART is applicable on a wide range of other types of evaluations.

- Within the virtual continuum as defined by Milgram and Kishino this project focusses on augmented reality with a focus on the spatial variety because it is specifically potent in visual spatial communication.
- Applying spatial augmented reality on an entire factory at the same time is (and will probably remain) too costly. The context of application needs to be carefully considered so spatial augmented reality can be applied where it brings the most value.

Chapter 4

Contextual Research

On 11 September 2019, a visit was brought to the Smart Factory department of Magna in their factory plant in Graz, Austria. Presentations were given about Magna's efforts to move toward the industry 4.0 paradigm, their AGVs, and developments in the fields of AR and VR, big data, and Internet of Things. In chapter 4.1. the key insights from the visit are discussed. In chapter 4.2 this information is processed to formulate the vision of Magna regarding the smart factory and its components such as AGVs. In chapter 4.3. we discuss the three distinct factory states, which are abstractions of the technological state of the current factory (current state), the future factory (intermediary state), and the factory in the far future (future state). Chapter 4.4 talks about four different application contexts, which are specific user roles and scenarios for which AR designs could be made. The factory state and application contexts are variable factors of the scope.

4.1 Key insights Graz visit

See appendix B for a complete set of notes concerning the visit to Graz.

AGV prototypes

The Smart Factory team has created three AGV prototypes of which the last one is ready for use in a real manufacturing context.

The lighting system used in prototype 3.0 covers a wide range of necessary Human-Computer communications such as a few status indications (loading, waiting, starting to park, etc.) and intentions ("will make a left turn")

Image 23: [REMOVED] A rendering of the Magna AGV Prototype 3. Further information was removed to protect sensitive business information.

Image 24: Magna AGV Prototype 1 in action with a storage delivery rack mounted as a modular attachment.

Opportunities:

- Sound is not yet used for communication between AGV and workers.
- The first prototype contained a screen for showing sensor info, error states and other metrics. Prototype 3.0 no longer contains a screen. This information is found on the desktop application. A screen can be useful for workers that require more detailed information about an AGV (current task, error state, etc.)

Image 25: The screen on prototype 1 shows additional information such as the values of the sensors and the status of the AGV.

The AGV can be outfitted with different addons (robot arm, storage rack or a lift that can carry a Euro pallet). The AGV uses depth sensors to sense if an obstruction is nearby. If the obstruction is in the warning zone the AGV will slow down. If the object enters the Stop zone the AGV will make an emergency stop.
The AGV uses the SLAM method for navigation in combination with InCubed software. The SLAM information is shared with the central server so a real-time map of the factory is built which all AGVs can use.

Industry State

Many OEMs (Original Equipment Manufacturers) are researching technologies that allow for advanced intralogistics solutions (in line with the industry 4.0 vision). The way that these technologies are implemented will greatly influence the role of the AGV and the way it is controlled.

Supplementing the industry 4.0 paradigm, there is also a vision of the reconfigurable smart factory: a highly flexible factory floor on which all machinery and parts are transported by or mounted on AGVs. All hardware is only present where and when it is needed.
New technological integrations are needed to make this a reality. Innovations such as AR, VR, AI, IoT, big data, and predictive maintenance can help.

Magna has already successfully utilized a large range of these technologies in real cases:

- Product impression in VR (showing customers and clients cars in a VR environment).
- Ergonomics evaluation in VR.
- Walkthrough of a production set with the client (the manufacturing and assembly line) in a 3d model.
- Augmented reality is used for quality control. Going through the checklist with an AR headset on. Quick access to documentation. Automatically run down the checklist. This greatly reduces errors.
- A meeting space with 3 integrated projectors, and a large central touch screen which is engineered towards effective meetings both internal and with suppliers and clients.

The amount of sensor data collected in the factory is already enough to allow for a digital twin to be constructed. This amount of data can be used to have the system present decision-makers (supervisors) with actionable information.

The CoCoAs project proposal specifically mentions the development of swarm behavior that will allow groups of AGVs to transport larger units such as complete cars. However, this is currently not a development priority.

Current AGV implementation

In the current factory, forklifts are outfitted with a screen that shows the tasks assigned to that forklift (for example: 3 pallets labeled JM01 from loading dock C to assembly line 59).

AGV’s are also used inside the factory and are a vital part of the assembly line.
To give an example of a current AGV implementation: an AGV brings car seats from one side of the assembly line to the other, greatly increasing efficiency and reducing costs. The AGV is alone and mostly isolated from the other subsystems of the factory. Its behavior is simple and predictable and only deviates if a worker enters its direct surroundings. (a more detailed look on this can be found in ‘Industry state – current’)

[redacted]

Image 26: [REMOVED] A screen of the forklift driver gives a good indication of the distribution of tasks. Specific forklifts get tasks to deliver a specific number of pellets from a location to another. Further information was removed to protect sensitive business information.

The factory currently has a layout that is similar to a district with streets. Vehicles keep right and can not deviate far from their planned route. In a context like this the usefulness of autonomous wayfinding is limited. Obstructions are very temporary.

In the “reconfigurable smart factory” however, the street layout will disappear, and the layout will be in a state of continuous change. Adaptive wayfinding will then be essential for the efficiency of the AGV.

4.2 The Magna mission

Magna International (of which Magna Steyr is a part) has more than 60 years of experience in the automotive industry. Magna creates components and entire cars for a very large variety of car brands (General Motors, Ford, BMW, Mercedes, Volkswagen, and Tesla Motors, among others).

The automotive industry is moving more and more into a future where the car as a product is highly customizable. Current day manufacturing and assembly practices allow only for superficial customizations such as interior and software options. All other customizations are costly and require parallel production sets.
Industry 4.0 developments are offering an increase in the flexibility that can be imbued in the assembly line. car manufacturers are already moving from ‘dedicated manufacturing systems’ that are geared toward a single product to ‘flexible manufacturing systems’ that can vary certain parts of the production within pre-set values. In order for the vision of Industry 4.0 to become a reality another step needs to be made toward reconfigurable manufacturing systems that can make a large variety of different products by reconfiguring the system during a relatively short changeover period [50]. Leading in these developments is particularly interesting for Magna because as an independent manufacturing partner their factories see a lot more changeovers than other manufacturers that focus on making a single model for a very long time.

As described in the fundamentals chapter a lot of other high-tech components associated with industry 4.0 are necessary to make the smart factory as efficient, flexible, and safe as it can be. Magna has a head start in these developments by already actively using technologies such as AR, VR, Big Data, and Internet of Things in their manufacturing process. In addition, Magna already has workable digital twins that can be used by potential AGV swarms.

In the smart factory of the future supplies, machines and cars need to be where they are necessary to accelerate the process. The application of AGVs is an essential key to achieving this flexibility.

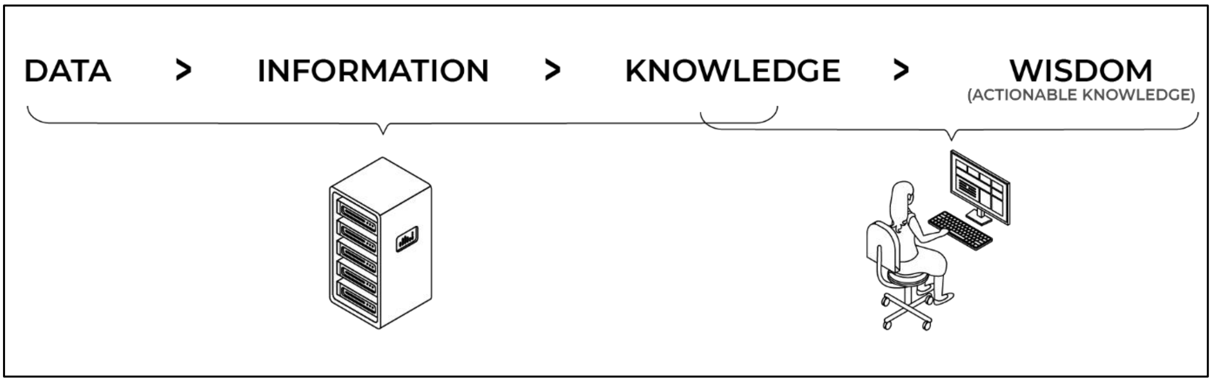


Image 27: Factory data is converted by the computer system into actionable knowledge. The point in the process where a human operator intervenes in this process is defining for the balance between autonomy and supervision.

The DIKW model [51] describes information as being structured in 4 levels: data, information, knowledge, and wisdom. Information is defined as data that is structured to contain meaning. Knowledge is defined as contextualized information. Wisdom is defined as knowledge that is fully understood and therefore actionable. This can also be called actionable knowledge.

One of Magna's goals for the future is to provide its process supervisors with more actionable knowledge. This indicates that in terms of the balance between supervisory control and autonomy as described in chapter 3.2 Magna wishes to move more toward autonomy of the system where only the highest level of decisions are made by human supervisors.

4.3 Industry State

The industry state is a measure to indicate how far a factory has progressed toward the industry 4.0 paradigm. This cannot be expressed on a linear scale because it is not standardized which technologies belong to this goal, in what way they are integrated into the manufacturing process, and in what order they are to be implemented. For this project, three phases are defined through which the Magna production set is expected to progress. On the following page, you will find three illustrations of strongly simplified fictional factories that show the Human-to-AGV interactions possible within it.

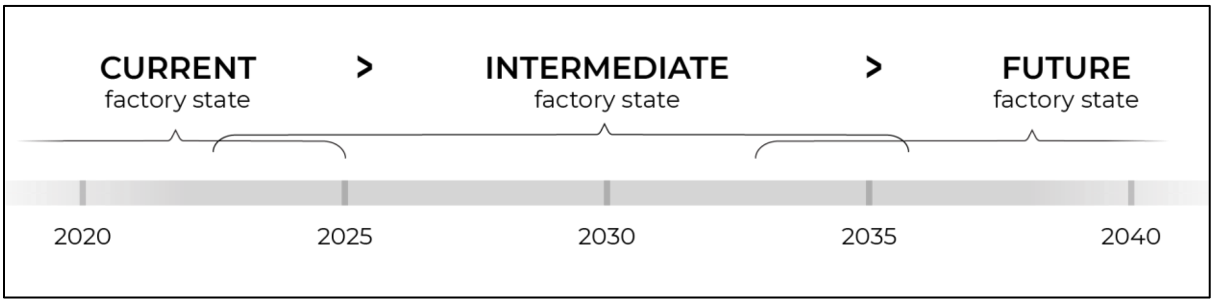
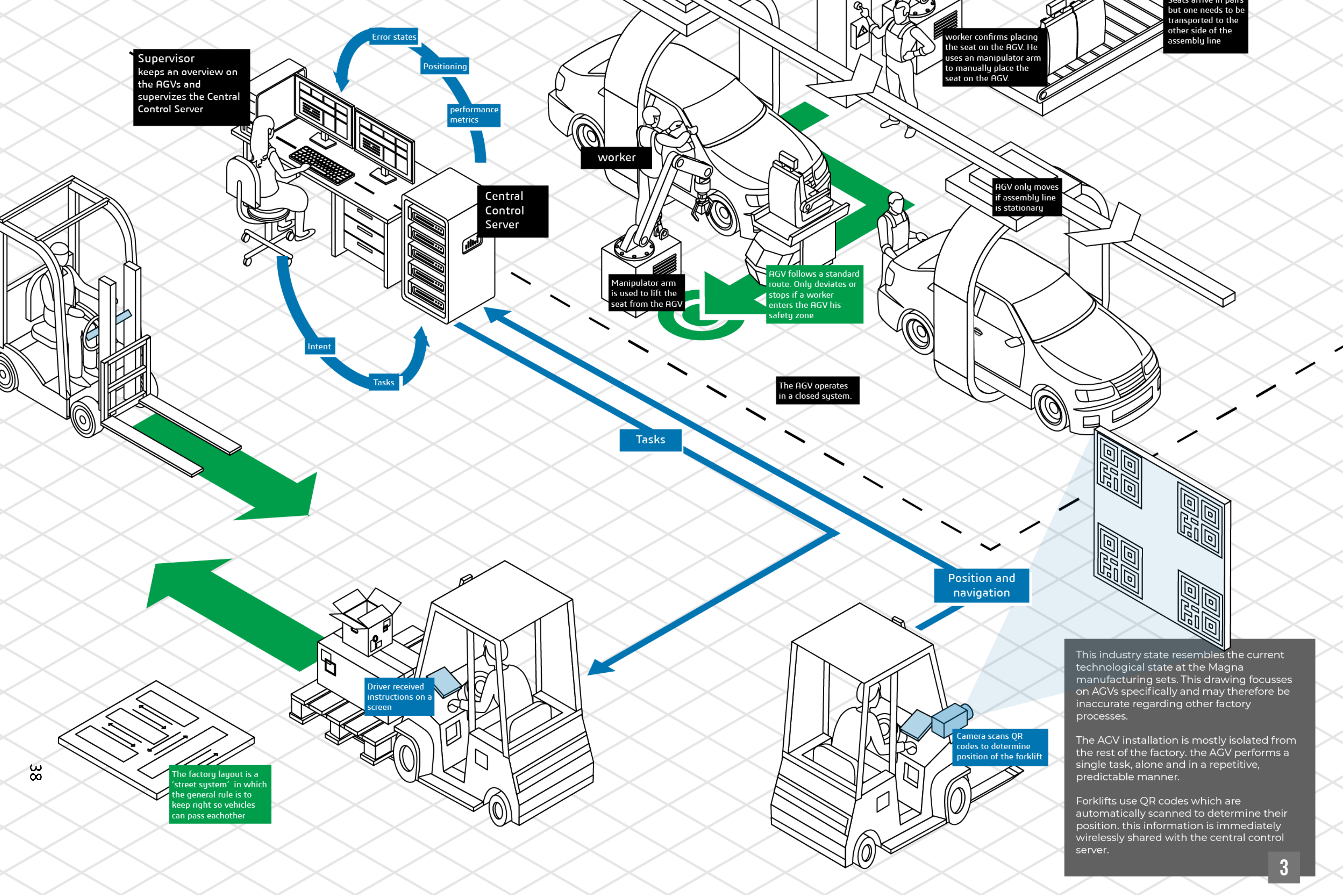


Image 28: Industry states are an abstraction of the state of technological integration. In what year other states are achieved is entirely dependent on business and investment decisions made by Magna. This image provides an estimation.

CURRENT INDUSTRY STATE



This industry state resembles the current technological state at the Magna manufacturing sets. This drawing focusses on AGVs specifically and may therefore be inaccurate regarding other factory processes.

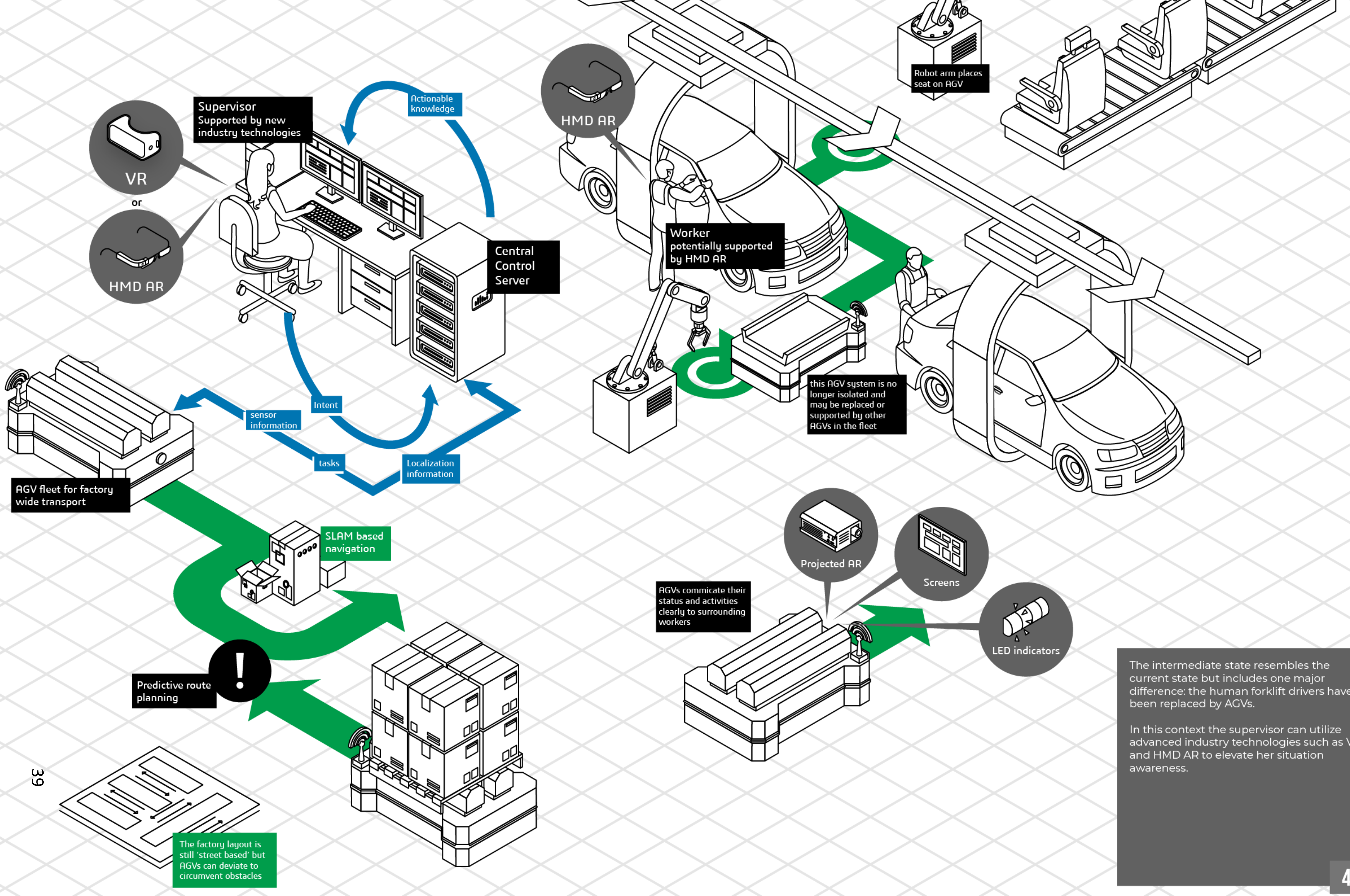
The AGV installation is mostly isolated from the rest of the factory. the AGV performs a single task, alone and in a repetitive, predictable manner.

Forklifts use QR codes which are automatically scanned to determine their position. this information is immediately wirelessly shared with the central control server.

3

INTERMEDIATE STATE

INDUSTRY 3.0



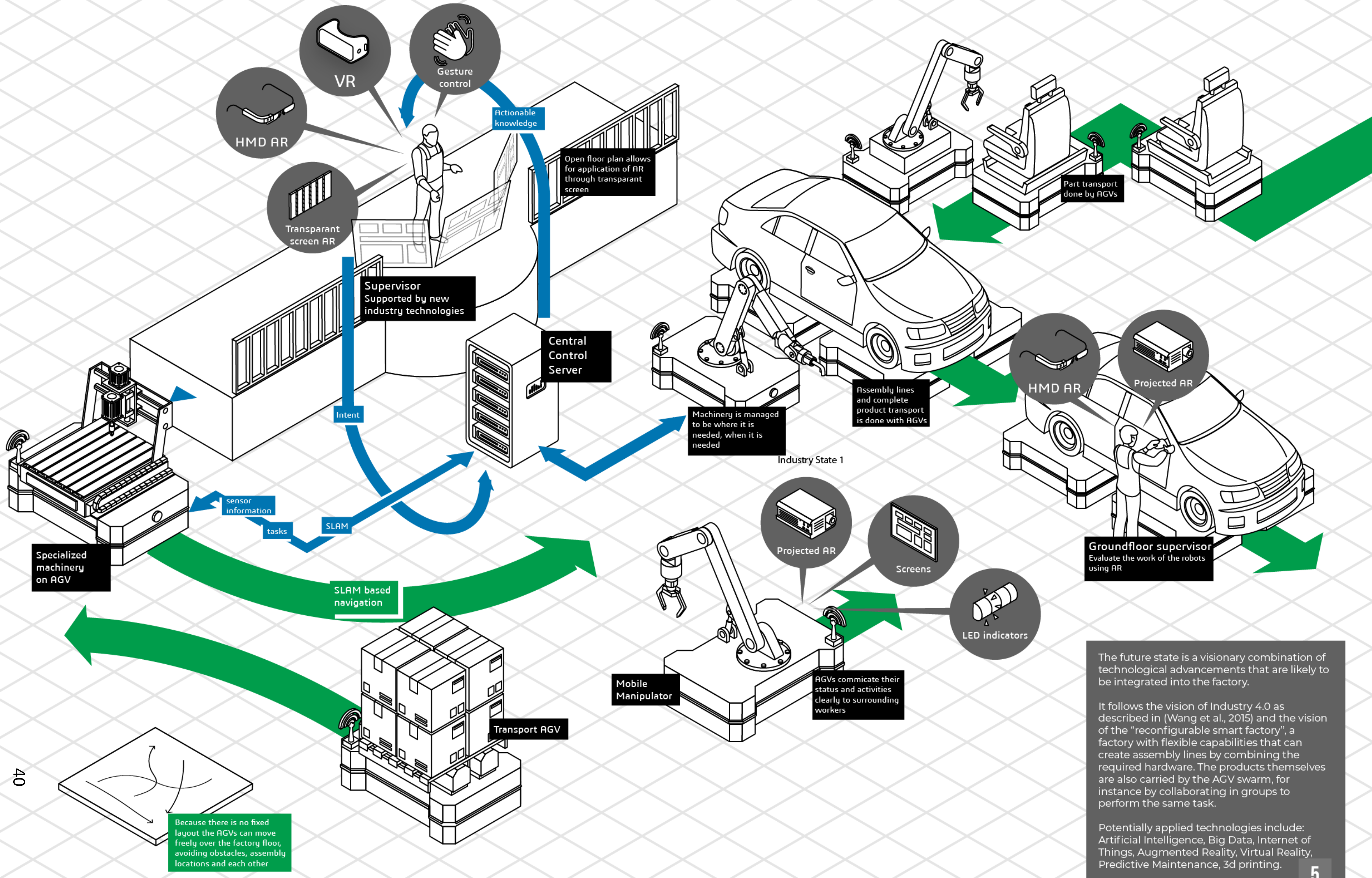
The intermediate state resembles the current state but includes one major difference: the human forklift drivers have been replaced by AGVs.

In this context the supervisor can utilize advanced industry technologies such as VR and HMD AR to elevate her situation awareness.

4

FUTURE STATE

INDUSTRY 4.0



The future state is a visionary combination of technological advancements that are likely to be integrated into the factory.

It follows the vision of Industry 4.0 as described in (Wang et al., 2015) and the vision of the "reconfigurable smart factory", a factory with flexible capabilities that can create assembly lines by combining the required hardware. The products themselves are also carried by the AGV swarm, for instance by collaborating in groups to perform the same task.

Potentially applied technologies include: Artificial Intelligence, Big Data, Internet of Things, Augmented Reality, Virtual Reality, Predictive Maintenance, 3d printing.

5

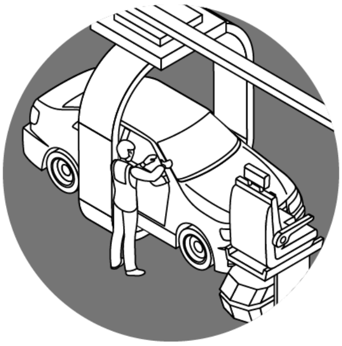
4.4. Application Context

De Pace et al. defines five major areas of application for AR in the industry domain: Human-Robot Collaboration, maintenance-assembly-repair, training, product inspection, and building monitoring [52]. Magna has already indicated to be actively applying AR and VR in at least the first four domains in this list. Four application contexts within the factory have been selected which are likely to benefit from AR solutions.

Supervisor/process- planner

The supervisor keeps an overview of all activities of the AGVs.
Future planning: the supervisor states his intent (e.g. we need to make 88 Jaguar E-pace with configuration X) to the central control server which translates this into tasks that are distributed among the AGVs. Alternatively, the supervisor enters a specific task for the AGVs to perform.
Status Quo: the supervisor monitors the current state of the assembly line.
Past: the supervisor evaluates irregularities and efficiency.

Factory floor worker



Workers on the factory floor share their work with the AGVs. It is essential that:

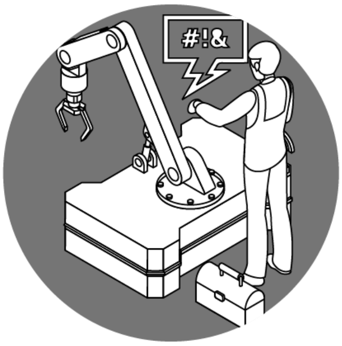
- They complement each other's work.
- Human workers do not block AGVs from fulfilling their tasks.
- Human workers feel safe and in control around the AGVs.

The responsibilities of the worker regarding the AGVs include:

- Execute small corrections of the AGV's actions.
- Solve small errors.

Larger constructive problems with the functioning of the AGVs are picked up by supervisors and maintenance.

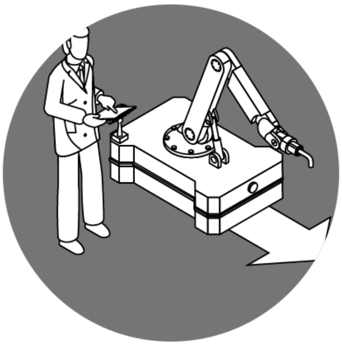
Troubleshooting / Maintenance



AGVs routinely need maintenance. Depending on the industry state the AGVs might be outfitted with predictive maintenance technology allowing it to evaluate and plan its own maintenance schedule. Explorations have been done to use AR as an indicative measure for the spatial locations of errors [53] [2] or using remote guidance to execute maintenance and repair tasks [54].

Troubleshooting is the activity of identifying and resolving an error state or incorrect behavior exhibited by the AGV. Much like a doctor diagnosing and treating a patient.

Installation



Installing an AGV solution is considered to contain the following steps:
Evaluation: assessing whether using an AGV is the most suitable option for the task.
Design: deciding how an AGV will execute the task.
Installation: The physical placement and connection of the AGV solution to the rest of the assembly line. (Cyber-Physical System design)
Testing: Evaluating whether the AGV installation was successful and making adjustments where needed.

This application context is mostly applicable to the current and intermediate industry state. In these factories, AGVs are matched by humans with specific activities. In the future industry state, almost all activities are executed by the AGV swarm autonomously and installation for isolated tasks is not needed. AR has found broad support for spatial planning tasks such as planning factory assembly lines [55].

Chapter 5

Research on related work

After defining the fundamental knowledge in chapter 3 and exploring the context of use in chapter 4, this chapter will look toward more specific research and technological applications. Several topics arise when the ‘ingredients’ from chapter 3 are combined.
In section 5.1 we take a look at the academic connection between the application of augmented reality and situation awareness. Section 5.2 gives an insight into the state of literature concerning AGV adaptation in the industrial context and what it means to create a ‘swarm’. Section 5.3 investigates the deployment of AR to monitor AGVs. That chapter also contains a section dedicated specifically to spatial augmented reality. Section 5.4 covers the four selected ways of creating AR, called *technological frameworks*, a variable factor of the scope of this project. In section 5.5 we recap the most important findings of the specific research

5.1 AR in relation to Situation Awareness

Because of the ability of AR to filter, select, and supplement information in a real-life setting it is often suggested as a technological means to improve situation awareness. Bell et al. explored this by providing workers with a miniature version of their surroundings in AR [56], thus providing them with improved situation awareness.

In the manufacturing industry, the relation between and AR and SA is very well researched. A valuable opportunity is the improvement of SA in remote collaboration [57] [58] as well as during the spatial planning of factories [59].

The link between Augmented Reality and Situation Awareness is also thoroughly investigated outside the manufacturing context. Lukosch & Lukosch [60] apply AR to create SA for collaborations in the security domain such as interactions between emergency and security personnel. Livingston did the same for a military context [61].

Image 29: Image adapted from Lukosch & Lukosch [60]. *Two policemen are virtually co-located using an AR HMD. The remote colleague can highlight suspicious objects in the scene or point in the direction of emergency exits.*

In these papers, a strong trend seems to be to limit the information found in mission-critical environments and to provide agents with contextually relevant information. The applications for the positive effect between augmented reality and situation awareness are not limited to any specific industries and the results found in academic research (improvement of situation awareness and reduction of mental and physical workload) are promising.

5.2 The smart factory and the AGV

The most striking difference between the past industry state and the intermediate state as seen in chapter 4 is the replacement of the human-operated forklifts by AGVs.
Toward the future industry state more and more machines will become AGVs as well (or become attachments for AGVs with more or less the same result)

The complete title of the CoCoAs project, of which this project is part (see stakeholder map in chapter 2) is *'Collaborating and coupled AGV swarms with extended environment recognition'*.

When we talk about a swarm, we mean a step beyond centralized control of the AGVs. In a swarm the loose elements (in this case the AGVs) are 'conscious' of each other's activities and can act to supplement each other resulting in a collective behavior rather than the sum of multiple individual behaviors. An example of this would be to use multiple smaller AGVs to move a car that could not have been moved properly with one single AGV. This kind of swarm behavior belongs to the 'future industry state' as described in chapter 4.3.

In a system that contains strictly machine-to-machine interactions, everything can be geared toward efficiency, cost, and risk reduction. Adding humans to the equation makes the situation a lot harder to optimize because the human to machine interactions are more complex and introduce more factors to the situation that need optimization. For the smart factory, it is no longer enough for the AGVs and workers to simply coexist, they need to collaborate in a shared work process [62].

One of the factors introduced when humans enter the equation is called 'social cost' and is a collective term for everything that is demanded from the human interacting with the AGV. Loss of trust or an annoyance with the way the AGV behaviors would be examples of social cost. Researchers such as Ramon-Vigo and Perez-Higueras apply 'inverse reinforcement learning' to derive social cost functions that can help predict what the most preferable robot behavior would be [21], [63]. These researches however were done for autonomous robots working in public spaces such as museums and boardwalks where socially acceptable behavior is very important. In the industrial context, the balance between social cost and financial cost will tend to move toward the financial side instead. The advantage of a specialized context such as a manufacturing factory is that users can be trained in the proper interaction with the AGVs and can be required to wear certain safety or guidance measures such as safety vests [40].

5.3 AR and AGVs

Augmented Reality and AGVs

De Pace et al. [52] describes that AR is a promising technology that can enhance the user's ability to understand:

1. The movements of a mobile robot.
2. The movements of a robotic arm.
3. The forces applied by a robot.

These are all metrics that, when communicated sufficiently with the operator, improve his or her situation awareness. Specifically, the first enhancement (movement of a mobile robot) is relevant for this project while the other ones becoming further stretching opportunities once AR frameworks are adopted within the factory.
While numerous innovations have been proposed to use AR technologies to assist in robotic path planning [14][64], these researches take a different approach to the application of AR. For example, Erdei et al. [14] use AR to scan QR-tags to locate AGVs in the factory. The AR is used as a sensory system for robot-to-robot communication instead of the robot-to-human communication investigated in this project.

Let’s take a look at two research initiatives that propose methods meant for increasing and improving the information available to the operator through AR, an endeavor more in line with the goal of this project:

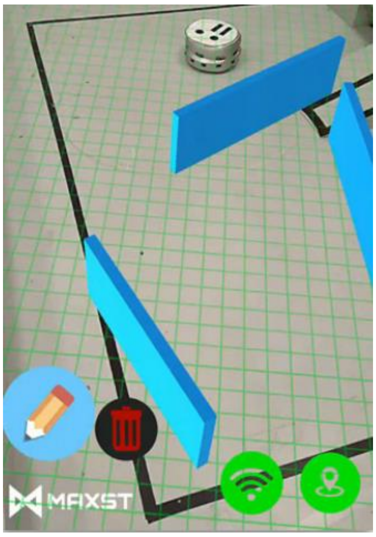


Image 30: Within the app the user can place and see virtual obstacles that the AGVs consider. The user can influence the AGV path and he or she can see the world like the AGV does (image adopted from Papcun et al. [23]*)*

Papcun et al. [23] propose a system specifically designed for the transition from the more static ‘fixed slotting warehouses’ to the dynamic ‘chaotic slotting warehouses’. This is a vision that is in line with the expected developments described in chapter 3.1 concerning the smart factory and which reserves an important role for AGVs. The proposed system uses recorded AR through a phone (see chapter 5.4. recorded AR) or smart glasses (see chapter 5.4 HMD AR) to highlight obstacles and paths for the user.

Piardi et al. [65] present a system called ‘ARENA’ meant for active experimentation in smart warehouses, aiming to promote the real characteristics of the factory floor. Video footage of the factory is overlaid with an AR layer which adds information about states, zones, AGVs, tasks, and other elements found in the factory (see chapter 5.4 for an explanation of the ‘recorded AR’ technological framework).

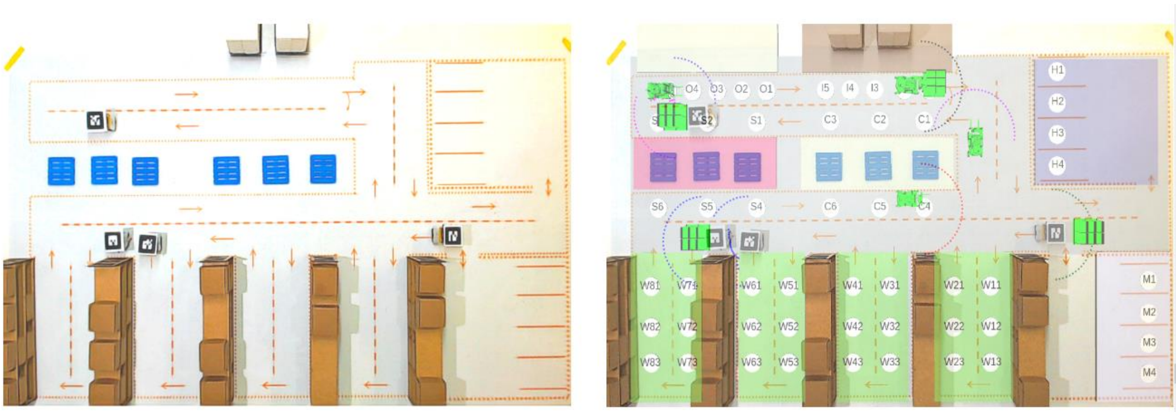


Image 31: visualization of the ARENA system [65]*. On the left we see an impression of the warehouse. on the right we see the same warehouse with a layer of information showing sections, AGV paths, and AGV safety zones.*

Spatial Augmented Reality and AGVs

When designing an interface solution for the problem of improving perceived safety and situation awareness in the study of Human-Robot Spatial Interaction (HRSI) It might be logical to resort to spatial interfaces.

There are promising leads that indicate that simple solutions such as lamp indicators (that communicate a navigational intention) improve the comfort experienced by the users [35]. However, this modality has a limitation in terms of expressing detailed navigation information such as future trajectory and context-dependent information [40]. Spatial augmented reality offers many advantages in this regard. Researchers like Chadalavada et al. and Matsumaru have done multiple experiments with a projector unit mounted on top of a mobile robot. By projecting simple information such as the future trajectory of the mobile robot and safe paths around it on the shared floor they were able to improve the communication, reliability, predictability, transparency, and situation awareness as it was perceived by the human subject [66], [67], [68]. Coovert et al. use comparable hardware to demonstrate that individuals can determine the upcoming movement of the AGV with high confidence [69]. Further advantages of the SAR method are demonstrated by Park [70], who shows that projections around an AGV can be an alternative to anthropomorphic interaction styles and can solve the ergonomic difficulties that touch screen interactions have.

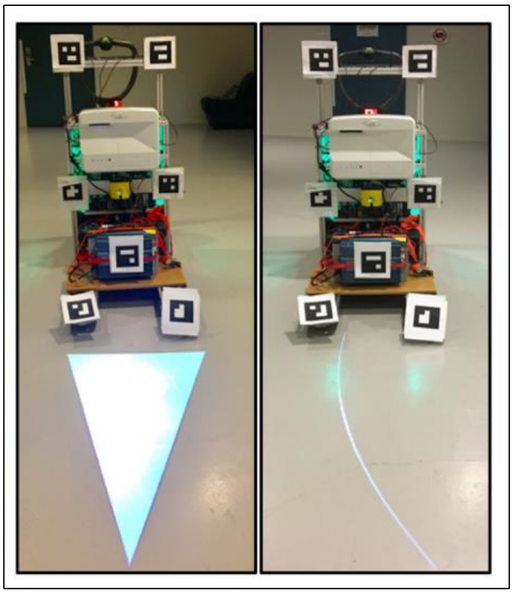


Image 32: adopted from Chadalavada [40]. The research compared the capability of intent communication of a projected arrow, a line, a blinking arrow or nothing.

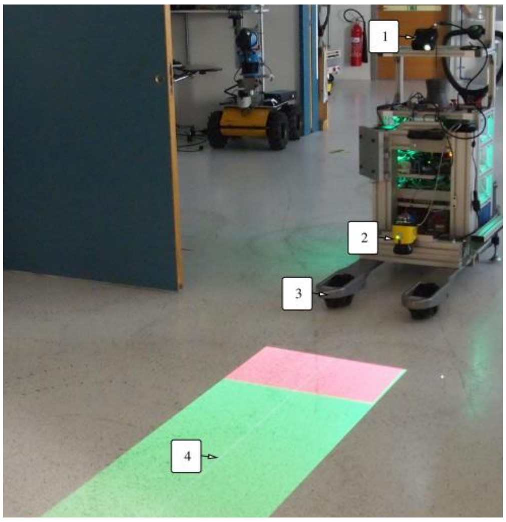


Image 33: adopted from Chadalavada [67]. a projected indication of the area needed for an emergency stop (in red) and the footprint of the robot in the next 5 seconds (in green). A barely visible white line should indicate the direction. The goal of these experimentations was to see if information like this spatially mapped would influence human trust in the robot. Trust was defined as a combination of 5 attributes: communication, reliability, predictability, transparency and situation awareness. The perceived values of the factors were measured in human subjects and a significant increase in all 5 attributes was found when the projections were provided compared to no projections.

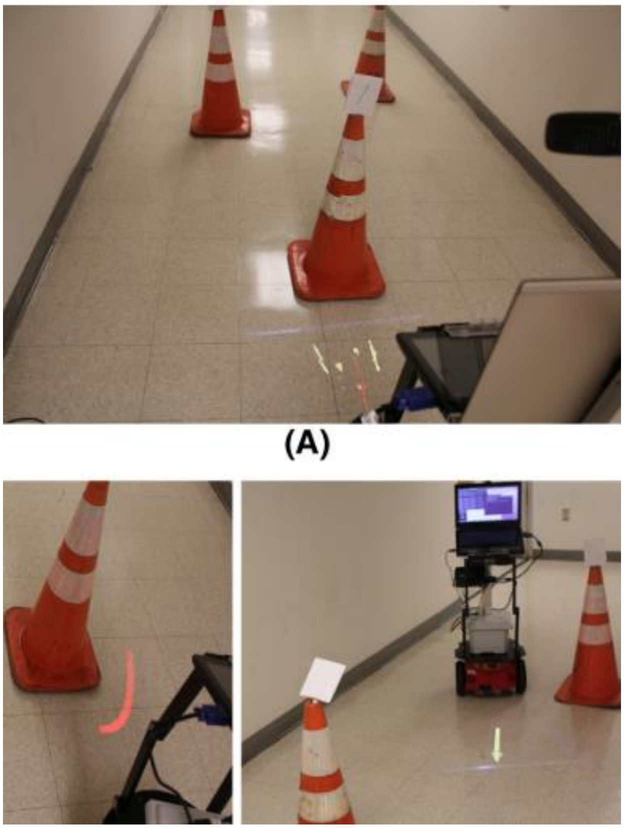


Image 35: an experimental setup by Coovert [69] *shows the user which obstacles have been perceived by the AGV. The sytem makes distinctions between short term, mid term and long-term problems and assigns visual cues which signal an appropriate amount of urgency.*

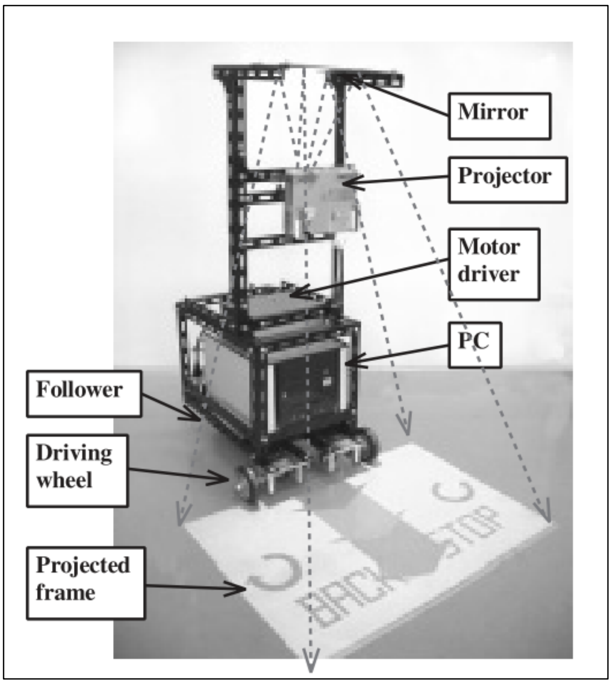


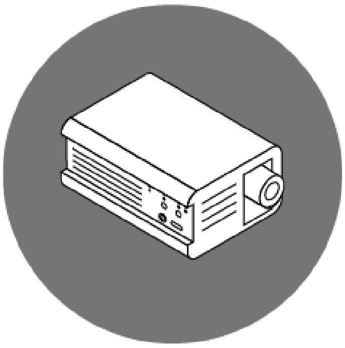
Image 34: Matsumaru [68] *shows various pieces of information in the projection: an arrow indicating direction and speed, status information, and incoming motions such as a revolution on the spot.*

Image 36: Park & Kim [70] *propose to use projections on an Autonomous robot as an alternative to the anthropomorphic interaction paradigm (imitation of human interactions). Interactions are facilitated through mobile devices or a laser pen.*

5.4 Technological Framework

Visual augmented reality can be achieved in a variety of ways. Considering the contextual research of chapter 4, four methods for creating AR have been selected that are deemed feasible for the manufacturing context. We call these methods 'technological frameworks' and they are a variable factor to the scope of the project (as explained in chapter 1.1), meaning that one will need to be selected.

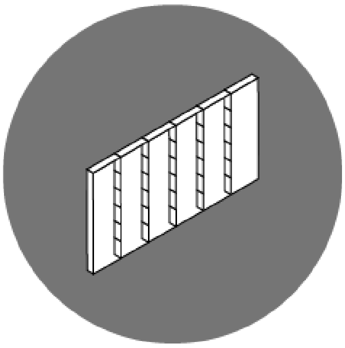
Projected AR



A projector is used to display information on the object itself.

This is a form of Spatial augmented reality. The augmented layer is created with hardware that is external to the user. A group of people can look at the same augmented object for cooperative purposes.

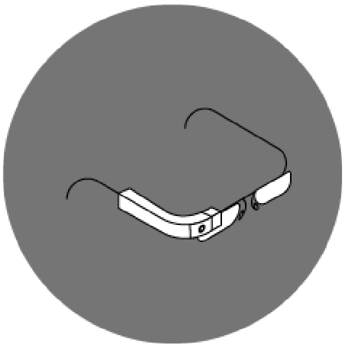
Transparent Screen AR



A transparent screen is used to add a layer of information to the real world.

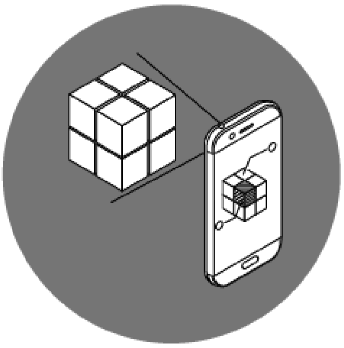
This can be done with transparent OLED or by using holographic glass such as the HOPS projection glass [71]. This is a type of glass that reliably redirects light if it hits the glass under a specific angle. Using a projector an image can be projected while the rest of the surface remains transparent.

Head Mounted Display (HMD) AR



The user wears a contraption on their head, similar to a pair of glasses which adds a digital augmented layer to the vision of the user. A large variety of methods can be used to create the augmented layer. Well known examples include Google Glass, Magic Leap, and the Microsoft HoloLens.

Recorded Augmentation



When a real-life scene is captured by a digital camera and digitally enhanced or supplemented before playback, we define this as ‘recorded augmentation’. Modern hardware reduces the playback delay to such low levels that it is perceived by users as a real-life display.

A popular example is the mobile game Pokémon Go, where apart from using the players’ actual GPS location for the game, monsters are augmented in footage that is recorded and played back on the mobile device. Because this can be done by almost any smartphone, this method is relatively cheap, and the technology required is widely available.

5.5 Key insights (Specific research)

The following list contains the most important insights from this chapter that are relevant for the project:

- Research has indicated that applying augmented reality is a useful measure to increase situation awareness in an industrial setting. Observing the development of factories becoming more dynamic and chaotic, many researchers focus on improving the information flow to the operators. Applying AR is a promising tool to facilitate this. Spatial augmented reality in this regard is especially interesting because it is a good fit for the highly dynamic and collaborative industry 4.0 future.
- Advantages of spatial AR compared to HMD AR and recorded AR:
    - Multiple people can look at the same augmented layer and they will be looking at the same information mapped in space in the same way, meaning they can discuss the information with confidence that it is presented to everyone in the same way.
    - Less expensive hardware is required.
    - Users do not need to fit an HMD on their heads and calibrate the display.
    - Communicating spatial information works the most intuitively when done in a spatial manner.
- When introducing a more autonomous behavior in AGVs, more social elements need to be introduced to make the AGVs capable of co-habiting and co-working with humans. Examples are social costs, the perception of the AGV behavior, and perceived safety.
  AGVs in closed environments such as a factory can however be approached differently than AGVs that interact with the public. Optimization can be shifted toward efficiency rather than the social desirability of the behavior because workers can be trained on how to interact with the AGVs.
- A future as described in the 'future industry state' (see chapter 4.3.) will probably bring swarm intelligence to AGVs enabling collective behavior and the pursuit of collective goals.
- With the 'ARENA' system. Piardi et al. [65] propose a set of information that may be overlaid on top of a factory layout to offer more information to operators. It should be noted that ARENA focusses on the design of new factory layouts rather than factories that are in full operation.
- As described by Park et al. [70] spatial augmented reality can provide an alternative to anthropomorphic interaction styles and can solve the ergonomics problems present in touch screen solutions.
- Personalizing the projected information can be an interesting opportunity, also proposed by Chadalavada [66].
- Lessons learned during this project may also apply to other mission-critical contexts since many of these industries are looking for suitable AR interventions and conditions are often comparable.

Part 2

Development & Iteration

Chapter 6

Solution spaces

As explained in chapter 1.2. (the scope) a solution space is a combination of all factors of the scope. Apart from the fixed factors, it consists of one chosen industry state, one application context, and one technological framework. Since there are three industry states (current, intermediate, future), four application contexts (supervisor, worker, maintenance, installation), and four technological frameworks (projected AR, transparent screen AR, HMD AR, recorded AR) this combines in a total of 36 possible solution spaces. Only if an AR intervention can reasonably be applied in the given combination a part of the morphological chart will be colored green and thus marked 'fertile' for AR solutions (see chart on page 55). For example: a transparent screen AR will not work for the supervisor in the current and intermediate industry state because it is expected that the street-like infrastructure will obstruct the direct view of the supervisor.
The decision about whether a solution space is fertile for innovation or not is not as binary as the chart suggests. The decision is based on multiple factors described in chapter 1 and the designer's vision.

6.1 Selection criteria for a solution space

Requirements derived from the assignment

As is described in more detail in chapter 1.2, the scope of the project is defined by the following fixed requirements. The project involves:

- Interaction with **AGVs** and not with other machinery or robots.
- The application of **augmented reality.**
- The **visual communication between human and machine.**
- Improvement of the **situation awareness** within the chosen application context.

Situation awareness is a less relevant measure in the application context of maintenance and installation. This makes the solution spaces for these application contexts less suitable for this project.

Requirements from Magna

Magna wants to have the augmented reality solution **integrated into the existing AGV platform**; this means that the next innovative step taken should connect to the factory context as it exists now while also extending further than the current possibilities. This indicates a strong preference for the intermediate factory state.

Of course, the solution will need to be **economically viable** for Magna, delivering value that exceeds the investment costs.

Magna has a strong preference for solutions that **aid the factory floor worker** and sees less potential value in creating AR solutions for the supervisor /process-planner position

Installation of new AGV systems is done by external companies which makes AR interventions meant for the **installation process** less interesting for Magna.

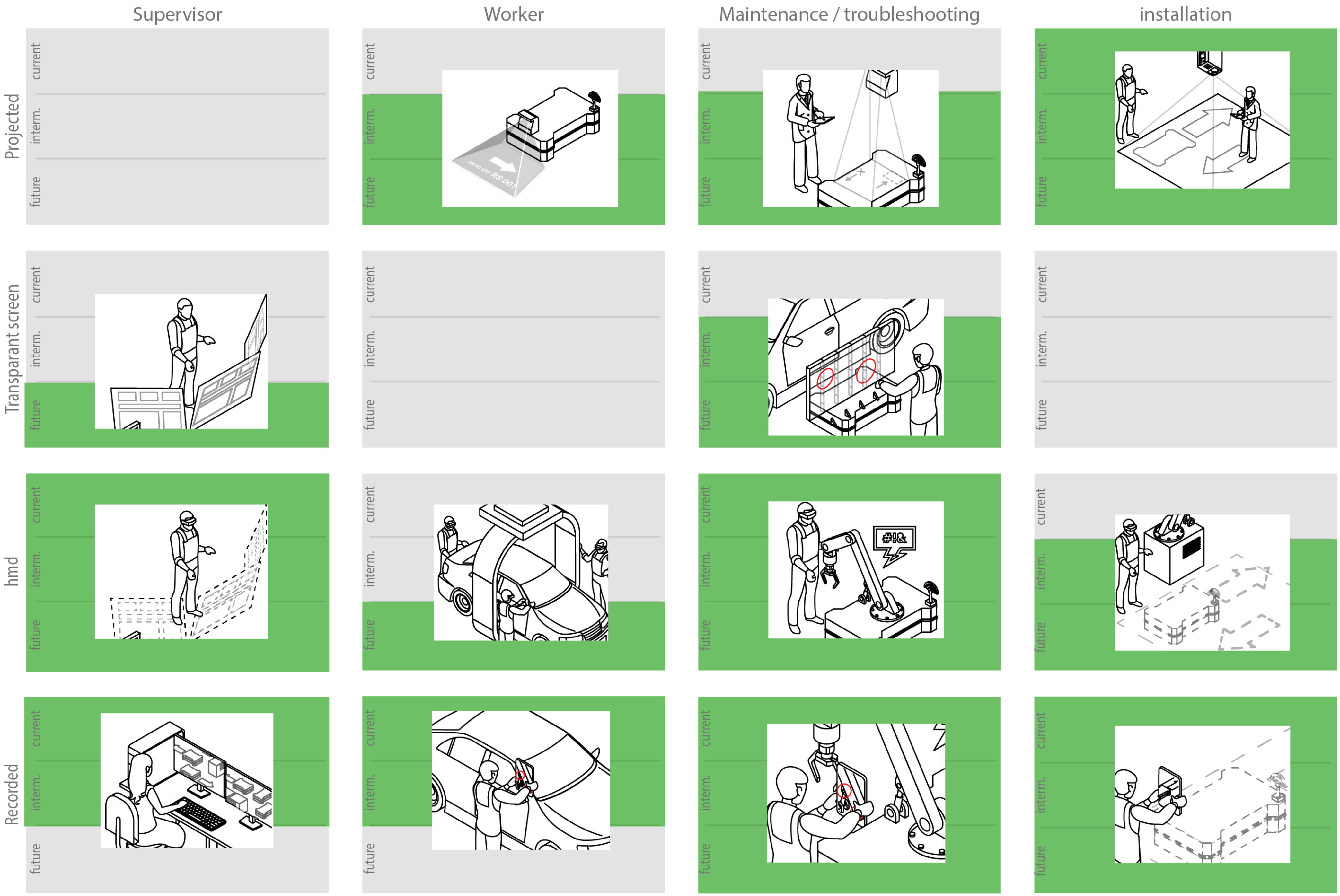
Directions from personal vision

In my vision, augmented reality solutions will become not only an important part of the industry but also in our personal lives. Although augmented reality has the ability to enhance the communication between machines and humans it should not limit or obstruct communication between humans in the process. Technological solutions such as head-mounted displays create a personalized augmented layer which may become a barrier for human-to-human communication if not correctly calibrated. This may become an obstacle that makes the AR technology less accessible. Because of these observations a preference exists toward a projected spatial augmented reality solution.

Vision-based design

A big design challenge within this project is created by the fact that many research fields discussed in this report are all under active development or still in their infancy. The design problem does not yet truly exist because the technological conditions in which that design would be necessary are still in their early phases.

The approach for this project will therefore be based on a vision of the smart factory and the technologies that are part of it. This might mean that the world in which this ideation is performed might develop in a different way than was assumed in this report. An example of vision-based design is the industry states as illustrated in chapter 4.3. A lot of substantiated assumptions need to be made in order to assess what the factory will look like beyond the year 2025. However, this practice does allow for meaningful ideation with a clear goal without having to resort to generalized conclusions because of the unfinished state of the industrial development.


Supervisor
Worker
Maintenance / troubleshooting
installation
Projected
Transparant screen
hmd
Recorded
current
interm.
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JM 00 VTF RS 001
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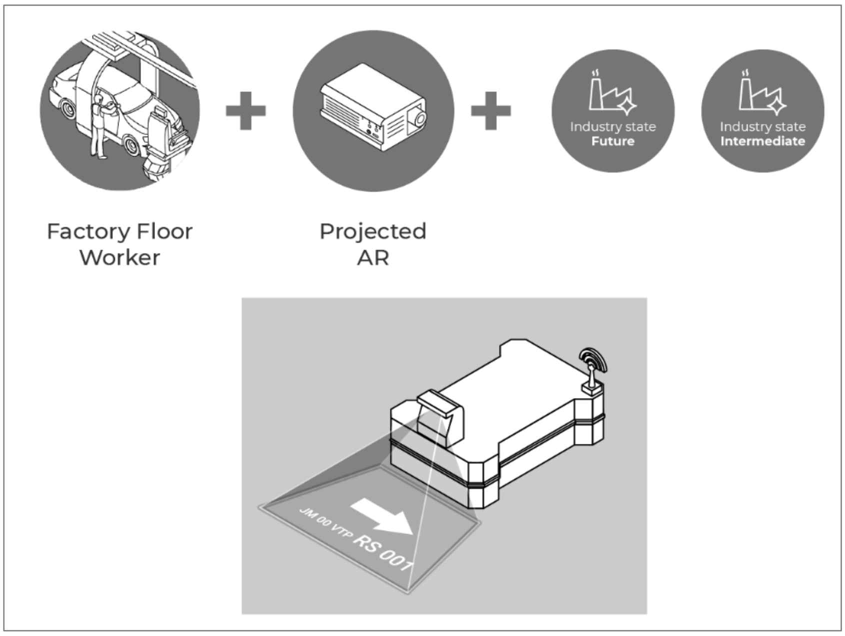
6.2 Nominated solution spaces

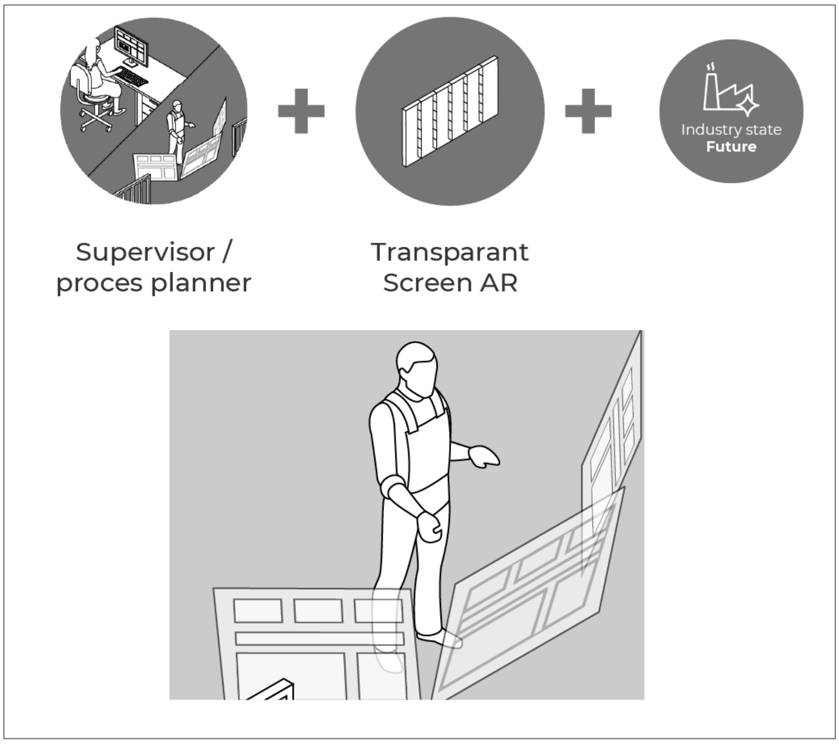
Two solution spaces were selected as suitable for the project.

AGV with mounted projector



An ultra-short throw projector mounted on top of an AGV could illuminate the ground around the AGV offering numerous opportunities for enhanced communication between human and AGV as demonstrated by Chadalavada, Coovert, Park, and other researchers [40], [66], [68]–[70], [72].

AR cockpit with a transparent screen



From an unobstructed point of view a factory supervisor or process-planner can see the real factory with augmented layers provided by transparent screens.
This is a design direction not yet pursued by academic discourse. This may be the case because a design of this kind would require a factory floor that grants open view over a large section of the factory. Currently, many factories do not offer such an unobstructed view. The future smart factory as it could be envisioned might offer a suitable context for this design.

6.3 Selected solution space

Although both solution spaces fit the criteria set for this project (see chapter 6.1.) the **AGV with mounted projector** fits more closely with the wishes of Magna and the vision of the designer. Furthermore, academic research shows a promising perspective for this type of design intervention while still leaving more than enough space for further innovation.

Magna

The design intervention could be applied directly into the current factory state contributing to the transition toward the intermediate factory state. This design direction focusses on the factory floor worker which is the application context in which Magna sees the most potential.

Personal Vision

The use of projected AR fits more closely to the vision and skill of the designer.

Other

Research efforts toward comparable solutions have resulted in favorable results, indicating a potential for this kind of solution in the manufacturing context to improve situation awareness and reduce both physical and mental workload.

The concept of an AR cockpit with a transparent screen is further developed by a student team in the course 'Advanced Embodiment Design' (Course code: ID4175) at the faculty of Industrial Design at the TU Delft. Their concept will be adopted and further developed inside the SAM | XL research lab in Delft (see stakeholder map in chapter 2).

Chapter 7

Design Iterations

7.1 Method

The iterative process is here summarized into three main iterations. In reality, each iteration consisted of multiple smaller trials and design interventions (which may or may not be reverted at a later stage).
Simplifying the design process into these three main iterations is not representative of the real process but does allow for the documentation of the important conclusions of all trials.

Iteration 1 focusses on the initial practical implications of rigging a projector on an AGV and the direct contextual factors such as lighting conditions and the driving surface. The only observers are the researchers themselves.
Iteration 2 introduces external observers and focusses on the interaction between those observers, the AGV, and the projections.
Iteration 3 was planned to be a session of iterative testing (RITE method) but was finally executed as a formal test with two different conditions (with projected arrows and a control group without). More details about that can be read in chapter 8.4.

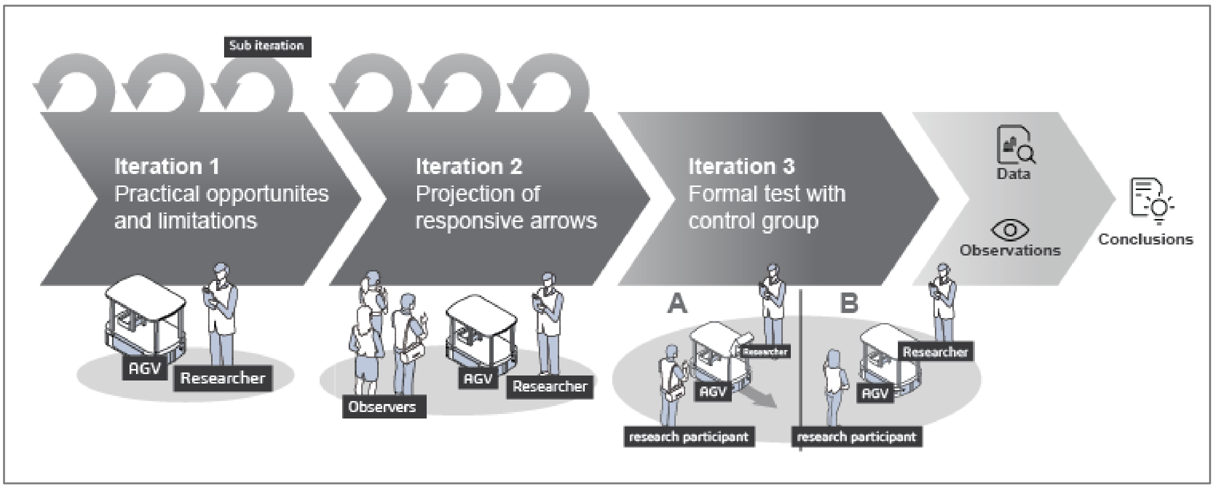


Image 37: Visualisation of the method of testing and the different iterations.

7.2 Iteration 1 – Practical opportunities and limitations

Goal: practical testing of rigging, positioning of the projector, lighting conditions, stability, and the driving surface
Diagram of communication:

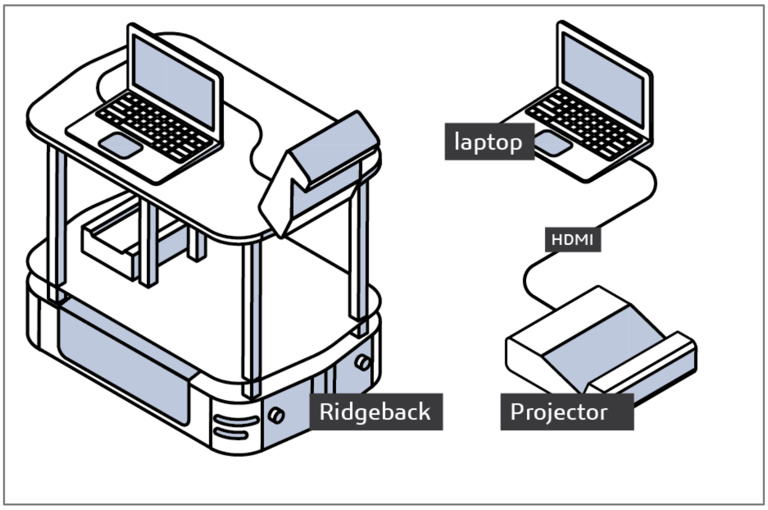


Image 38: A simple setup with the projector and the laptop both mounted on the ridgeback. although easy to install this did pose practical implications in terms of controlling the projection.

Conclusions:

- It is positive if the projection extends a little bit along the sides of the AGV, this way people approaching from the backside of the AGV can also see the robots next move in case it intends to move toward the side the observer is walking

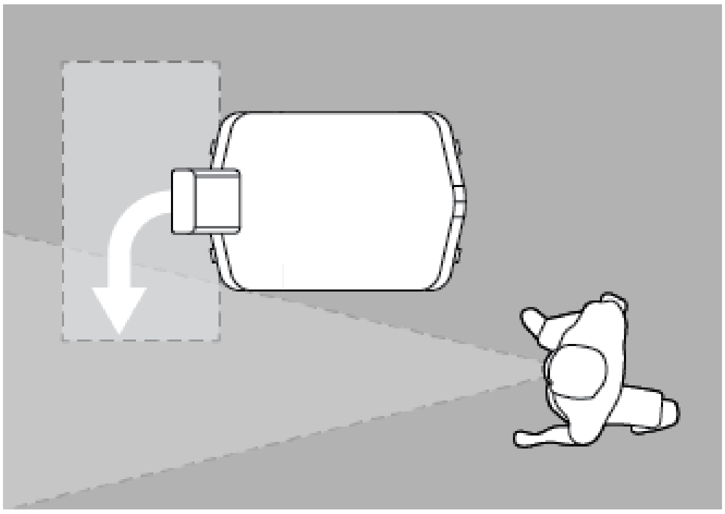


Image 39: Because the projection extends beyond the sides of the AGV it is possible to see an arrow indicating a potential collision course with the walking individual.

- There is still a lot of shaking in the rigging. However, this mainly occurs at acceleration and breaking and occurs less when the robot is moving at a constant pace. The shaking is not to the extent that it is problematic for testing. It might limit the readability if text is projected.

- Having the rigging adjustable in terms of angle is useful for adjusting the projection range and therefor projection size between testing.

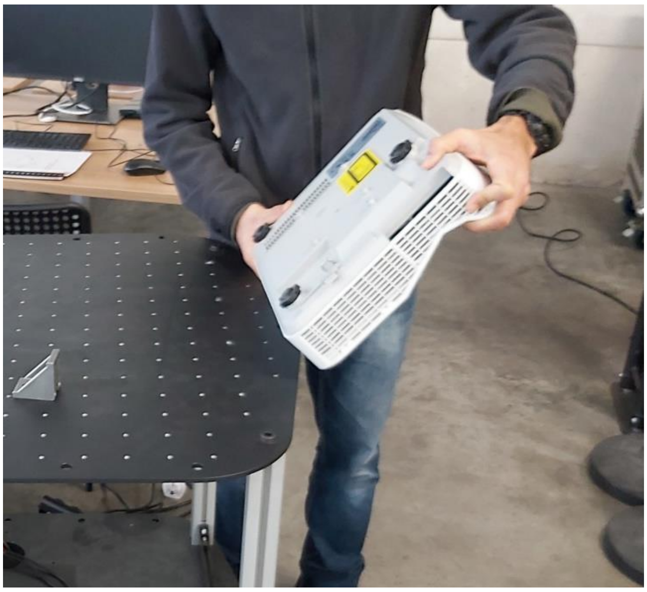


Image 40: The projector is held at the preferred angle and position for an ideal 'canvas'.

- The projection needs a slight perspective correction because of the angle of incidence.

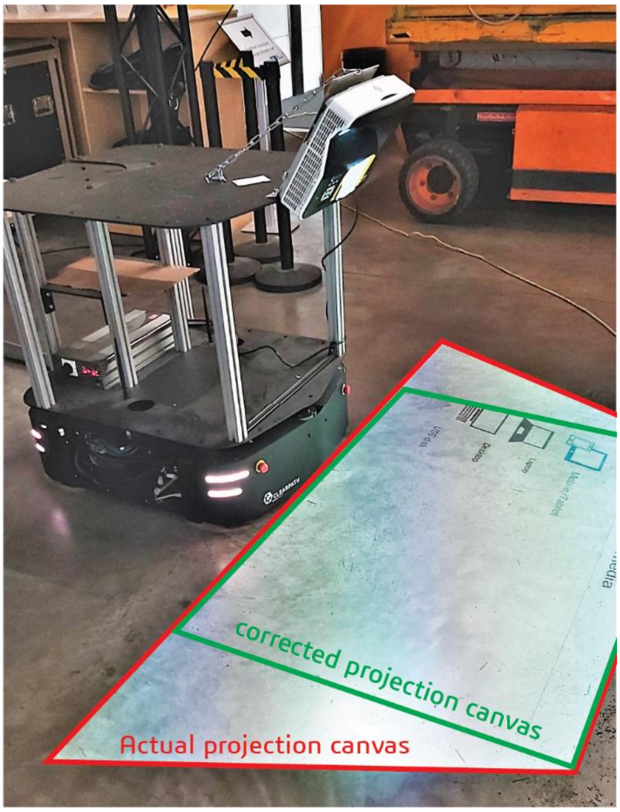


Image 41: Because the projector is not mounted perfectly perpendicular to the floor the projection is warped. The red line indicates the actual projection canvas. The green line indicates the corrected canvas.

- 3000 ANSI Lumens seems around enough for the factory conditions, in the selection of the projector brightness should be prioritized above contrast. the contrast ratio of the projector is almost entirely irrelevant.

- A laser projector is needed because of the excessive shaking the projector is subject to. Laser projectors are far more resistant to vibrations compared to traditional lamp-based projectors.
- Textures on the factory floor are not problematic for the visibility of basic shapes (such as an arrow). Reflective surfaces can however be problematic. very dark floors can also be problematic and would require a projector with a higher light output (4000+ ANSI lumen)
- An uneven floor can cause the projection to throw short shadows, warping the projected image slightly. Brownfield applications might be more problematic.
- Wireless control over the projection is preferred because it makes testing more practical.

7.3 Iteration 2 – Projection of responsive arrows

Goal: getting first reactions to the responsive arrows from outside observers.
Initially, the arrow responded to the controller input. Later it was adjusted to react to the movement vector of the ridgeback.

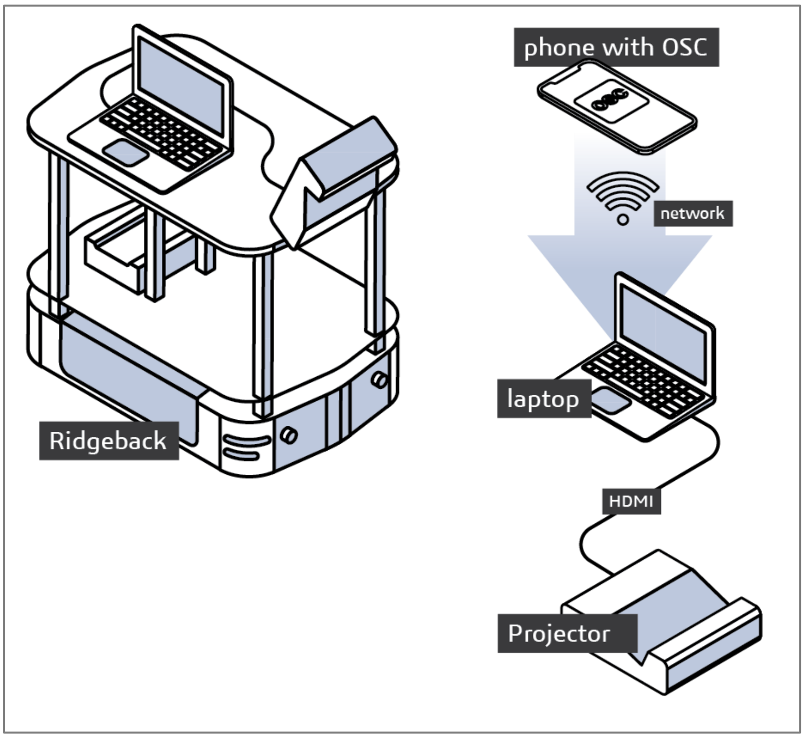


Image 42: For testing purposes, signals can be sent to the projector through a smartphone using 'Open Sound Control (OSC)' a protocol for sending wireless messages. This allows the researcher to control the projection wirelessly from a distance.

Conclusions:

- Based on the findings in iteration 1 a projector was selected and tested

i3 L3502W Laser Projector

This projector was selected based primarily on these three factors:

Throw distance: this is what's called an 'ultra-short throw' projector which means it can make a large image from a short distance. With a throw ratio of 0.27:1 it makes an image of 1,5 meters wide at a distance of 40cm.

Brightness: with 3500 Lumens this projector can easily create highly visible figures even in a bright lit factory hall.

Resistance to vibrations: The light source of this projector is a LED-Laser module. Traditional projectors use a bulb as the light source which wear down quickly or can malfunction under the vibrations and shocks that the projector might endure. A LED-laser module is far more durable in this regard and can produce light for up to 20.000 hours before the module needs replacing.

- The rigging (as can be seen in image 43) can be adjusted to change the angle of the projection

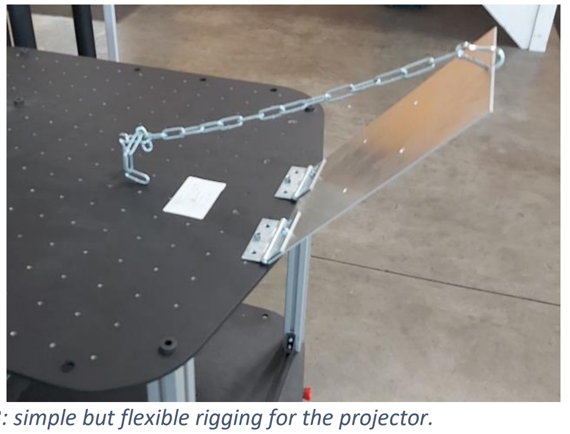


Image 43: simple but flexible rigging for the projector.

- Passer-by's and other invited observers experience the projected arrow as a natural indicator for direction. The arrow is appreciated far better in this regard than a single line (this was also confirmed by Chadalavada et al. [73])

- Having the arrow extend instead of turning brighter is a better metaphor for acceleration

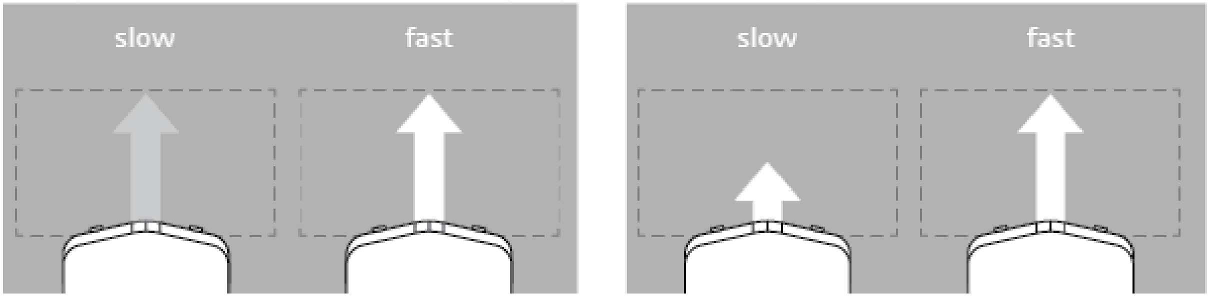


Image 44: (left) initial concept for the visualization of acceleration during iteration 1. (right) improved visualization. Observers deemed this as a more natural metaphor for speed.

- Because projectors are best at projecting white light the white color creates the most contrast and works best on the factory floor.
  colors with less white light in it such as red make a far less vibrant impression on the floor.
- Visuals are triggered manually at this point (at Industrial Design Engineering at the TU Delft this is often referred to as the 'Wizard of Oz-technique') Because the AGV and the laptop are moving we need to be able to trigger visuals remotely. Touch OSC is a standard for sending wireless messages mostly used to communicate between music- or lighting devices. It can be used to control the projections with extremely low latency. This allows for wireless control of the projection, but the laptop still needs to be mounted on top of the AGV
- By using a MiraCast device the laptop may be removed from the AGV, connecting wirelessly to the projector. The MiraCast introduces a slight delay (200ms) which is noticeable but acceptable for testing. This final information infrastructure is visualized in image 45.
- The Ridgeback is capable of omnidirectional movement. Observers consider this type of movement to be very unpredictable. Luckily, the model of AGV used by Magna is not omnidirectional and will therefore only require projection on the front of the AGV. For further testing the omnidirectional movement of the Ridgeback will not be used.

7.4. Iteration 3 – Formal test with a control group

Original plan

The original plan of iteration 3 was not primarily to do a validation of a specific design but to iterate further on the design supported by the input from test participants. The intention was to use the RITE method for this (Rapid Iteration Testing and Evaluation) [74] in which it is customary to make design changes in between tests. Participants would be invited to the lab and given a task in a controlled environment. An example of such a task would be 'walk straight ahead at the crossing'. During the task the user would encounter the AGV with a pre-set behavior.
A short quantitative questionnaire would be given for each scenario (the TLX and SART methods would be used, which will be explained later in chapter 8) followed by a qualitative discussion with the participants. This qualitative discussion would form the basis for design interventions to be made before the next participant arrives.

Corona plan

because of the COVID-19 pandemic testing in person in the lab was not possible. A plan for filming was hastily drafted and executed in order to get the right video material for remote testing. The scenarios drafted for the original plan were adopted in remote testing.
The original goal of iterating on the design was replaced by a more formal goal to validate the merit of projected AR on AGVs.

Alternatively, testing is now conducted through a remote questionnaire with videos. The method used is a derivative of the 'freeze-probe' methodology. The participant is placed in a simulated environment (in this case a 'POV'-video). Once the video leads up to a decisive moment the video suddenly cuts to black. the participant must then decide what to do, as well as answer several standardized questionnaires.

Chapter 8 goes into more detail regarding the experimental setup of this test, but first, the final information infrastructure used for testing is illustrated on the next page (image 45).

Information infrastructure

The figure below illustrates the infrastructure used to control the ridgeback and the visuals.

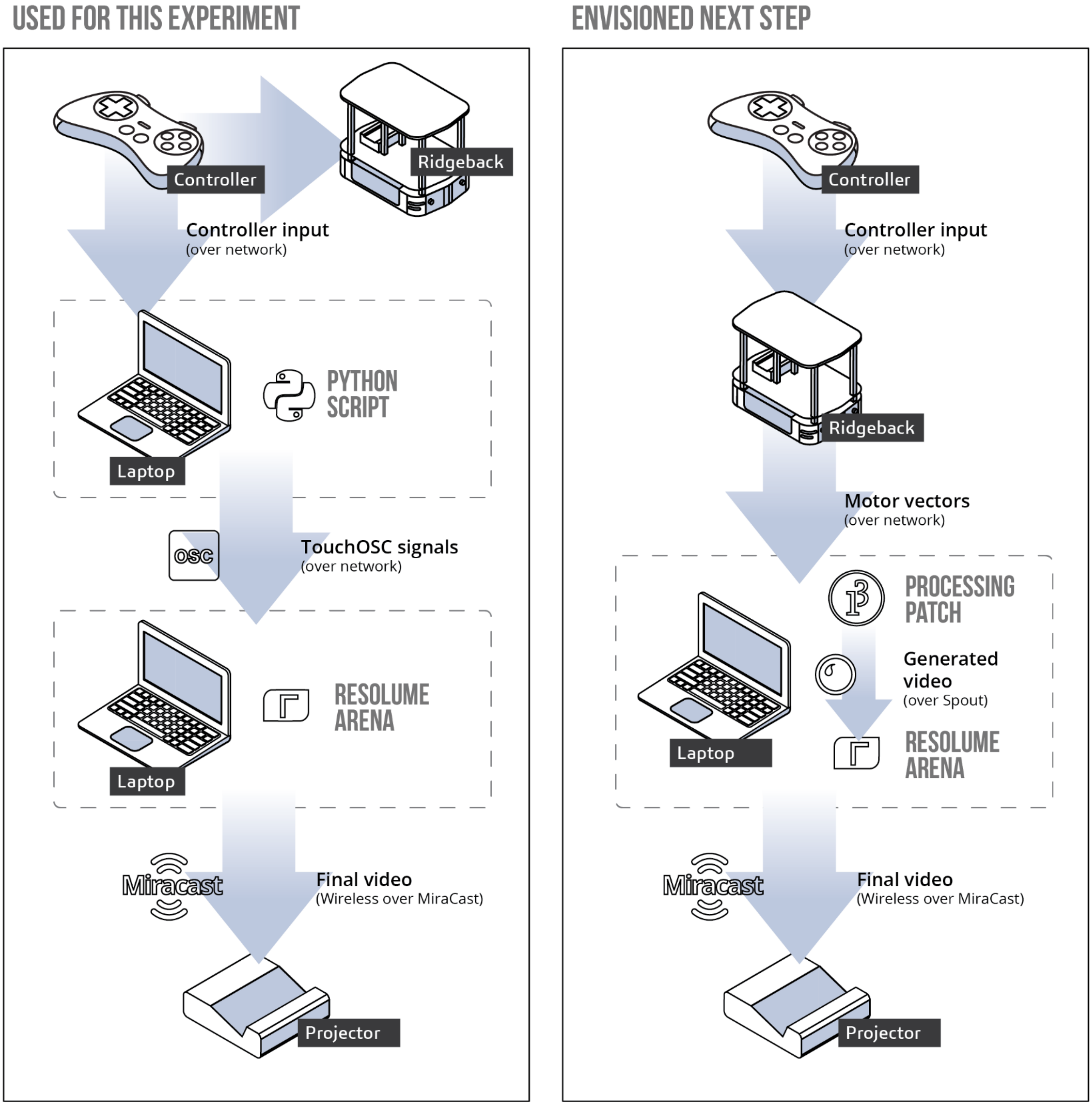


Image 45: Illustrations showing the infrastructure from the controller input up to the projector. On the left, the setup used during this experiment. On the right, the envisioned next step to make the setup more accurately respond to the AGVs direction

Controller input is picked up on the network. specific controller inputs are translated to TouchOSC messages using a python script. The TouchOSC messages are used to trigger images such as arrows.

This stream of video is sent to the projector mounted on the AGV.

This process was run on separated computers because of the practical availability of specialized software and operating systems but may be configured in a singular laptop instead.

In this envisioned next step, the arrow would be generated live based on the motor vectors of the Ridgeback.

The video is processed in two different software packages because Processing can renderer the arrow and Resolume can effectively apply the perspective warp as well as other effects.

The diagram on the right was envisioned but not executed. The COVID-19 crisis forced the experimentation to be executed in a remote fashion and live generation of the visuals was not required for creating the videos needed for remote testing.

Part 3

Validation

Chapter 8

Experiment setup

This chapter aims to explain the structure and setup of the formal experiment. In section 1 an overview is given, and the used questionnaires are explained. In section 2 the scenarios that were tested are explained.

8.1. Overview

1. Preperation

1.1 Consent form

1.2 Preliminary questions
- age, gender, nationality, education
- topic specific experience
- technological aversion
- skill in the english language

1.3 Synthesize
tell the participants what will be expected from them.

2. Testing

2.1 Scenario 1 - AGV turns left
Condition A or B

2.2 Scenario 2 - Diagonally behind AGV
Condition A or B

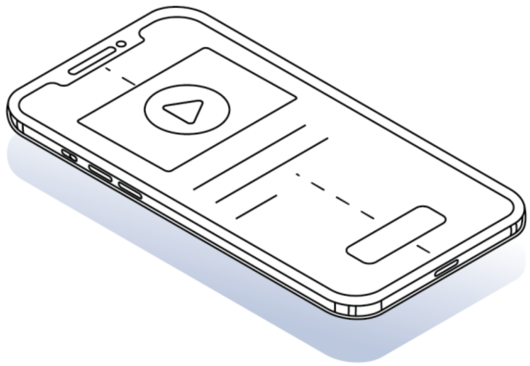
2.3 Scenario 3 - You are in the way
Condition A or B

2.4 Scenario 4 - AGV reaches goal
Condition A or B

2.5 Comparison section
Participant is shown both conditions next to each other. Followed by qualitative questions.

3. Finish

3.1 Final information
Thank the participant for their participation and provide contact information again.



PROCESS FOR ALL SCENARIO'S

Every participants gets only one condition for every given scenario

1. Warning and instruction:
"pay attention, you may only view the movie once". Tell the participant the intention he/she has in the movie.

2. Show movie. The movie cuts of at the pauze sign (see illustrations) and the screen immediately turns black.

3. Response questions

4. SART Questionairre

5. TLX Questionaire

Goal

The goal of this experiment is to see if there are merits to the use of projection-based visualization (Spatial Augmented Reality) of AGV's spatial intent. This is done by comparing the reactions to an AGV with a projected arrow to the reactions toward an AGV with no projection. The goal is to produce leads for design direction for the further development of this system and to see if any verifiable statistical relationships are present.

Experimental design

This experiment is conducted as a between-groups experimental design. A within-group design would lead to a significant learning effect and would enlarge the effect of demand characteristics (Participants guessing the goal of the experiment and altering their behavior because of this).

Participant selection

At least 20 participants will be needed for the main experiment (10 for each group). Whenever possible the participants will be distributed over the A and B groups based on age and gender. Age is the most important for the distribution because it is strongly correlated to technology aversion.

Pilot

A pilot will first be conducted with at least 3 participants to optimize the design of the experiment. For this pilot participants will be recruited that are knowledgeable about the project because they can not be used for the main experiment and because they can give more detailed feedback. During the pilot additional text boxes will be available at each step of the experiment to allow the pilot participants to leave additional feedback.

Questionnaires

See appendix C for the complete research questionnaire.

Preliminary questionnaire. Contains standard demographic questions. Additionally, questions are added to measure the participants' experience and affinity with technology because it is assumed that this may influence participants' approval of the demonstrated techniques.

Single Ease Question (SEQ). As the name implies this is a single question with a 7-point rating scale to assess how difficult users find a task. It performs well as a measure of usability even compared to more elaborate measures [75]. The SEQ is asked as the first question directly after the 'task' of viewing the video.

Response questions. The test was originally planned to be a lab experiment in which the response of the participants and their assessment of the situation could be observed by the researcher. In the new remote situation this information is found through these open questions (e.g. 'describe the action you will take at the end of the movie').

Situation Awareness Rating Technique (SART). A rating technique that was originally developed for the assessment of pilot situation awareness. It uses ten dimensions on a 7-point scale to calculate a standardized score [33]:

Domains	Construct	Definition
Attentional demand **D**	Instability of situation	Likeliness of situation to change suddenly
	Variability of situation	Number of variables that require attention
	Complexity of situation	Degree of complication of situation
Attentional supply **S**	Arousal / alertness	Degree that one is ready for activity
	Spare mental capacity	Amount of mental ability available for new variables
	Concentration	Degree that one's thoughts are brought to bear on the situation
	Division of attention	Amount of division of attention in the situation
Understanding **U**	Information quantity	Amount of knowledge received and understood
	Information quality	Degree of goodness of value of knowledge communicated
	Familiarity	Degree of acquaintance with situation experience

The final SART score is calculated using the following formula: SA = U – (D – S), where:
U = summed understanding
D = summed demand
S = summed supply

The questionnaire used for this research was missing one question. Details on how this came to be and how it was handled can be read in chapter 11.1.

Nasa Task Load Index (TLX). A widely used assessment tool to measure workload. Seven dimensions are measured on a 21 point scale: Mental demand, physical demand, temporal demand, performance, effort, and frustration [76]. After data collection, the 21-point scale is changed to a 100-point scale for each dimension.

Short explanation of software used

Python script: this script uses the controller joystick input and sends one of five (OSC) messages every 50ms. Each message corresponds to a preset arrow (left, slightly left, forward, right, slightly right).

Touch OSC: Touch OSC is a standard for sending wireless messages mostly used to communicate between music or lighting devices. It can be used to control the projections with extremely low latency. It can be seen as a variation on the MIDI standard.

Processing: open source software that can generate live output based on a large variety of possible inputs. Here it would be used to generate an arrow visual (or other visuals) in real life.

Spout: software that acts as a bridge between software packages that generate pixel matrices. Here it is used to bring the output from processing into Resolume. (for macOS see Syphon for the same functionality).

Resolume Arena: Powerful software meant for VJs, video technicians, and video artists. It is included in this chain because it allows the researcher to change visual aspects on the fly, allowing for rapid iteration.

MiraCast: Essentially 'HDMI over Wifi'. It can send Full HD video with 30 frames per second wirelessly to a device on the same network. The network needs to be optimized to limit latency.

8.2. Scenarios

Scenario 1 – AGV turns left

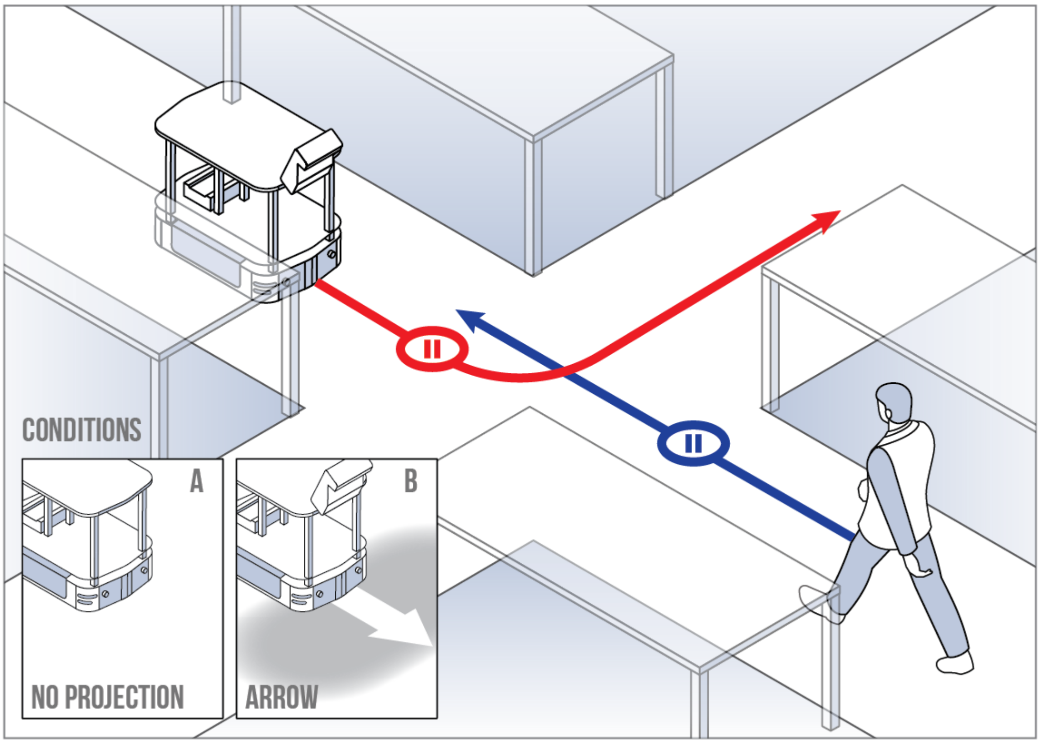


Image 46: scenario 1, the pause signs indicate where the movie cuts off.

The participant and the AGV are moving toward each other. The AGV is about to turn left into the trajectory of the participant.

Scenario 2 – Diagonally behind the AGV

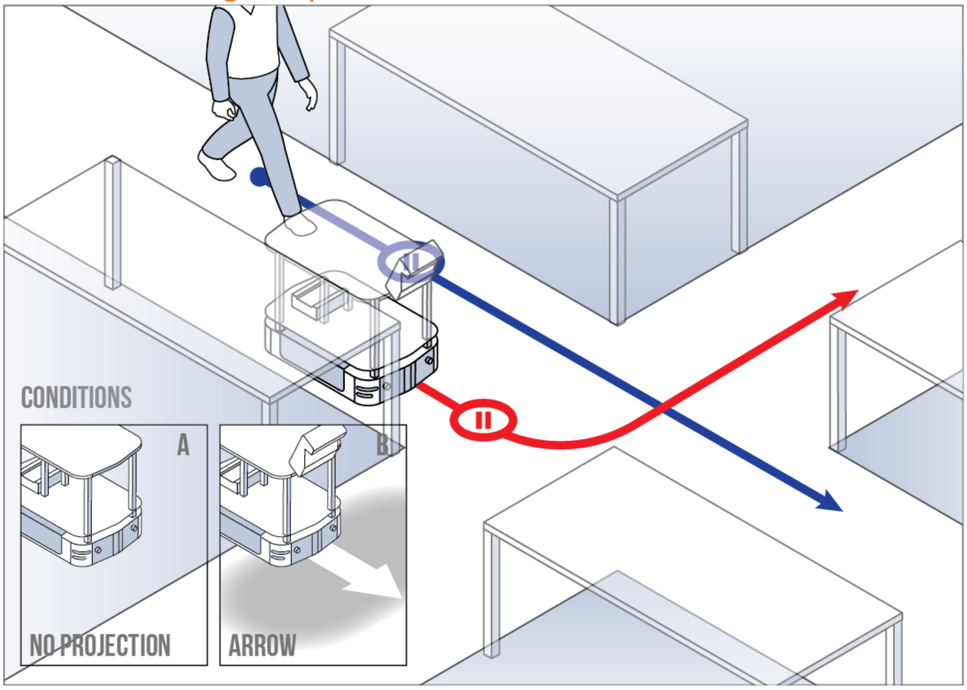


Image 47: scenario 2, the pause signs indicate where the movie cuts off.

The participant is walking diagonally behind the AGV. The participant is going faster than the AGV and will soon overtake the AGV.

Scenario 3 – You are in the way

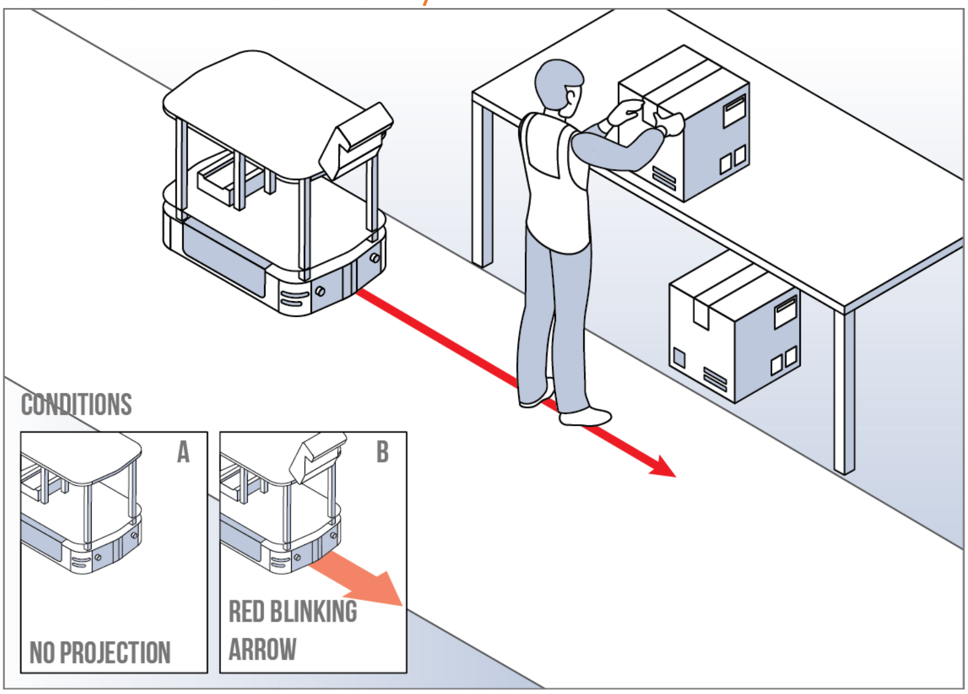


Image 48: scenario 3, the video cuts off after the participant has seen the AGV.

The participant is stacking boxes. The AGV approaches and either indicates (condition B) or does not indicate (A) that the participant is in the planned trajectory (using a projected red blinking arrow).

Scenario 4 – AGV reaches goal

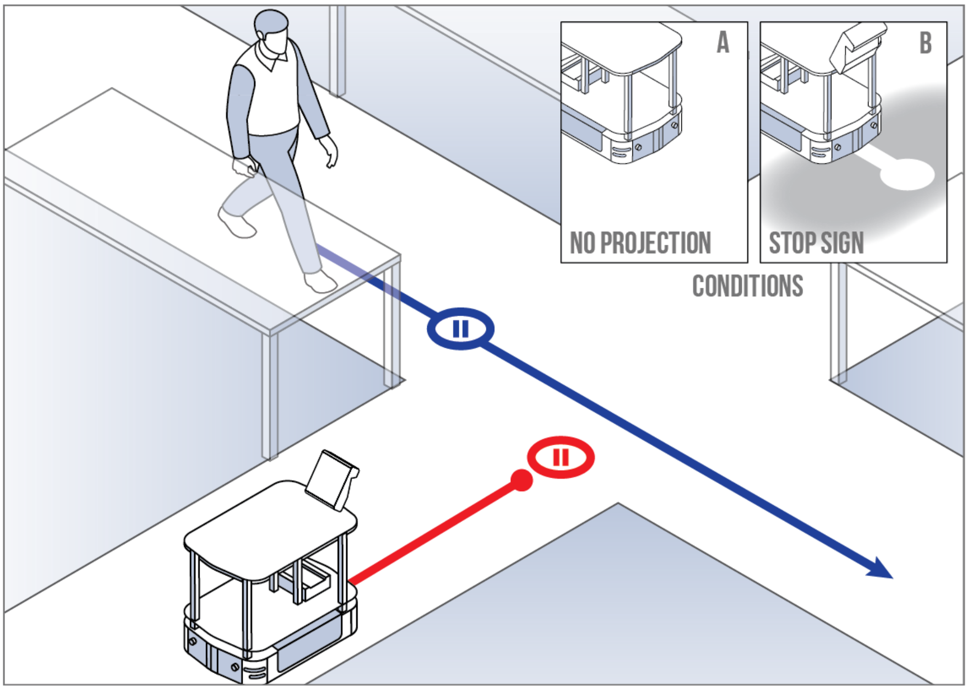


Image 49: scenario 4, the pause signs indicate where the movie cuts off.

The participant has the intention of going straight at the crossing. An AGV approaches from the right. The AGVs destination is just before the crossing so it intends to stop before it's trajectory ever crosses the intended walking path of the participant.

Other scenarios

The selected scenarios are the ones most frequently occurring in a factory environment and also the ones where the projections could be used to communicate spatial intent.

These scenarios were also filmed but not selected:

AGV standing still. The AGV would either indicate that it is at a loading dock or indicate that there is a problem that prevents it from moving. Designs for the projection were not tested or iterated in previous sessions.

Boxes are in the way. This is comparable with the content of scenario 3. Scenario 3 was chosen instead of this scenario because scenario 3 concerns the participant directly, soliciting a more immediate response.

Passing straight on. The AGV and the participant pass each other while going in opposite directions. The amount of interaction in this scenario is limited.

Chapter 9

Pilot

Before launching the main questionnaire, a pilot was held to see if participants understood the line of questioning. Finding technical mistakes within the questionnaire was also important.
Another concern to be addressed was whether the participants experienced the questionnaire as too long.

The pilot questionnaire contained additional ‘pilot boxes’, open question boxes at the end of each page which allowed for feedback from the participant.

Responses

A total of 7 responses was recorded for the pilot. 4 participants filled in all questions with proper attention given to the content and line of questioning. The other 3 participants mostly checked for technical problems within the questionnaire.

- Age, gender, and country of origin are well spread.
- All pilot participants score high on affinity with technology.
- Experience with production environments, AGVs, and Augmented Reality is spread.

Changes and considerations

General

- Some text was made bold for emphasis, a short test with outsiders concluded this was a helpful graphical change.
- The total length of the questionnaire was deemed long. It was considered to shorten it by removing the TLX-questions, but this option was not taken because some researchers would like to have the results of the TLX nonetheless.

Synthesizing

- The videos were considered very short. A warning text was added to make sure participants are fully focused on the video before pressing play because the video may only be played once.
- The text explaining to the participant what the ‘intention’ is that he or she has in the video was confusing for some participants. It was confused with the intention of the robot. The text was reformulated to a ‘task’ description which also made answering the standardized questionnaire more natural. Especially the TLX strongly builds on the assumption that the user has just completed a task.

Questions

- Changed the phrasing of multiple questions in cases where pilot participants indicated confusion or ambiguity.
- One very important change was to supplement the text of the response questions with “*from your perspective*” to make the answers less ambiguous (especially the distinction between left and right matters here).

- Opinions differ about the formulation of the scale of the 'experience' questions. (preliminary questions). No changes were made because this scale is the most unambiguous option.
- Changed video game question (preliminary questions) to the same 7-point scale as the other 'experience' questions. Asking for the frequency of gaming can be misleading when users have game experience but do not frequently game currently.
- Reformulated questions about the experience to be more specific about the user being 'experienced in its use'.

Videos

- Changes were made to ensure that:
    - The video cuts off before the participant can see what the AGV will do next.
    - Videos between groups A and B are comparable in everything except the controlled condition. For example: equal factory audio was added to all videos.

NASA TLX

- Multiple participants indicated having problems answering the TLX questions. Because of this, the SEQ was added as an alternative in case the TLX did not return useful results.
- Question 2 of the TLX concerns physical demand. Since no physical activity is undertaken by the participant at all it was deemed necessary to remove the question.

SART

- The word '*aroused*' in question 4 was considered awkward by multiple pilot participants. It was also not interpreted with the right meaning by these participants. The word was replaced with '*alert*'.
- SART questions 6, 7, and 8 were deemed confusing by some participants. However, no changes were made to ensure the validity of the standardized test.

Chapter 10

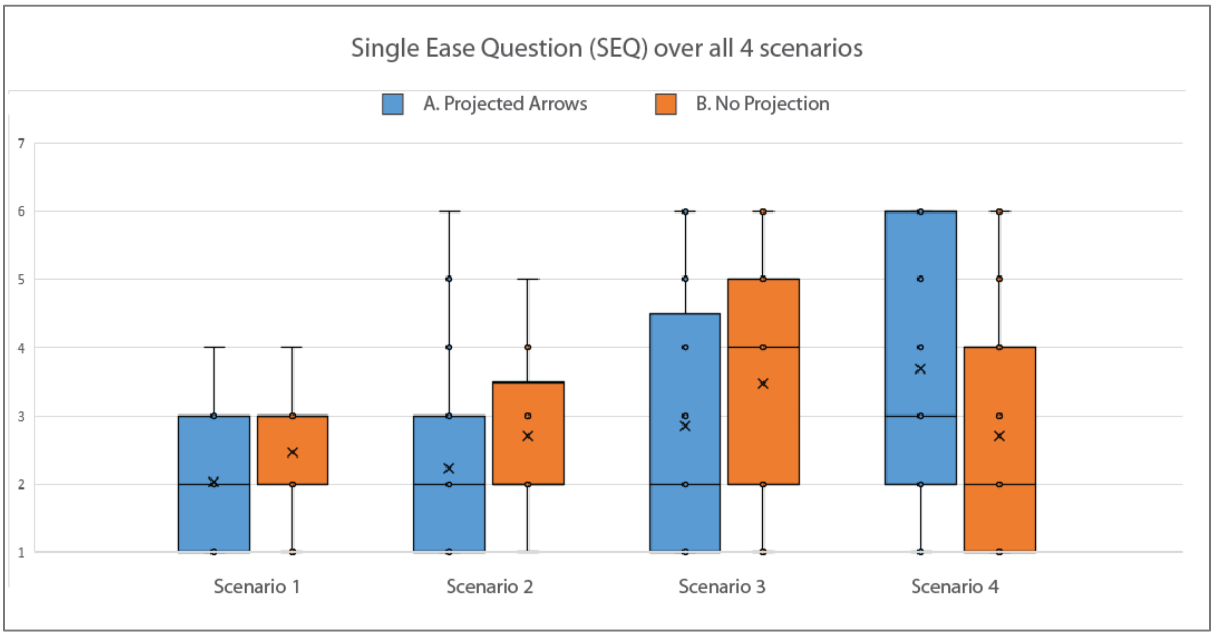
Results & Conclusions

In this chapter results and conclusions will be shown of the statistical analysis of the data gathered in the research. The structure will follow the structure of the research.

27 responses were received for group A but one entry was excluded because the participant seemed inattentive (seemingly random answers, quick completion time, and short open question answers), resulting in 26 responses for group A.
21 responses were received for group B.
The full data set produced by this research can be found in appendix E.

10.1 Single Ease Question (SEQ)

This question was asked directly after the movie of the scenario: *Overall, how difficult or easy was the task to complete?* The participant could respond on a 7-point scale with 1 meaning *very easy* and 7 meaning *very difficult*.



We can see that in scenarios 1, 2, and 3 the 'no projection'-group found the task more difficult on average.

A t-test points out that the positive effect of the projected arrows is significant in scenario 1 ($p = 0.003$, MD = 1.313). Levene's test points out that for scenario 1 the variances cannot be assumed equal. In Scenario 4 the effect is negative but not significantly so ($p = 0.065$, MD = 0.978).

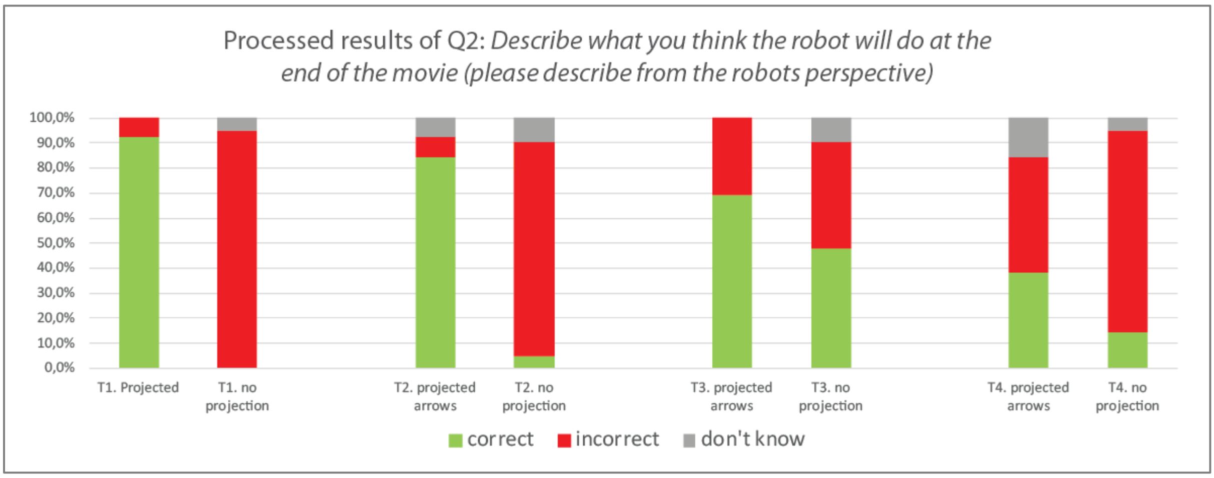
10.2 Response Questions

Analysis process

Questions 2, 3, and 4 for each scenario are open questions and therefor return qualitative results (labeled as '*RAW*' in the dataset). In order to do quantitative analysis all data was converted to more general categories first (In the dataset this is labeled as '*CAT*'). After that, every description was then classified again in order to fit within a 'verdict'. In question 2 (Q2), for example, we are interested in whether the participants can correctly guess the robots' next action or not (*correct* and *incorrect*) a third verdict, *don't know,* is used when the participant cannot give a clear answer. (Verdicts are labeled '*VERD'* in the dataset*)*

Assessment of the AGVs next action (Q2)

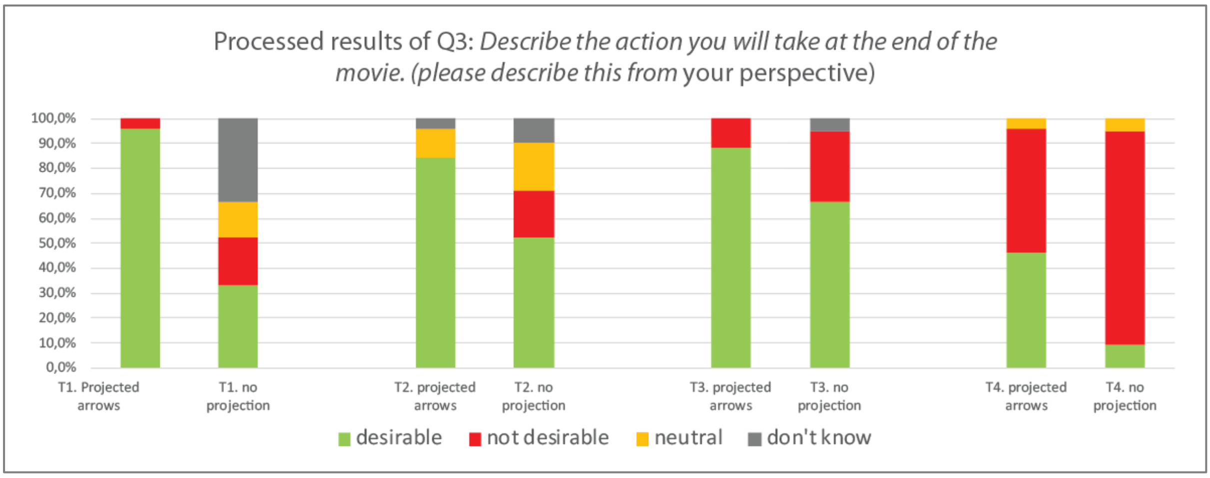
The second question after each scenario movie: *Describe what you think the robot will do at the end of the movie (please describe from the robot's perspective)*. This was an open question. Responses that accurately described the next action of the robot were deemed '*correct'*. If the participant could not give a clear answer it was labeled *'don't know'*. Everything else was labeled '*incorrect*'.



A Pearson Chi-Square test points out that in scenarios 1 and 2 the participants with projected arrows were significantly more often correct ($p < 0.001$.) We can see in the graph that scenario 3 and 4 that the group with projected arrows also scored more correct answers than incorrect but the difference is not significant ($p=0.145$ and $p=0.051$ respectively).
In Scenario 4 it seems particularly hard to assess the robots' next action for both conditions.

Action response of the participant (Q3)

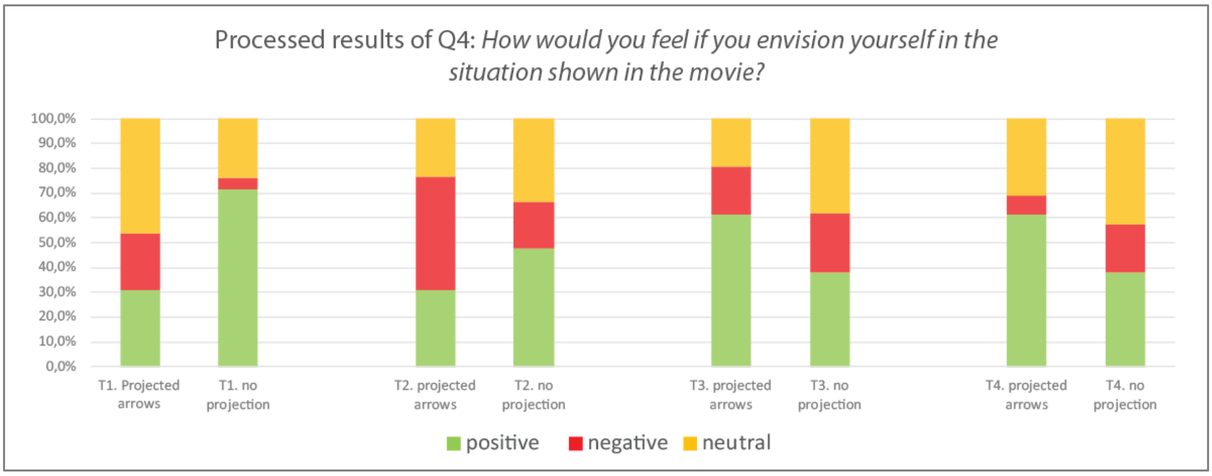
The third question after each scenario movie: *Describe the action you will take at the end of the movie. (please describe this from your perspective).* This is an open question. When participants can not make a clear choice, it is labeled '*don't know*'. Desirable actions are labeled *desirable* while actions that might bring harm to the participant, AGV, or factory process are labeled '*not desirable'*. Actions that are neither are labeled *neutral*.



A Pearson Chi-Square test shows that the response from a participant that is shown projected arrows has a significantly higher chance of being correct in scenarios 1 and 4 ($p < 0.001$ and $p < 0.05$ respectively). Scenario 2 and 3 also show a positive effect from projected arrows but the effect is not significant ($p=0.053$ and $p=0.157$ respectively).

Experienced feeling (Q4)

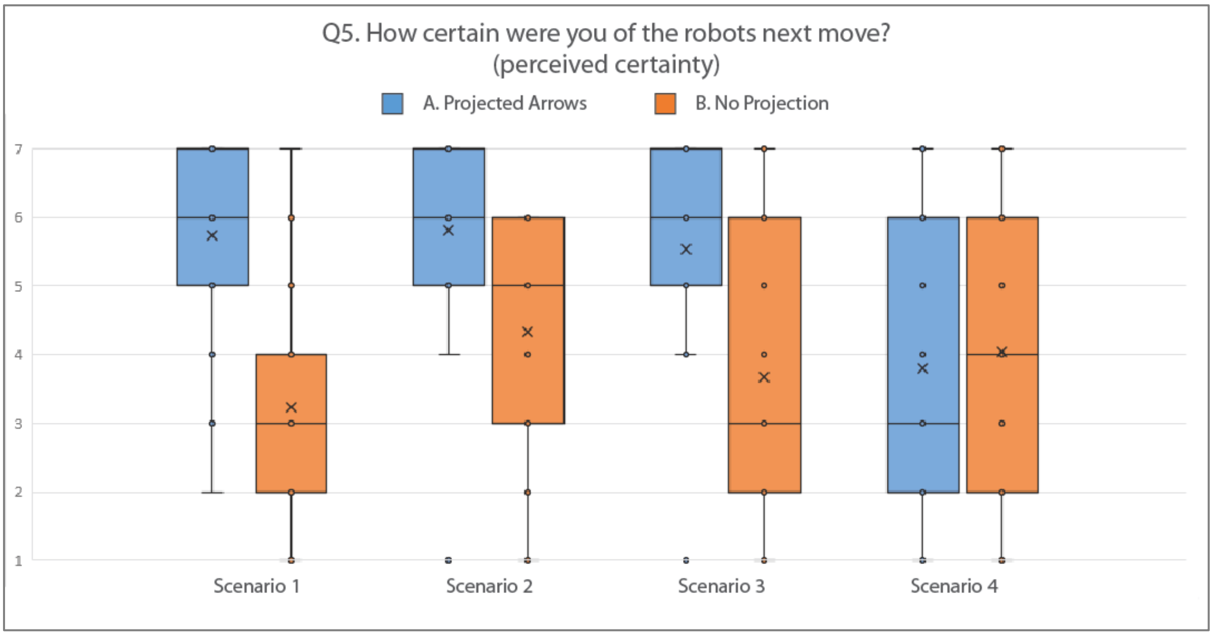
The fourth question is: *How would you feel if you envision yourself in the situation shown in the movie?* This question required rigorous labeling. The first step was to label all emotions and feelings in the responses. These were then categorized into 26 groups (for example: *anxious, nervous,* and *worried* were grouped) these groups were deemed either positive, negative, or neutral.
If a response counted multiple of these feelings, they were counted. If the positive emotions had the majority, it was labeled positive and the same for the negative emotions. A response is labeled neutral if there was an equal amount of positive and negative emotions.



In scenarios 3 and 4 we see more positive reactions in the projected arrows group. In scenarios 1 and 2 we see approximately the opposite. The difference in scenario 1 is the only one that is significant ($p < 0.05$).

Perceived certainty (Q5)

Question five is as follows: *How certain were you of the robot's next move?* Which the participants answer on a 7-point Likert-scale.



As can be suspected from the graph Levene's test points out that in scenario 3 the variances cannot be assumed equal. In scenarios 1, 2, and 3 we find that the projected arrows significantly improve the certainty experienced by the participant.

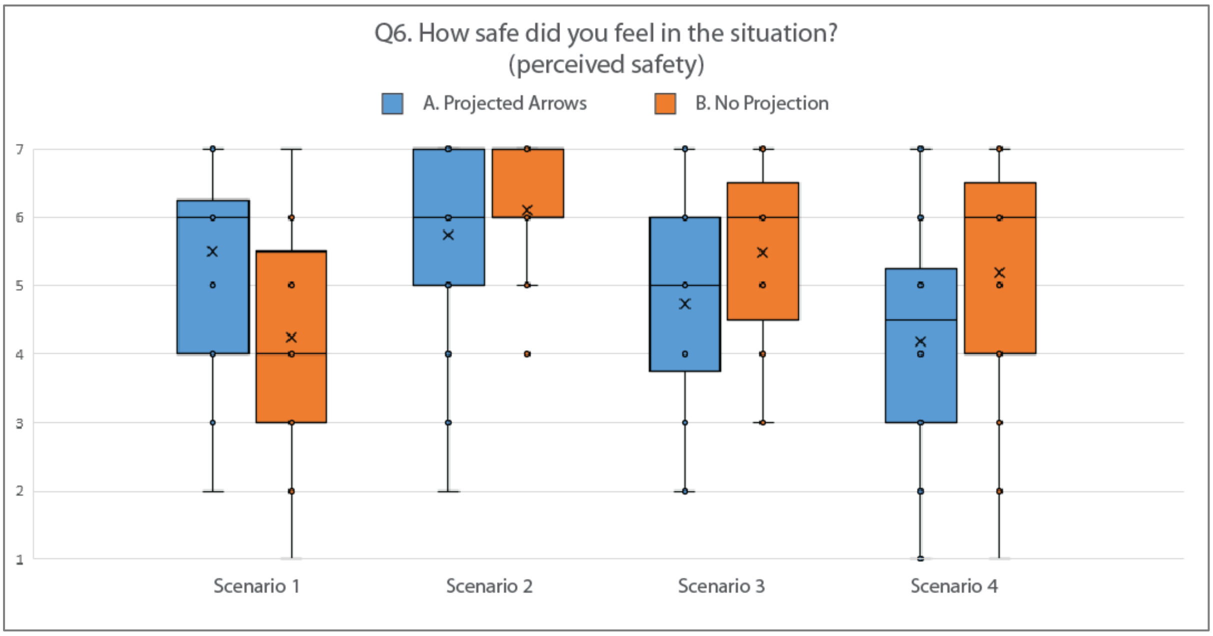
In scenario 1 with a p-value lower than 0.0001 and an effect size of 2.5 points

In scenario 2 with a p-value of 0.04 and an effect size of 1.5 points

In scenario 3 with a p-value of 0.01 and an effect size of 0f 1.9 points.

Perceived safety (Q6)

Question 6 concerns perceived safety: *How safe did you feel in the situation?* Again, the participants are asked to answer on a 7-point Likert scale.

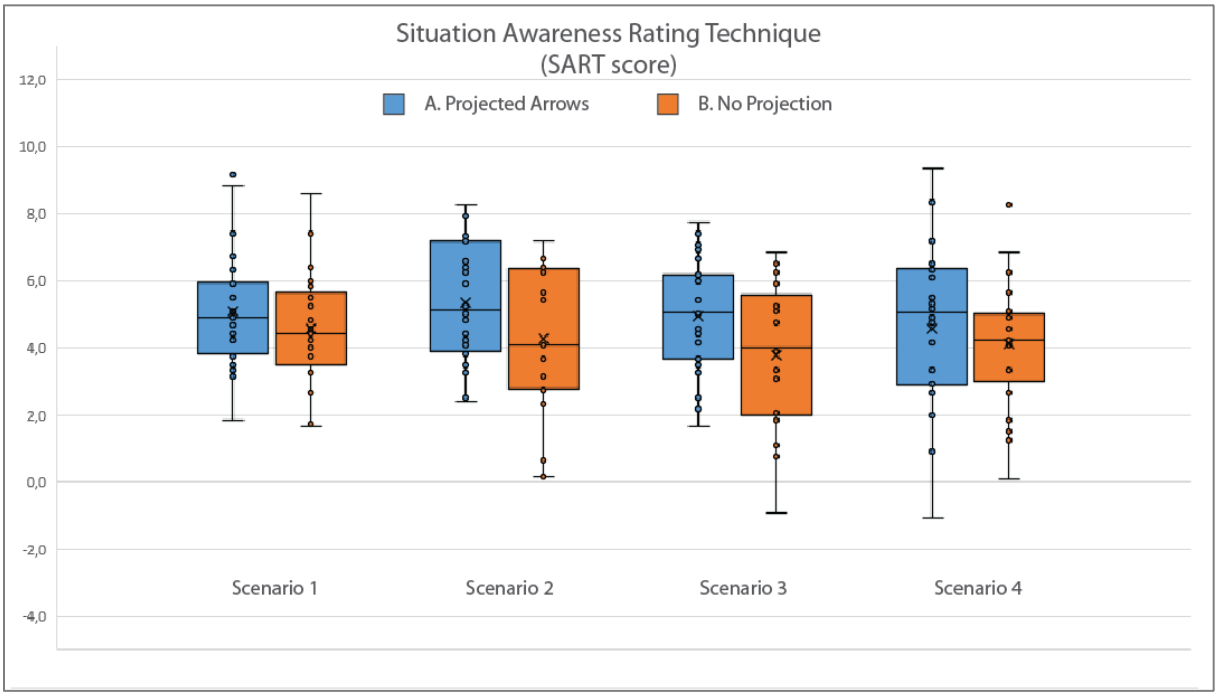


Only scenario 1 yields a significant effect ($p < 0.005$, MD = 1.3). Interestingly in scenarios 3 and 4 there is a tendency toward a reversed effect: the projection seems to lower the perceived safety, although the difference is not significant ($p > 0.05$).

10.3 Situation Awareness Rating Technique (SART)

The calculation of the SART score is explained in chapter 8.1.

Discussion on the validity of our execution of the SART score can be read in chapter 11.2.

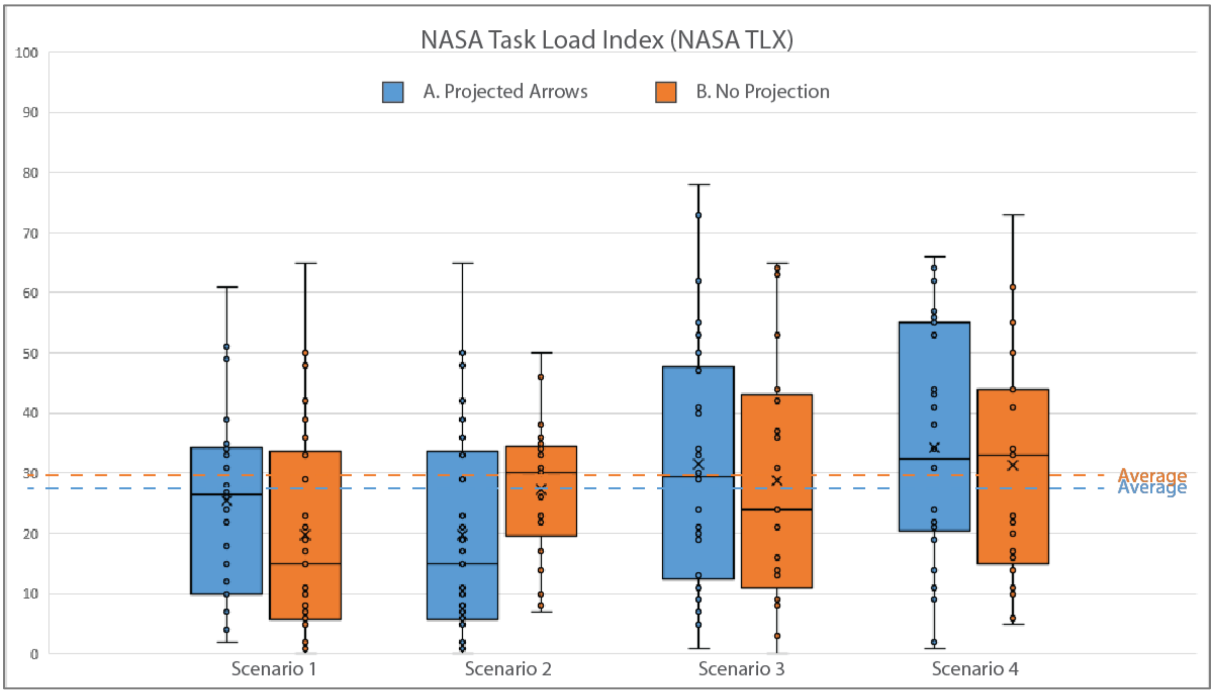


The situation awareness is higher for the participants with projected arrows in all scenarios, but this effect is only significant for Scenario 3 (p = 0.0037, MD = 1.2) and is leaning toward significance in scenario 2 (p = 0.07, MD = 1.1).

The strongest effect is measured in SART question 8: *How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?.* On average (all scenarios included) participants that are shown projected arrows score 1.2 points higher on this question than participants that are shown no arrows. The effect is significant in scenarios 1, 2 and 3 (p < 0.01)

10.4 NASA Task Load Index (TLX)

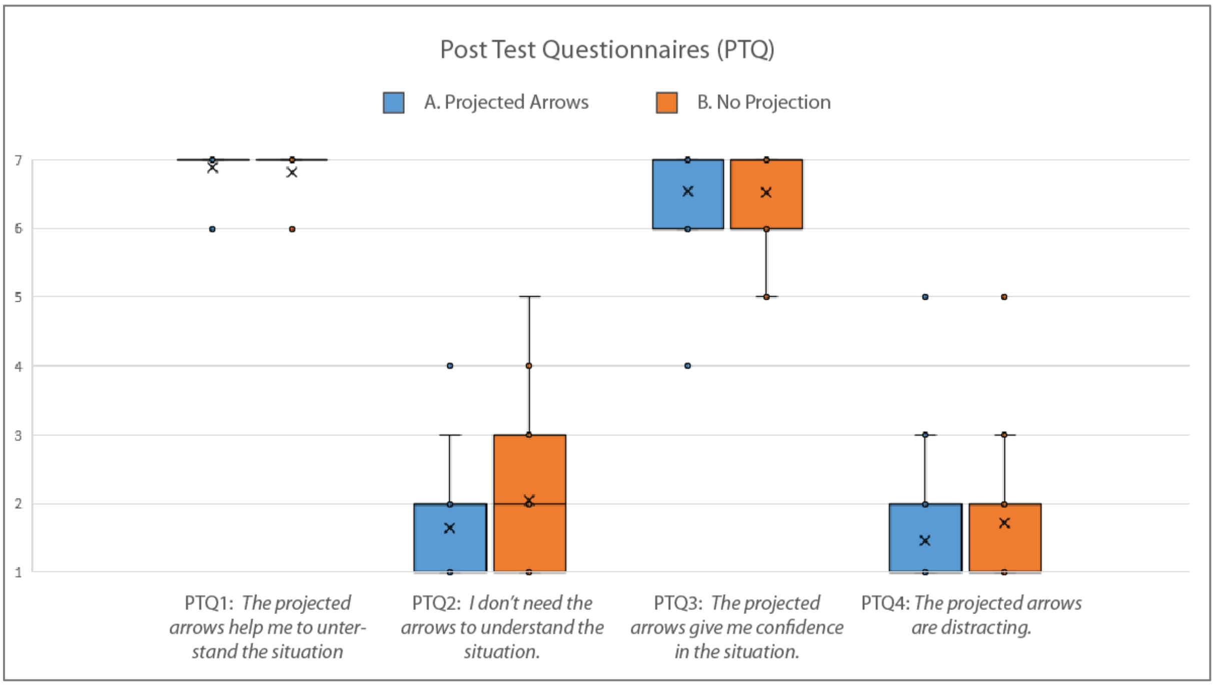
The calculation of the NASA TLX score is explained in chapter 8.1.



The t-test points out that none of the differences between the A and B groups are significant.
It could be concluded that the projected arrows bear no influence on the experienced task load of the participants.

10.5 Post Test Questionnaire (PTQ)

After all scenarios and associated questions have been handled the participants see a movie showing both conditions (projected arrows and no projection) next to each other.
They are then asked 4 questions to be answered on a 7-point Likert scale with 1 meaning *disagree* and 7 meaning *agree*.



Since both the A and B groups get the same question with the same movie (see image 50) there should be no significant difference between the groups. A T-test points out that this is correct.

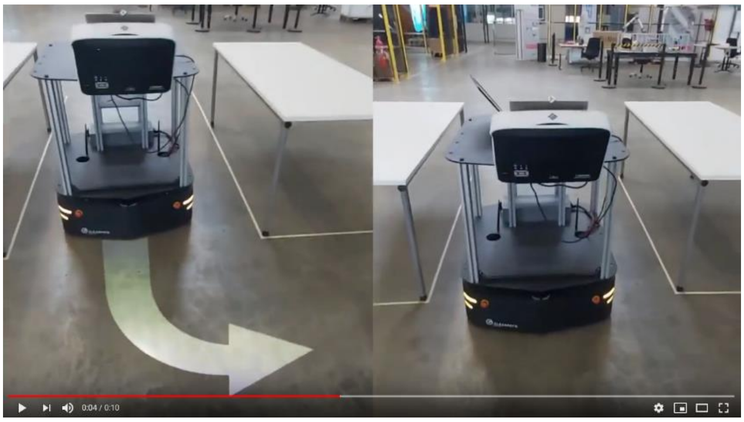


Image 50: screenshot from the movie shown during the last part of the research.

The results are highly favorable toward the projected arrows. However, the participants by now have most probably understood that the researcher is the one designing this system. It may therefore very well be that these answers are simply meant to pander to the researcher.

10.6 Technological affinity

Using preliminary questions PQ5, PQ6, and PQ7 (*How familiar are you with smartphone / desktop computer/video games)* a score was calculated and labeled TAS (Technology Affinity Score).
We wanted to see if this score correlates with any performance scores such as the SART or TLX

and SEQ for all tasks. A Pearson's correlation test was executed. Aside from a weak correlation (Correlation = 0.362, p = 0.012) with the SART score of task 3 no correlations were found. Leading us to conclude that the technological affinity of the participants did not influence the test results in this setup.

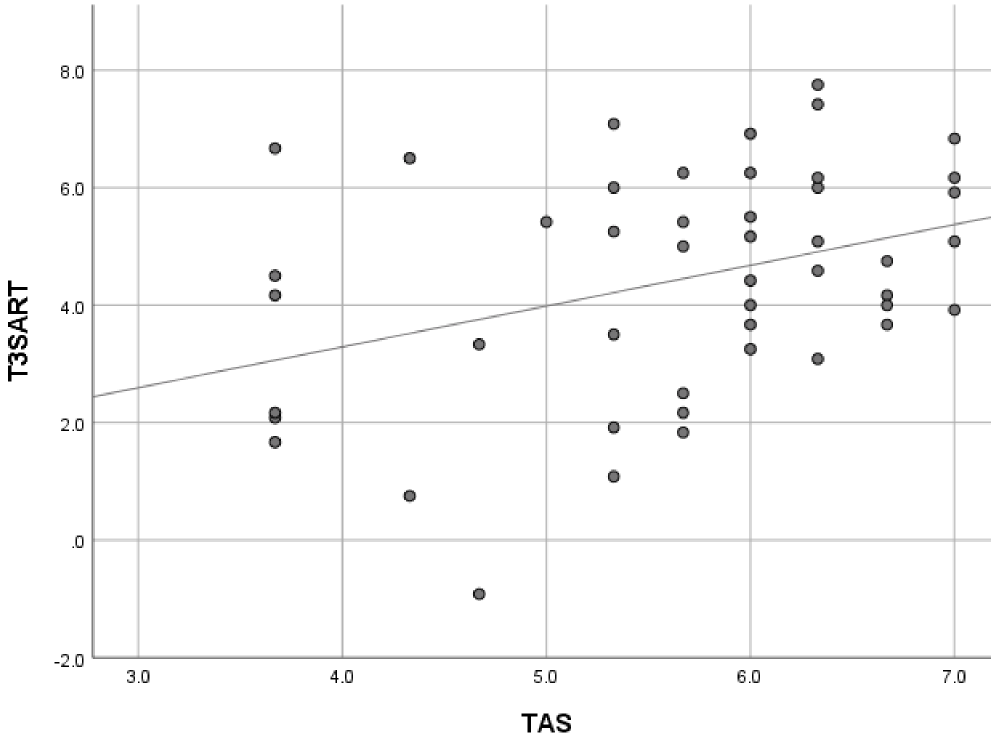


Image 51: figure showing the correlation between the Technological Affinity Score and the Situation Awareness Rating of the third scenario.

10.7 Experience with technology

Using preliminary questions PQ8, PQ9 and PQ10 (*How much experience do you have with AGVs / production environments / AR)* an average score was calculated and labeled FES (Familiarity & Experience Score).
We wanted to see if this score correlates with any performance scores such as the SART, TLX, or SEQ using a Pearson's correlation test. Apart from a weak correlation between FES and the SART score of task 3 (Correlation = 0.291, p = 0.047) no correlations between FES and other parameters were found leading us to conclude that familiarity and experience with technology do not significantly influence the results in this test setup.

10.8 Summary of Results

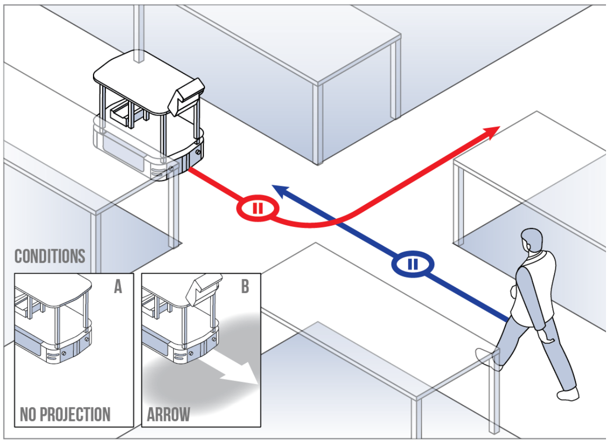
The most relevant and significant results of this research:

- Projected arrows made scenario 1 significantly easier to assess as evident from the SEQ.
- Assessment of the robot's actions (Q2) was improved in all scenarios. In scenarios 1 and 2, the chance of a participant correctly assessing the robot rose dramatically when the projected arrows were used. Participants also had a heightened certainty of this assessment in scenarios 1, 2, and 3. In scenarios 1 and 3 this relationship was very significant.
- Projected arrows increased the chance of a participant taking a desirable spatial action in all scenarios.
- Emotional responses greatly differed. Anxiety was an often-reported emotion especially in scenario 3.
- The Post Test Questionnaire indicated that:
    - Participants find the projected arrows helpful in understanding the situation
    - Participants think the arrows are needed to understand the situation
    - Participants are confident in the situation because of the projected arrows
    - Participants do not think the projected arrows are distracting
- As evident from SART question 8, the project arrows caused the participants to gain more information about the situation in scenarios 1, 2 and 3. The average score was 1.2. points higher than for participants that are shown no projection.

Please see next page for scenario-specific descriptions

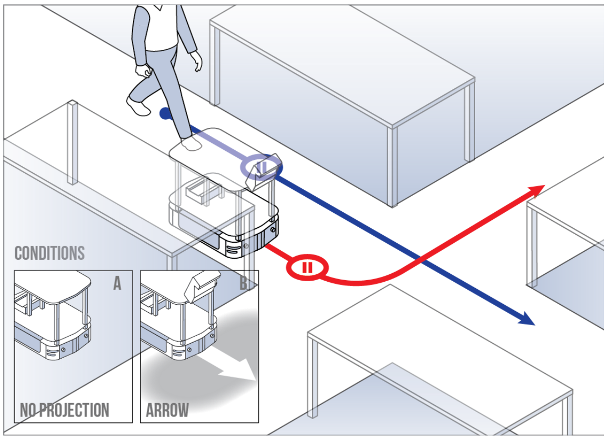
Scenario 1

Projected arrows made the situation significantly easier to assess (Q2, Q3). Participants also experienced that this assessment was easier to make (SEQ, Q5). Participants felt safer because of the projected arrows (Q6) but were more likely to feel negative emotions (Q4).



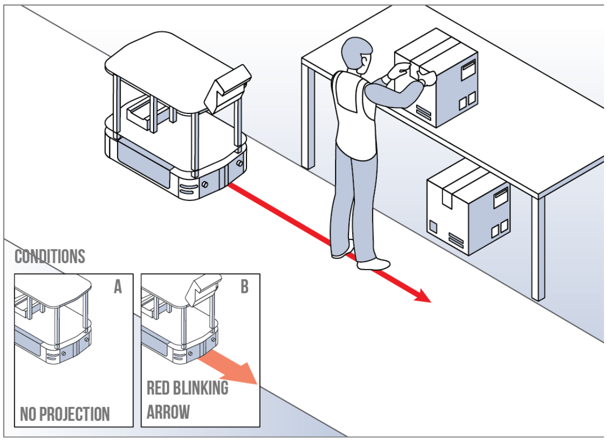
Scenario 2

Projected arrows greatly increased the chance the participant could correctly assess the robots next action (Q2). Participants also experienced that this assessment was easier to make (Q5) and it did provoke a (non-significant) rise in situation awareness (SART).



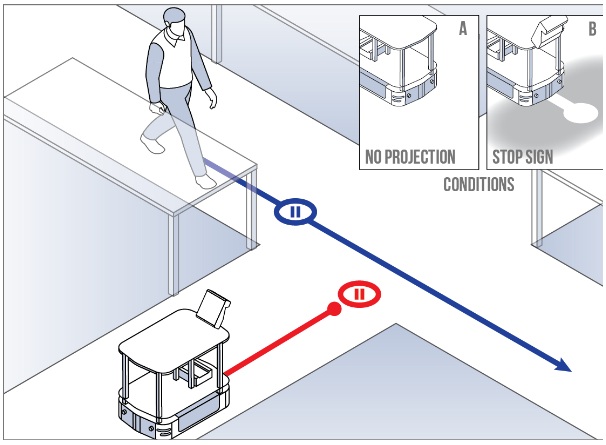
Scenario 3

The projected flashing red arrow increased anxiety (Q4) and made the participant feel unsafe (Q6). However, it did very clearly communicate the robots next action (Q2) and increased the participants situation awareness (SART). It made participants more certain of the next action of the AGV (Q5).



Scenario 4

The projected visualisation made a (non-significant) positive impact on the experienced ease of the task (SEQ). This is confirmed by the fact that participants significantly more often took desirable action (Q3). However, it did provoke more negative emotions such as anxiety (Q4) and might lower perceived safety (Q6) compared to the situation without projection. The results indicate that the design confuses the participants and does not clearly communicate that the robot is about to stop.



10.9 Conclusions

In the previous chapters, statistical results are presented at length, but the question remains what this means for the industry, the concept of the smart factory, and for the merits of spatial AR applied in this manner and context. The results seem to indicate great potential for SAR within smart factories with a high degree of cooperation or coexistence between mobile robots and humans.

The results indicate that the projected visualizations have a risk of inciting anxiety in the users. Although we suspect that training and habituation can greatly lower the occurrence of this anxiety, it should also be noted that future development should involve special attention toward making the visualizations consistent and calm.

Edge-cases such as scenarios 3 and 4 need to be better explored so more effective visualizations can be created. Training can help workers properly understand the visualizations in these more exceptional cases.

In the most regularly occurring cases (such as scenarios 1 and 2) where the main communication concerns the projected arrow, the SAR setup provides an intuitive way for workers to quickly assess the robot's movement intention. In terms of subjective measurements, the projected arrows seem to positively influence the situation awareness, although this relation is only significant in scenario 3. Furthermore, the perceived safety is increased. In terms of objective measurements, the projected arrows lead to a far better assessment of the robots' actions and lead to a far greater chance of humans taking actions that are desirable for themselves and the factory. In the factory, this can lead to a decrease in incidents involving AGVs and an increase in worker wellbeing because both the experienced and the real safety are improved.

Applying this technique may mean that AGVs could now be applied in industrial situations that were previously considered unfit for AGV installations. This would accelerate the progress toward the factory 4.0 paradigm.

Chapter 11

Discussion

11.1 Remote testing

As discussed earlier in this report the experiment had to be executed remotely because of the 2020 COVID-19 crisis. Because the entire testing experience is virtual, control over the participant is limited. He or she can for example watch videos multiple times or be less attentive. The time the participants uses for the experiment could not be measured with the used survey tool (Google form).

Because of the use of videos, participants feel less immersed in the situation and the videos are barren of external stimuli.

A positive aspect of the use of videos is that they could be more easily controlled. Manual operation would have created variations in the exact path and speed of the AGV.

11.2 Validity of the data

Response Questions

Labeling qualitative data is a tedious process, but in the end, this seems to be the data showing the strongest results. From the open feedback questions, it can be concluded that participants had a lot of trouble ‘roleplaying’ the feelings they were asked for in the SART and TLX questionnaires. However, providing their own response to the situation and assessing the robot’s actions seem to come more easily to the participants. This is also evident from the low amount of data that needed to be labeled ‘*don’t know*’.

SART

The data collected through the situation awareness rating technique is useful to some degree.

A major problem with the execution of the SART is that one dimension *(information quality)* is missing. Many sources online seem to spread an image that is missing this dimension. Regrettably, the questionnaire was adapted from one such image.
The ‘information quality’ was removed from the calculation that defines the SART score. The SART scores can be compared amongst themselves within this research but do not account for the dimension that concerns the quality of information. Furthermore, the SART scores in this research are not comparable to other researches. The scores now have a range between -5 and 13.

NASA TLX

One question was removed from the TLX for this research (*How physically demanding was the task?)* The five remaining dimensions contribute equally and the scores from separate tasks can be compared to each other. But because of the excluded question, the results cannot be compared to other researches where the NASA TLX was deployed.

NASA TLX concerns tasks. Watching a movie can not truly be considered a task. It requires a lot from the participants' imagination to imagine all the types of strain and workload. Because the NASA TLX builds on participants' experience of the workload rather than their imagination of it, this resulted in the participants not knowing what information to give. This is also evident from the relatively high variance in the data. In hindsight, this method should not have been deployed in this remote setting.

Visualizations of scenario 3 and 4

The results indicate that the visualizations designed for scenario 3 and 4 did not properly communicate the status quo and intent of the AGV or that the visualization would otherwise negatively affect the participant.
The values for T3TLX5 show that the flashing red arrow in scenario 3 is evaluated as frustrating. And the results from Q4 show that scenario 3 and 4 made participants anxious.

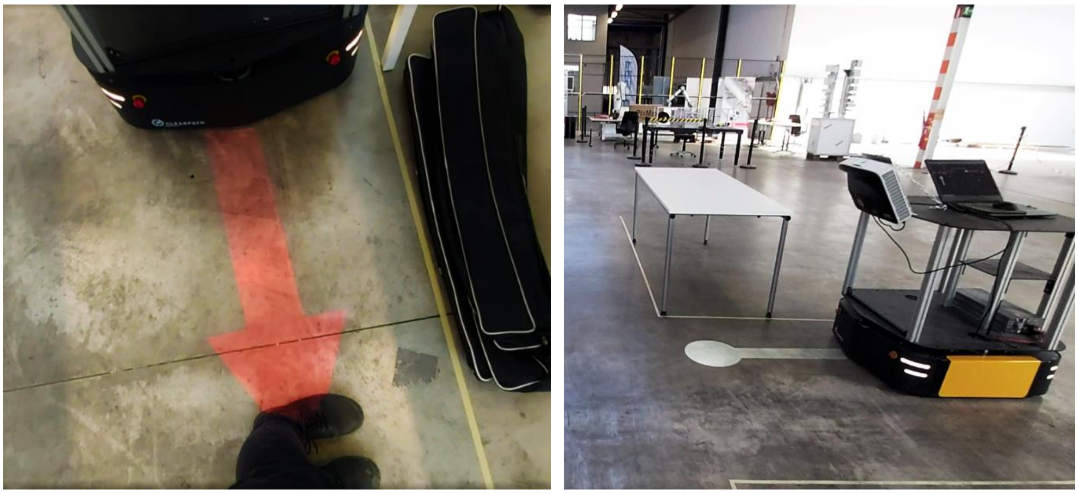


Image 52: (left) Scenario 3 visualization (rIght) Scenario 4 visualisation.

Post-test questionnaire

By the end of the post-test questionnaire, many participants might have figured out what the research intention of the research is. The results here might therefore be strongly influenced by participants pandering to the researcher.

Technological Affinity

The questions that were included to measure technological affinity and experience were improvised without proper academic reference. In the future, a standardized and verified test might be used such as the ATI scale (Affinity for Technology Interaction scale) [77].

11.3 Benchmark selection

The decision to execute the research remotely was hastily taken because of the COVID-19 situation developing in April 2020. Because it was uncertain if the lab would remain open, a plan to film the required materials was made and executed within a 20-hour period.
Regretfully this resulted in filming the two conditions as they are described in this research. The ridgeback AGV (like most AGVs) has indicator lights that are used in a comparable fashion in cars. In hindsight testing the projected arrows against a benchmark of the integrated turning indicator lights would have been far more meaningful.
However, even if this realization had come in time it would not have been possible to film the movies with indicator lights on short notice because:

- We did not yet get the indicator lights working.
- We did not obtain detailed information regarding the behavior of the indicator light in the industrial setting.

11.4 Practical design limitations

The way that the projector is rigged to the AGV causes a practical problem. In the Magna factory, a pallet is picked up by an AGV in a special pick-up station. They enter the station on one side and exit it on the other. The projector rigging would block the AGV from entering the pick-up station.

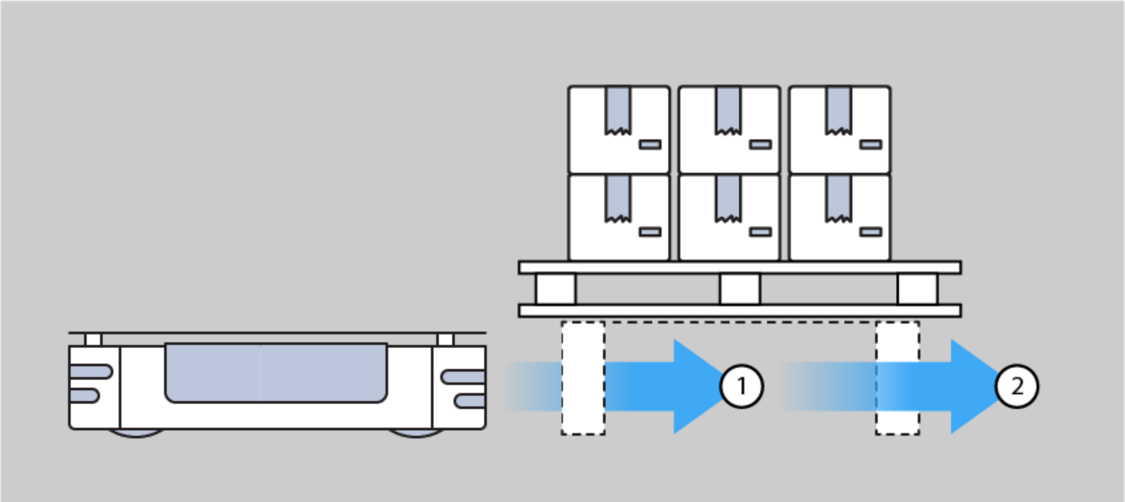


Image 53: The AGV enters a special pick-up dock from one side (1) and then continues out on the other side (2).

This could be solved by developing an ultra-short-throw projector that can be implemented at a height of 20cm from the projection canvas. If optical lenses are developed specifically for this application, it would be possible. It does need to be noted that this will cause ridges and debris on the floor to cast large shadows in the projection, making it unfit for brownfield applications.

A secondary option is to change the pickup behavior so the AGV enters and leaves on the same side of the pick-up station. This could be implemented without costly development, but it might delay the pick-up process. This design restriction does not apply when machinery is permanently fixed upon the AGV as is the case for the ‘Mobile Manipulator’, a robot arm installed on top of an AGV.

Part 4

Design and Research Opportunities

Chapter 12

Design Opportunities

During the runtime of this project and as a result of the research described in chapters 9, 10, and 11, multiple design opportunities were identified that would capitalize on the projected Spatial Augmented Reality setup. In this chapter, these opportunities are explained and in some cases examples of designs are given. The solutions go beyond the scope of this project but are provided so they might inspire future design efforts.

Presence acknowledgment

Participants and visitors to the lab often expressed doubts concerning the question 'whether the robot has seen them'. In day to day interactions and in traffic, humans use cues to acknowledge each other and this creates a high certainty regarding the question of whether he or she has been seen. The projection may very well be used to accommodate this acknowledgment (see image 54).

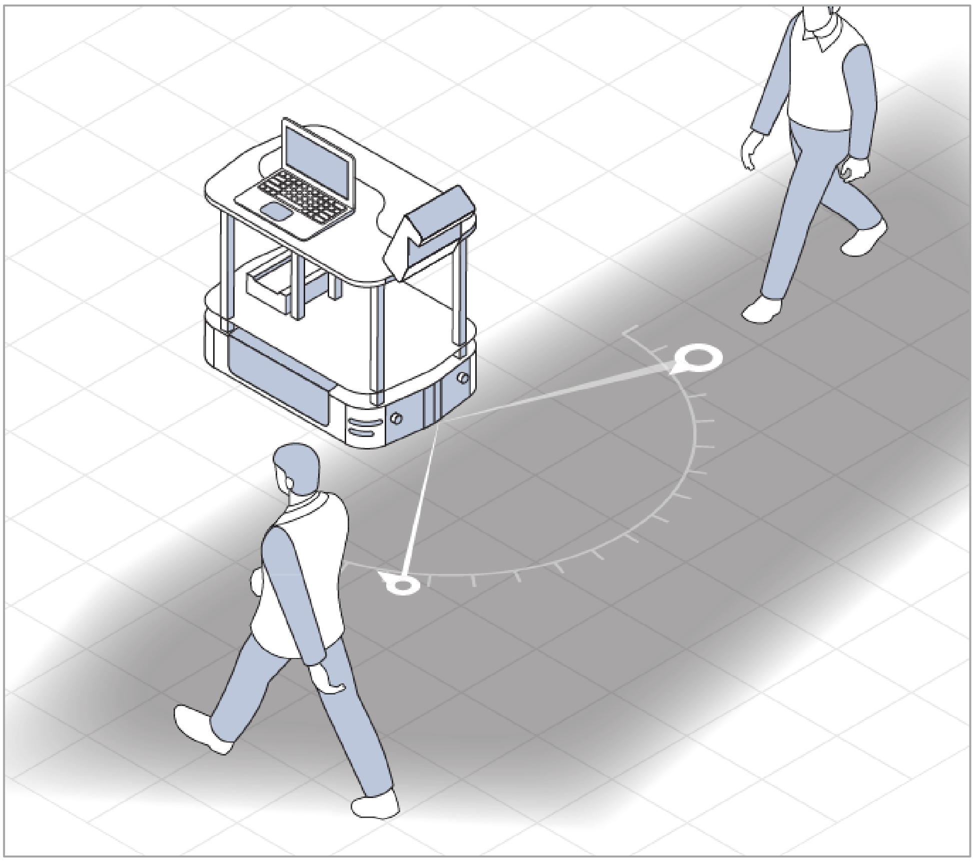


Image 54: The AGV projects an indicator that points toward obstructions that the AGV (through the SLAM system) has identified as human. This will communicate to the human workers that the AGV has 'seen' them and that it will plan its route accordingly. The design may vary to indicate more information such as the proximity of the human or it's assumed walking direction.

Contextually dependency

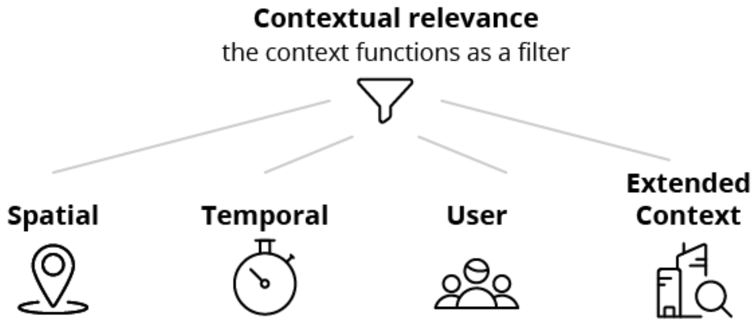


Image 55: Illustration showing the ways that contextual relevance can function as a filter for the shown information

Considering that the AGVs operate in a factory that has a digital twin, a lot of information is known about its environment. The context can be made to function as both a filter and a means to prioritize the information that passes the filter. There is a lot of information that could be shown, too much to practically comprehend. The concept behind the application of contextual relevance is to use factors of the context as a filter for which information to show and which information to exclude. If multiple pieces of information are still to be shown, then the context should provide a means to prioritize the information. Some examples:

- **User:** e.g. Maintenance workers may require different information than forklift drivers;
- **Spatial:** The visualization as it is shown from far away may evolve to give more details once it comes closer to the observer;
- **Spatial:** The visualization could adapt to the viewing point of the user, so the visualization is always 'right side up' and readable.
- **Extended context:** Information regarding the role of the AGV in a multi-AGV coupling can be given (see image 56):

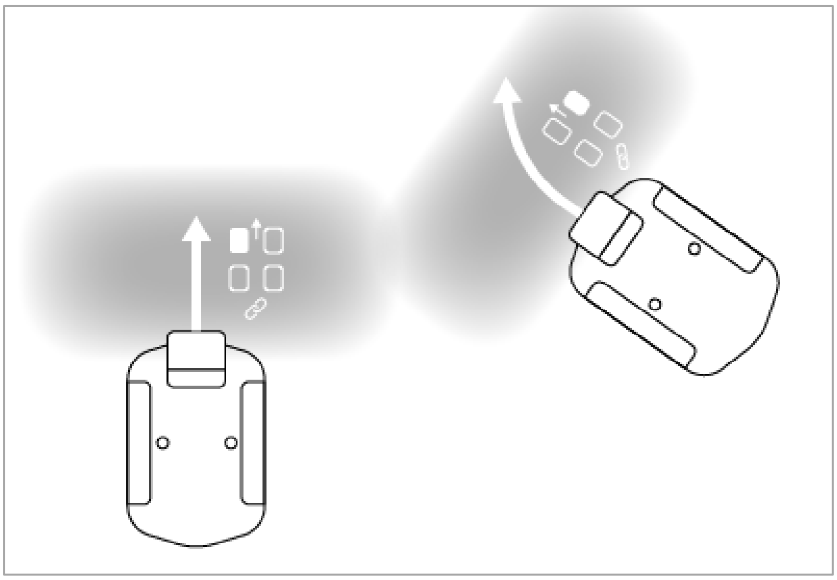


Image 56: As the AGVs prepare for a collaborative operation they show their respective roles.

- **Spatial:** Breaking zones may be shown when the AGV is speeding. The zones would extend when the AGV is moving fast and would disappear as the AGV slows down (see image 57).

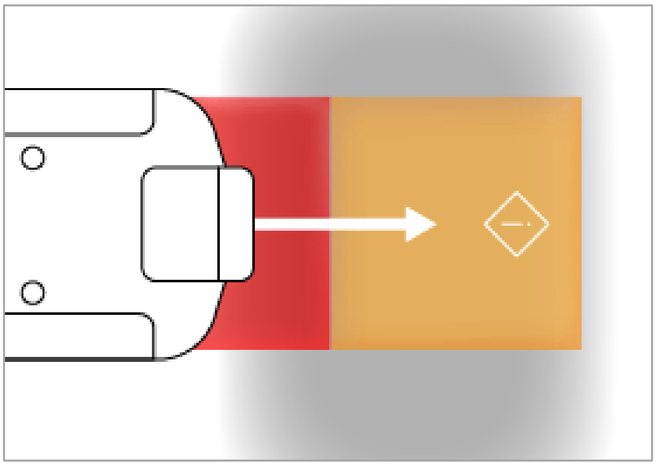


Image 57: A visualization of breaking-zones.

Multimodal interaction

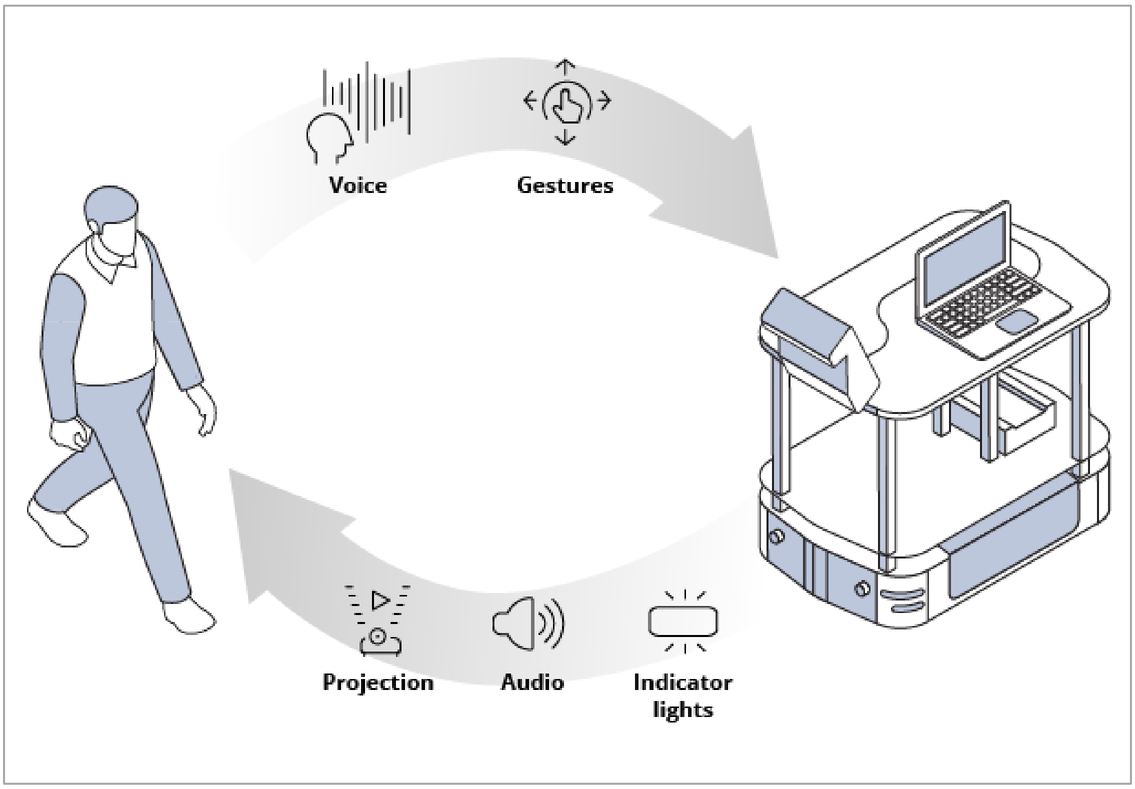


Image 58: An illustration showing the different modalities in which humans and AGVs could potentially communicate.

This project has specifically focused on visual information from the AGV to the user. However, other modes of communication could improve the interaction and create a more effective, safer, and more user-friendly environment. For example: audio signals from the AGV could prove useful in situations where the user is not facing the AGV (like scenario 3 in the experiment). Another example is that users could use voice commands to engage with the AGV.

Spatial communication of spatial intent of robot arms

Once the AGV is outfitted with a projector, the same concept could be extended to other machinery in the factory. The projected information could for example also be used to show the spatial intentions of s robotic manipulator arm mounted on an AGV.

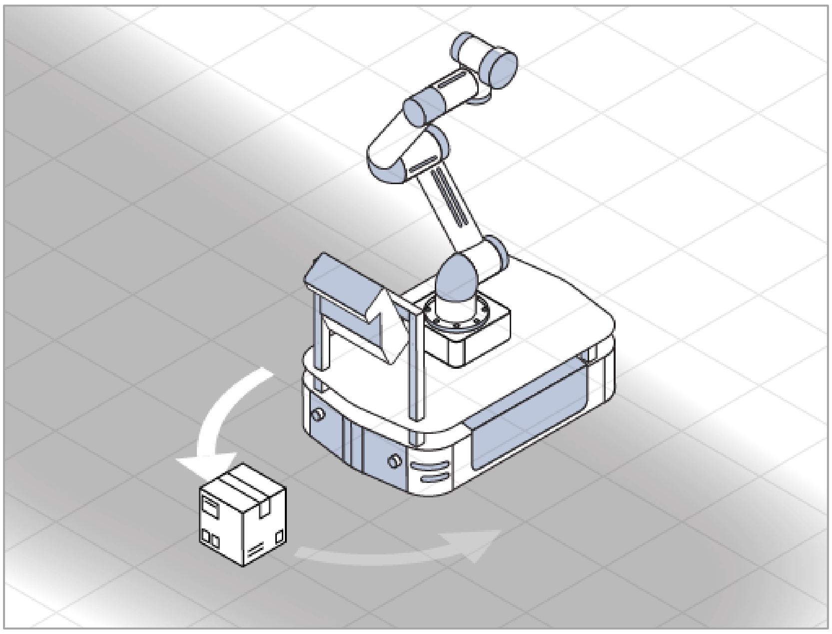


Image 59: The projection may be used to visualize the motions of a robot arm as well.

Projecting on the environment

In the hectic factory environment, the AGV can often run into obstructions it can not surpass. By projecting directly on these obstructions, it can clearly communicate to its human co-workers what the problem is. This will also assist in troubleshooting situations where the AGV perceives objects that are not actually there (for example due to a sensor malfunction).

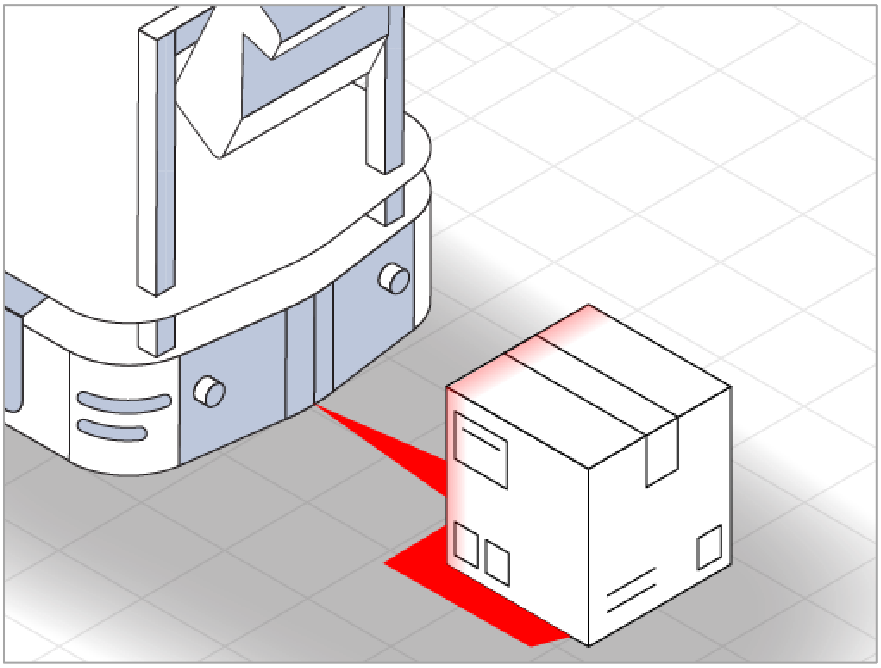


Image 60: the AGV indicates where it has observed an obstruction.

Evaluation

Spatial Augmented Reality can help with evaluating the performance of an AGV system because it is easier to connect the actions of the robots to its perception. After all, the perception is spatially visualized in real-time.

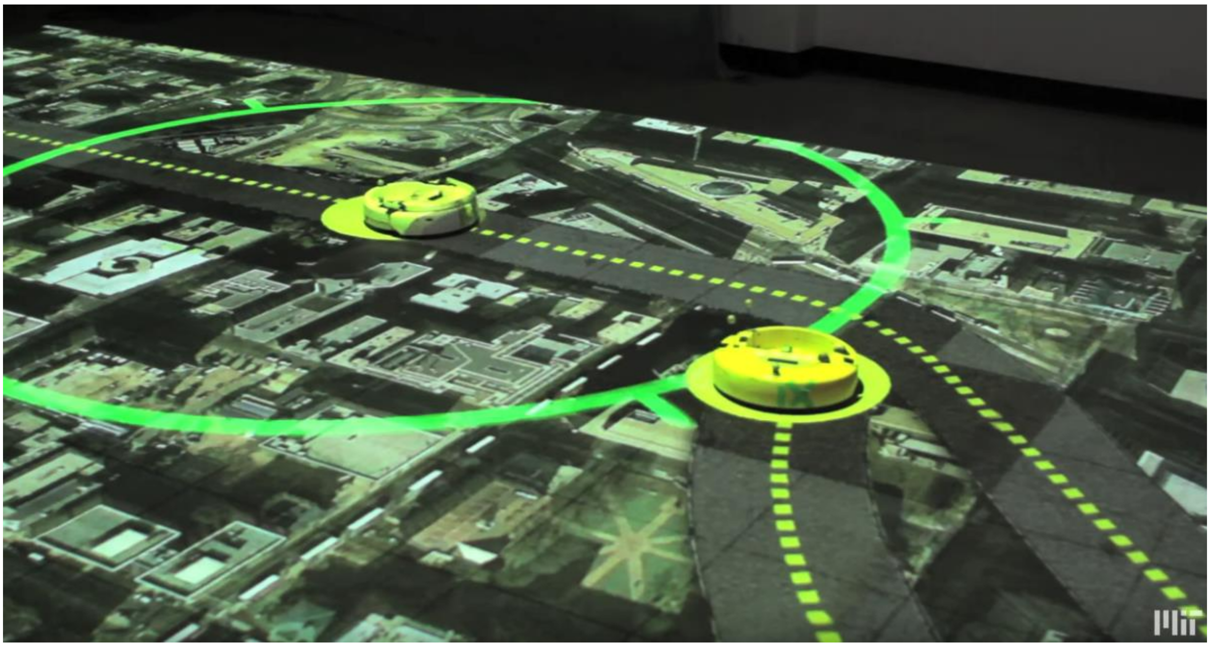


Image 61: Video by the Massachusetts Institute of Technology. [78] *In this setup the behavior of robots is evaluated within a modeled city. A fully projected environment visualizes the available data in real-time allowing researchers to quickly see mismatches between the real model and the robots' interpretation of it.*

Chapter 13

Research Opportunities

13.1 Potential research

The experimental setup as described in chapter 8 could be repeated but with some key changes to make the results more valuable for industrial application and academic discourse and to iterate on the findings in this report.

- Interviews should be held with multiple types of factory workers within their working context. The goal would be to find which design opportunities (see chapter 12) facilitate their information need best and which interaction scenarios are most likely to occur. This information can then be used to create realistic scenarios and design the visualizations and behavior exhibited by the AGV in that scenario.
- Specifically, better visualizations are needed for more complex scenarios such as 3 and 4. The research results indicate that the visualizations did not properly communicate the current status and intent of the AGV. This should be done in an iterative fashion first (using the Rapid Iterative Testing and Evaluation (RITE) method) to find a good design before doing academic measurements. The effect of training personnel to interpret visualizations in these rarer cases could also be researched.
- The experiments should be executed in a lab environment with a real AGV. This will improve how realistic the testing environment is, which will improve the reliability of standardized scores such as the SART. Also, this will give the researcher more control over the testing environment.
- The experiment described in this report used two groups: 'Projected arrows' and 'no projection'. In a future experiment, the 'no projection' should be replaced. AGVs in factories use signal lights to communicate their intent. This would provide a more realistic real-world benchmark to test against.
  AGV installation experts should be consulted to verify whether the behavior of the lights in the experiment is representative of the behavior in a factory.

Image 62: Most AGV's (like this ridgeback AGV) that are used in a factory context have indicator lights just like cars. They are used to communicate intent or the robot's current status.

- As described in the discussion (chapter 11) the NASA TLX did not seem to produce reliable data on account of the remote testing. A pilot for these experiments should focus on finding out whether this improves when the scenarios are enacted in a lab environment. In addition, the complete SART question list should be used.
- To measure the technological affinity of the participants a standardized test should be used such as the ‘Affinity for Technology Interaction (ATI) Scale’ [79]. This way the technological affinity of the participants can be compared to other researches or to the average technological affinity of the target user group.

Other proposed research

- The concept of ‘presence acknowledgment (see chapter 12) could be evaluated to see if it lowers the participants experienced anxiety. It is suspected that this method, if designed properly, can greatly help improve the participants' trust in the workplace robots.
- The evaluations described in this report are all based on first impressions; the participants have no experience with the situation they are exposed to (AGV with projections). In reality, factory workers will be trained to interpret the AGV’s communications and to communicate back adequately whenever needed and they will quickly grow experienced in this interaction.
  Although first impression research can tell us a lot about the successfulness of the design efforts it does not fully account for the expert roll that the real users have and although experience and training will generally mean that the AGVs communication will be more easily correctly interpreted it also increases the demands and expectations the user has regarding the interaction. A follow-up research in which participants are either trained or experienced in the interaction would be a logical next step to see how the design fares with these users.

13.2 Solution Spaces Chart as a tool for framing research efforts

The image seen below (image 63) is the 3-dimensional chart that was used in chapter 6 to define potential solution spaces for AR innovation in the smart factory environment.

This chart may be used to communicate the position of a research project and help it to achieve a narrow scope. For example, this may be used for research within the TU Delft. Research efforts that fall within the same solution space could be connected to share insights and tools. The three dimensions of the chart could easily be expanded if needed.

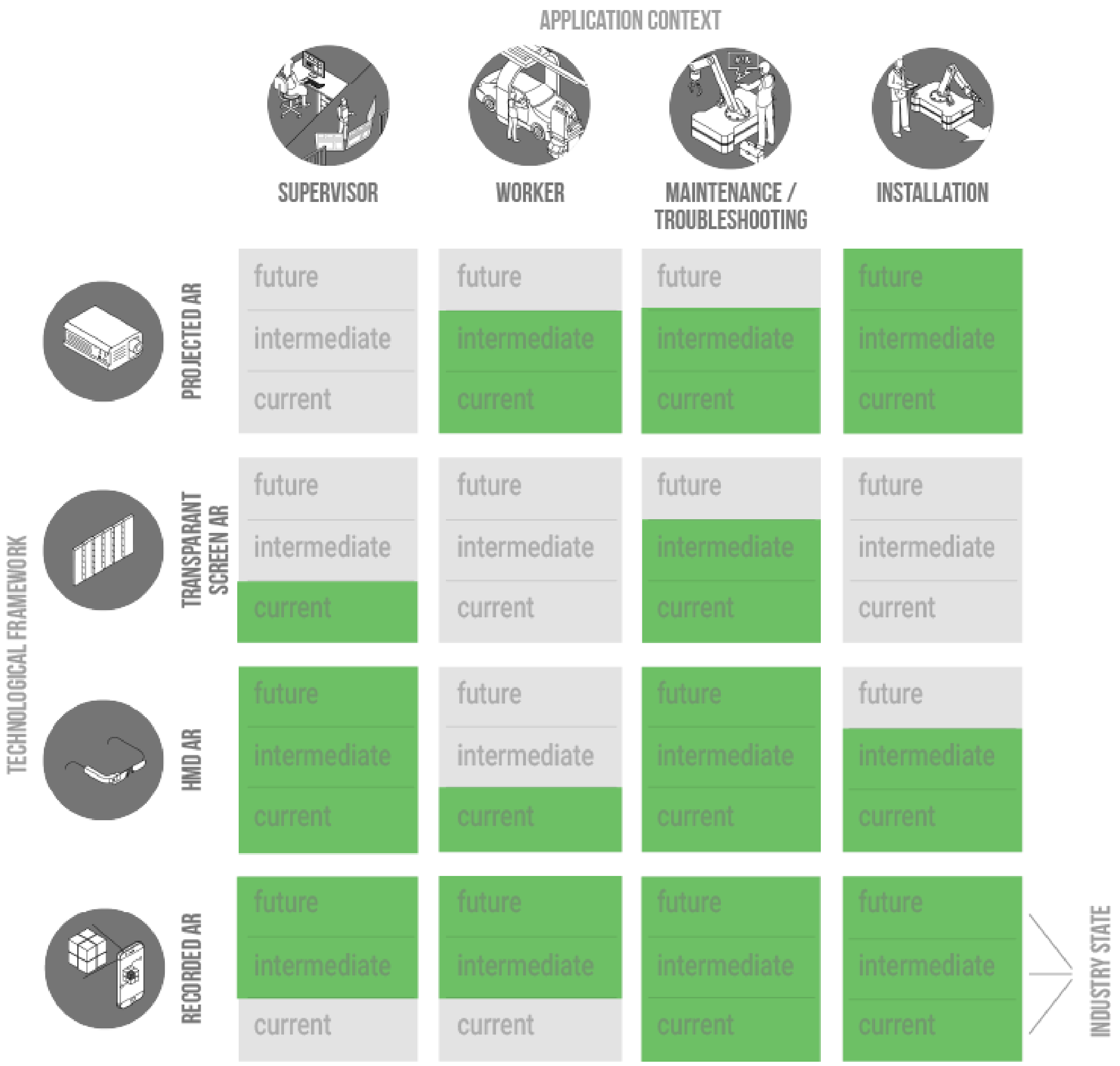


Image 63: Solution spaces chart with three dimensions: Application context (y-axis), Technological framework (x-axis), and Industry state (three options within each cell). The green cells are the ones that were considered 'fertile' for design innovation within this project. This will need to be reconsidered for each project individually.

Acknowledgments

Finishing my master's degree was quite an amazing journey. It would not have been possible without the guidance and critical notes of my mentor Zoltán Rusák and the enthusiasm and knowledge of the chair of my graduation committee, Doris Aschenbrenner.
In extension to this, I also want to express my appreciation to all other members of the Smart Manufacturing Lab at the SAM|XL Lab and the applied labs of Industrial Design Engineering. They are an incredibly driven collection of people who have motivated me with their enthusiasm and expertise. Special thanks go to Neel Nagda for being a great programming expert and sparring partner.

I wish to thank the people at Magna Steyr for welcoming us and showing us around in their amazing factory.

My thanks also go to the more than 50 people who have participated in the numerous questionnaires and pilots included in this research. Especially the participants of the final questionnaire which was once described by Doris as "torture".

Finally, I thank my girlfriend, Sam, for always supporting me, even when I was making impossible 80-hour workweeks.

Closing Statements

Having to finish this graduation thesis in a time which can easily be described as turbulent for both myself personally as well as the world as a whole, has been an enormously educational experience. I realize this especially when I look back upon the steps I've taken during this project and consider all the things I would now do differently. I believe this signifies both the experience I have since gained as well as the knowledge still to be obtained.

I sincerely hope this project may provide some guidance to other future projects such as the 'AR cockpit with transparent screen' -project which was executed as part of the AED course (Advanced Embodiment Design) and in this way generate matches between augmented reality and the smart manufacturing environment. A matchmaking process that I sincerely believe will produce a variety of innovations that will prove to be beneficial to the manufacturing context and the humans that work in it.

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Appendix

Appendix A

Original Design Brief

35by

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Verbeij
initials: M.M. given name: Martijn
student number: 4150015
street & no.: [illegible]
zipcode & city: [illegible]
country: Netherlands
phone: [illegible]
email: [illegible]

Your master programme (only select the options that apply to you):
IDE master(s): ( ) IPD (★) DfI ( ) SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: ( ) Honours Programme Master
specialisation / annotation: ( ) Medisign
( ) Tech. in Sustainable Design
( ) Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Doris Aschenbrenner dept. / section: DE / MM
** mentor: Zoltan Rusak dept. / section: CPS
2nd mentor: TBA (Someone from SAM | XL or Magna Steyr)
organisation: SAM | XL or Magna Steyr
city: Graz country: Netherlands / Austria

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 1 of 7

Procedural Checks - IDE Master Graduation

TUDelft

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Doris Aschenbrenner date 01 - 09 - 2019 signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 18 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 18 EC

List of electives obtained before the third semester without approval of the BoE

(V) YES all 1st year master courses passed

NO missing 1st year master courses are:

name D. Keansle date 6-9-19 signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: (V) APPROVED / NOT APPROVED

Procedure: (V) APPROVED / NOT APPROVED

comments: abbreviations are not allowed in the title. Please adapt the title.

name A. Huwae date 17-9-2019 signature

Initials & Name M.M. Verbeij Student number 4150015

Title of Project Explorative study for application of Spatial AR on factory AGV

Explorative study for application of Spatial AR on factory AGV — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 06 - 05 - 2019 — 25 - 10 - 2019 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

CURRENT STATUS: Automated Ground Vehicles (AGVs) are autonomously functioning vehicles often used in factory context for transport. The new generation of AGVs are no longer predictable, train-like vehicles, but quite literally have a mind of their own. The dialogue between machine and men needs to be properly facilitated otherwise the AGVs are perceived as unpredictable by the human operators and thereforecreate physical danger. An additional problem is, that supervisors lose the overview of the swarm of AGVs.
The supervisory operator is currently using desktop applications to read out the sensor data from vehicles and associated hardware. Multiple screens are used to display the information and keyboard and mouse are used for input. The information is plenty and complex but should primarily provide three insights: what has the fleet done, what is it doing and what is it going to do. When errors occur the operator should quickly be able to understand the problem that was created and provide input to solve it.
The information complexity in both of these situations could be improved using AR solutions that provide a better flow of information within the factory. AR solutions will become more prevalent in the future, but not all contexts allow the usage of head-mounted displays. Spatial AR utilizes only hardware that is external to the user and offers many advantages in terms of ergonomics and communication between humans.
PROJECT CONTEXT: The specific context for this research is applying Spatial Augmented Reality to improve situation awareness of autonomous factory transport. The project is conducted in cooperation with the TU Delft faculty of Industrial Design Engineering, the SAM XL lab in Delft and Magna Steyr in Austria. Problems in the factory working place are derived from high information complexity. AR offers the means to filter and provide contextually specific information. This fits within a broader perspective of applying AR in complex work environments to relieve human operators (more about my vision on complexity in the personal project brief).
OVERALL OBJECTIVE: The first objective is to analyze the interactions between factory supervisors and the AGVs. Focus will lie on interactions that are A. the most critical B. have the most potential for improvement, and C. are most susceptible to a design solution using Augmented Reality. This design solution should improve the situational awareness of the human controller, reduce risk and increase performance and employee wellbeing. The merits of applying spatial AR will be researched for this purpose.
MAIN STAKEHOLDERS: Magna Steyr smart factory in Austria. SAM|XL Lab and it's associated partners. The TU Delft, specifically the faculty of Industrial Design Engineering and the Applied Labs. The stakeholders all expect insights into the application of AR in a complex workplace. They wish to learn what impact AR can have in this context in its current technology level but also it's potential for future development when AR has become more socially acceptable, has been further developed to make it deployable for a broad range of applications and will be more affordable.
LIMITATIONS AND CONSIDERATIONS: There are also certain limitations that should be kept in mind. AR is a rapidly developing technology, this means that discoveries and insights may quickly become deprecated or design solutions may become obsolete when solved by other technological means. Therefore I will not only try to demonstrate the merits of AR in this specific use case but also outline more general insights for the application of AR in complex work environments. Many teams working on the development have a computer science or robotics background and will have a strong focus on data structures and efficiency optimizations. I will attempt to complement this by applying a human-centered approach to my design work, using metrics that allow the effect of these efforts on humans to be measured.

space available for images / figures on next page

introduction (continued): space for images

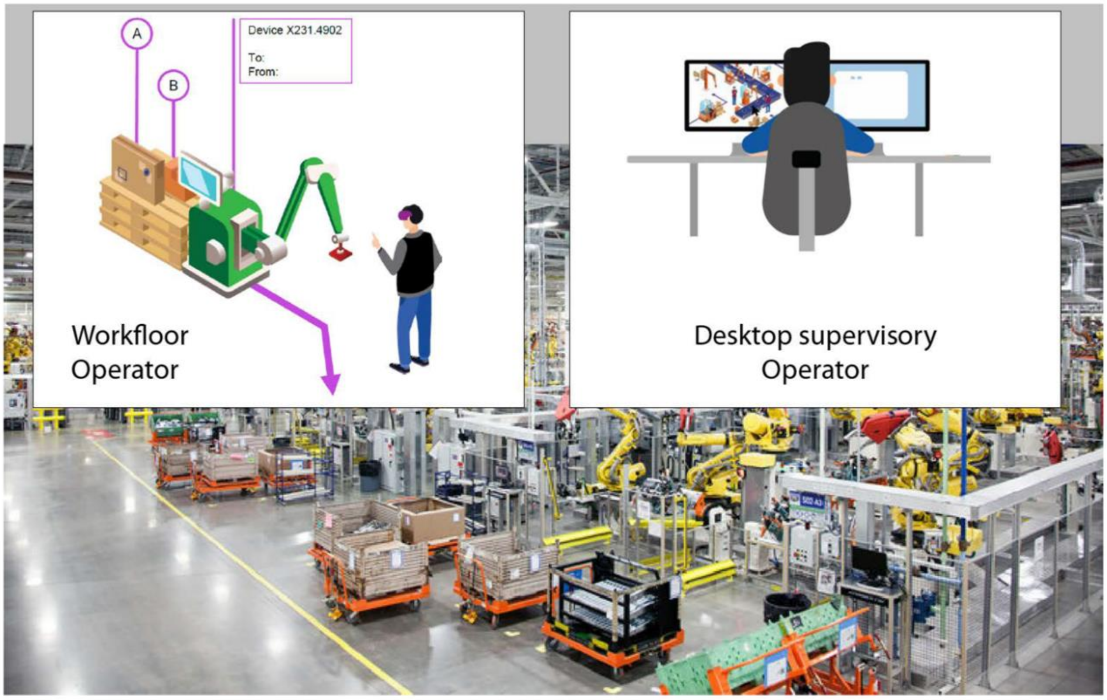


image / figure 1: Two potential contexts for the applied spatial AR, both in a factory with autonomous vehicles

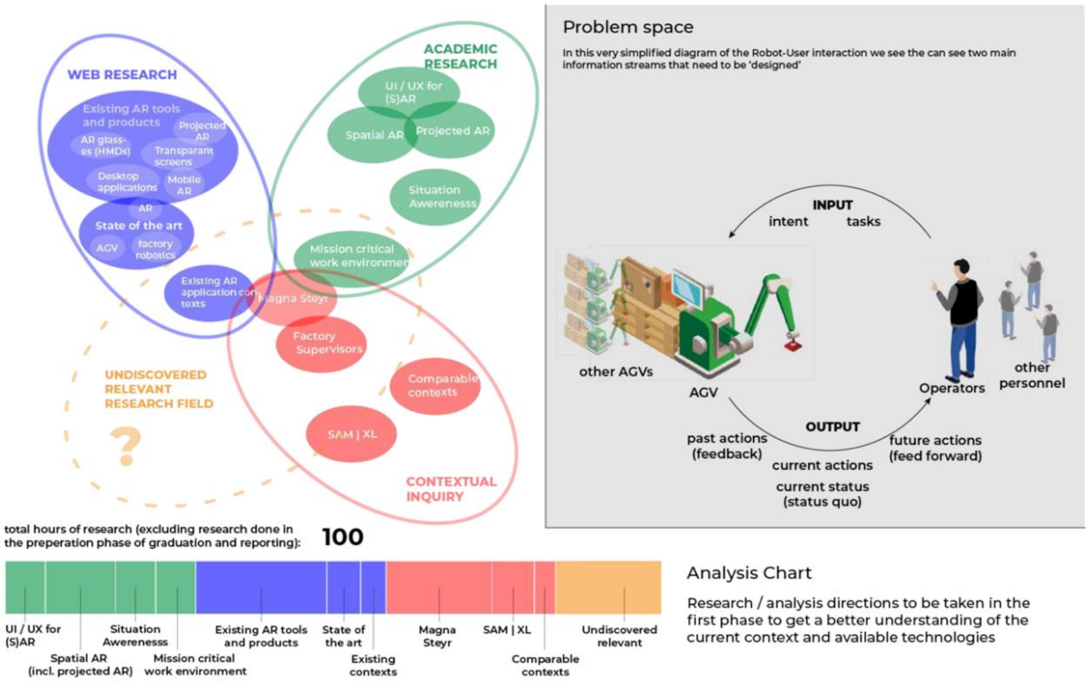


image / figure 2: Analysis chart (left). Simplified information framework of the factory (right)

Initials & Name ______ Student number ______

Title of Project ______

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

SOLUTION SPACE
The first phase of the project will concern indexing the responsibilities and challenges of the fleet supervisors and the current state of AR application.The solution space is where appropriate AR technology and the appropriate context meet. A profound contextual inquiry at the beginning is required, to find those opportunities. This contextual inquiry will take place during our planned visit to Magna Steyr (10.09 until 12.9). The analysis phase will be used to narrow the solution space down, so that the conceptualization will either focus on the information complexity facing the workfloor operator or the information complexity facing the supervisory operator. A UI framework or interface prototype will be designed using existing AR development tools (such as Unity AR / VR).
LIMITATIONS
There is limited access to the context of use. I will need to prepare properly to make the most of the contact moments. At this moment a lot of assumptions are made about the operators and their responsibilities, problems and interactions with the AGVs. Before doing the contextual inquiry it is unclear exactly at what place in the factory process the most improvement can be achieved. Multiple issues still persist within the concept of a Smart Factory. A lot of these issues will need to be assumed fixed in order to focus on the problems with the user-robot interaction. The project will not address associated AR challenges such as tracking, calibration, the display technique itself, graphics rendering and information processing.
ISSUES TO BE ADDRESSED: Sensory and mental overload of the supervisor needs to be limited, mission-critical information needs to delivered to the appropriate agent with a high degree of reliability. Other communications and processes in the factory should not be obstructed in any way.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

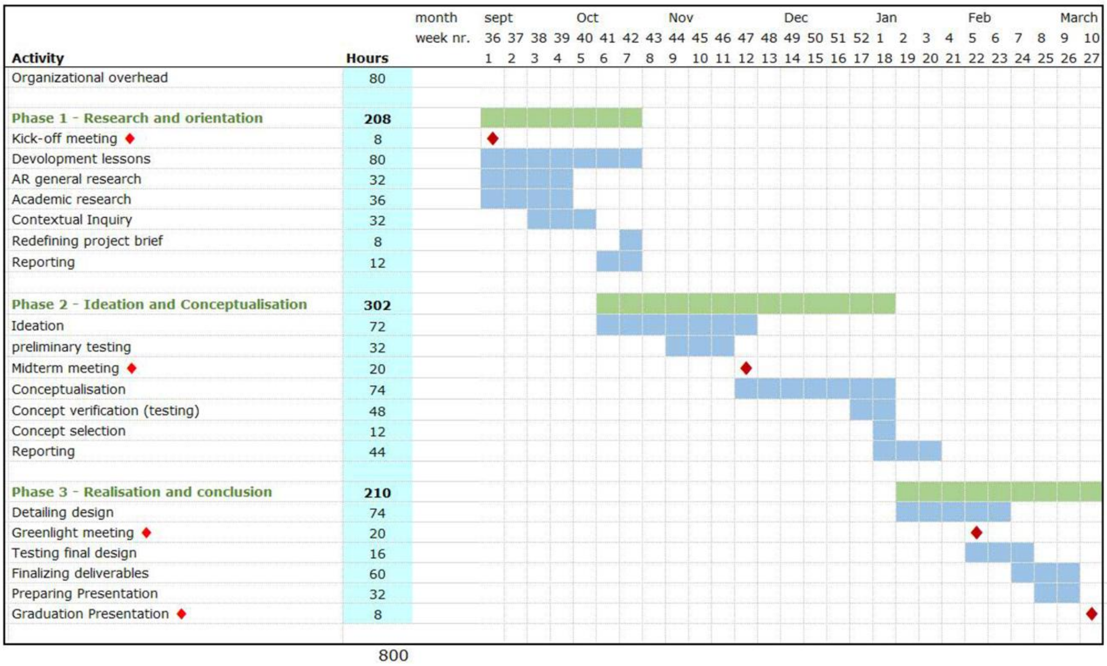
This project will identify (Spatial) AR solutions, that are suited to facilitate the interaction with an AGV (autonomous guided vehicle) swarm in a smart factory setting. The focus is to identify problems experienced by factory supervisors such as information overload or lack of oversight, and to design a AR user interface solution, that will increase situation awareness.

RESEARCH. I will research the context of supervisors working with the AGVs, what are their tasks, responsibilities, and challenges? What tools are they currently working with and what are their limitations? There are two roles within the factory (see image 1), the workfloor operator and the supervisory operator, that have potential for an AR intervention. The flow of information within the factory should be mapped on a fundamental level. This should include sensor information, how it is displayed and also the role of human operators in the information distribution.
The second part of the research phase is to better understand the practical application and limitations of AR. When both the context and the technology are properly understood, I can identify which interaction with an AGV swarm for intra-logistic can be supported by Spatial AR based on the smart factory scenario of Magna Steyr .
See image 2 for more specified topics of research.
CREATE. In the ideation phase, the solutions identified in the research phase are explored and rough design directions will be created accompanied by mock-ups, prototypes, and sketches. Toward the conceptualization phase, these ideas will become more detailed and will be tested to become more detailed concepts.
REALIZE. The project will be concluded by an interactive prototype to be tested through simulation. A first iteration will be tested with subjects without context knowledge. A second iteration would focus on relevant factory personnel although it is currently unclear if this will first within the project scope and will be practically possible (the factory being in Austria). Along with this, a report will be made in which (apart from a disquisition of my entire process) a summary will list all other useful insights concerning the application of Spatial AR in complex work environments.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 6 - 5 - 2019   25 - 10 - 2019 end date



The image above is a global planning which will be subject to change and will be accompanied by more detailed planning-documents, which will be proposed to the graduation team at the start of each phase. These planning documents will contain day-to-day activities.
In discussion with my graduation team we have agreed on a 32 hour a week workload for 25 weeks to fulfill the 800 hours. I would prefer to schedule short meetings on a bi-weekly basis with my mentor.

DELIVERABLES:
- Research report, to be discussed at the end of Phase 1. This includes test results and interpretation of these results.
- Ideation summary. Summarizing the process and results of the ideation phase (to be discussed in phase 2).
- Concept presentation. Summarizing the process and results of the concept phase including prototypes and testing.
- A final report containing all information above. A preliminary version to be discussed during the green light meeting.
- Summarizing sheet as specified in the 'deliverables document'.
- Demonstration of the final selected concept. This may be a prototype or video depending on the outcome.

RESOURCES:
If possible, I would prefer to have a fixed place to work. I will require access to AR tools. I will be better able to assess what exactly is needed at the end of phase 1. All other hardware (such as a powerful computer to run simulation and make prototypes and projectors) I already own.
The most important resource required is external knowledge concerning the development and deployment of AR. This knowledge is available represented in the stakeholders already involved in this project.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

MOTIVATION
Vision: We live in world that is not only increasing in complexity but this increment is accelerating exponentially. My grandmother got out of touch with technology when she was 60, my parents lost track when they were 40 and sadly it does not look like this acceleration will be more kind to my generation.
Not only technology itself is accelerating in complexity, it also allowing other aspects of our experienced world to 'complexify'. Technology has added value but also complexity to our social relations, politics and economics in more ways than I can describe here.
Designers should adopt the role of guide for other people to deal with this ever increasing complexity.
Augmented Reality as a concept has the potential to change the way we relate to technological development and the potential to untangle much of the complexity it accompanies.
The technology itself provides the absolute bridge between technological world and the 'real' world as we experience it every day.

COMPETENCES
Experience with projection mapping and prototyping using (a simulated) spatial augmented reality
A strong visual and graphical background in both academic as industrial sense. A good understanding and experience in the design of classical user interfaces.

LEARNING GOALS
I believe augmented reality has the potential to be a very prevalent technology in our future and as a designer I wish to learn how to harness this potential to make meaningful and functional user interfaces that improve the context of use. Furthermore, I wish to become more experienced in the work context where academics and industry work together. (such as the Sam | XL Lab)

CHALLENGES AND CONSIDERATIONS
The project will contain the development of prototypes that will need to be developed in Unity. The project may have the tendency to lean more toward development than toward design. I will need to deploy proper expectation management to ensure all stakeholders expect a design solution rather than a solution in code.
The content matter of the project could be easily expanded to a PhD-sized project. I will need to take care that the problem definition and solution spaces become specified enough to restrain me to a specific design problem and stay near the 800 hour limit.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

It's hard trying to outline my entire graduation and although orientation on the process is very useful I will also remain opportunistic and flexible, stirring my graduation in the direction that seems most fruitful while at the same time staying within the outline discussed in this document.

Initials & Name ______________________ Student number ____________

Title of Project ______________________________________

Contextual Inquiry Magna

Graz Meeting CoCoAs

Key Insights

AGV prototypes
The Smart Factory team has created 3 AGV prototypes of which the last one is ready for use in a real manufacturing context.
The lighting system used in prototype 3.0 covers a wide range of necessary Human-Computer interactions.
Opportunities:

- Sound is not yet used for communication between AGV and worker
- The first prototype contained a screen for showing sensor info, error states and other metrics. Prototype 3.0 no longer contains a screens. This information is found on the desktop application. Such as screen can be usefull for workers that require more detailed information about a AGV (current task, error state etc.)

The AGV can be outfitted with different addons (robot arm, storage rack or a euro pallet lift)
The AGV uses depth sensors to sense if an obstruction is nearby. If the obstruction is in the warning zone the AGV will slow down. If the object enters the Stop zone the AGV will make an emergency stop.
The AGV uses SLAM for navigation in combination with InCubed software. The SLAM information is shared with the central server so a real-time map of the factory is build which all AGVs can use.

Industry State
Many OEMs are researching technologies that allow for industry 4.0 integration. The way that these technologies are implemented will greatly influence the role of the AGV and the way it is controlled. Apart from the industry 4.0 paradigm there is also a vision of the 'all-factory', a highly flexible factory floor on which all machinery and parts are transported by or mounted on AGVs. All hardware is only present where and when it is needed.

New technological integrations are needed to make this a reality. Innovations such as AR, VR, AI, IoT, predictive maintenance can help. Magna has already successfully utilized a large range of these technologies in real cases:

- Product impression in VR (showing customers and clients cars in a VR environment)
- Ergonomics evaluation in VR (Video showed a woman sitting in a car seat. The car around her in virtual reality can be sliced to show the locations and ergonomics of the car.
- Walkthrough of a production set with the client (the manufacturing and assembly line)
- MR: quality control. Going through the checklist with an AR headset on. Quick access to documentation. Automatically run down the checklist. Reducing errors. ("digitally enhanced first part release")
- Magna meeting space with 3 integrated projectors. Large central touch screen. For clients and suppliers as well. Engineered towards effective meetings.

The amount of sensor data collected in the factory is already enough to allow for a digital twin to be constructed. This amount of data can be used to have the system present decision makers (supervisors) with actionable information.

The CoCoAs project proposal specifically mentions the development of swarm behaviour that will allow groups of AGVs to transport larger units such as complete cars. This is however not currently a development priority.

Current AGV implementation
An AGV brings car seats from one side of the assembly line to the other, greatly increasing efficiency and reducing costs. The AGV is alone and mostly isolated from the other subsystems of the factory. It's behaviour is simple and predictable and only deviates if a worker enters its direct surroundings. (a more detailed look on this can be found in 'Industry state – current')

The factory currently has a layout that is similar to a district with streets. Vehicles keep right and can not deviate far from their planned route. In a context like this the usefulness of autonomous wayfinding is limited. Obstructions are very temporary.

In the "all factory" however, the street layout will disappear, and the layout will be in a state of continues change. Adaptive wayfinding will then be essential for the efficiency of the AGV.

When working with humans accuracy is not essential. If an AGV for example needs to deliver a box of parts the human will not mind or notice if the box is placed 30cm to the left.

More information needed:

- The role of the supervisor is essential for the AGV ecosystem. We have limited information about the work environment of the supervisor.
- The factory is currently making a transition from human forklift operators to AGVs. In order to support this transition, the project team requires more information about the way tasks are distributed and communicated to the forklift operators

Complete notes 11 September ‘19

Introduction presentation
Franz Weghofer

In Graz there is complete engineering and manufacturing for a total of 9 OEMs
Body & Chassis / Seating / Exterior / Fuelling systems etc.

8-10.000 employees in Graz. 15.000 employees worldwide (Magna International)

Key challenge: keep the OEMs separated onsite because of confidentiality.

Graz team

Franz Weghofer, Project lead at the Magna Smart factory

Gottfried Krainer, Industrial management / AGV / Planning

Christian, Facility management / intralogistics / development AGV

Marcus, IT / Logic

Valentijn, technological integration

It is sometimes hard to convince management that focussing on long term innovation is important. Short term business cases need to show results fast to get approved. Frans his vision is to use the AGV to stay in the lead.

The digital factory is a digital twin model of production-sets and serves as the backbone to the smart factory. The digital factory should be able to react dynamically to the market.
A goal is to get real time mirroring between digital and real factories in order to go to Zero Defect manufacturing.

AGV prototype 1.0 in 2017
- First iteration, functional prototype for navigation.

AGV prototype 2.0
- To gain better understanding of vehicle behaviour a seat was placed on the platform.
- Specific hardware testing

AGV prototype 3.0 in 2019
- To combine findings of prototype 1.0 and 2.0

Specifically, for euro-pallets loading and unloading. Future vision it can transport
1. Parts and materials
2. Production / manufacturing machines (robot arms)
3. Products (cars)

Plug & Produce. Get production up and running right away (Production as a Service)

Use cases that are actually in use:
- Product impression in VR (showing customers and clients cars in a VR environment)
- Ergonomics evaluation in VR (Video showed a woman sitting in a car seat. The car around her in virtual reality can be sliced to show the locations and ergonomics of the car.
- Walkthrough of a production set with the client (the manufacturing and assembly line)
- MR: quality control. Going through the checklist with an AR headset on. Quick access to documentation. Automatically run down the checklist. Reducing errors. (“digitally enhanced first part release”)
- Magna meeting space with 3 integrated projectors. Large central touch screen. For clients and suppliers as well. Engineered towards effective meetings. Content is already loaded in when you enter.

14 minutes with AR headset is right now the maximum

“Moving from reactive to proactive”
Go directly to actionable knowledge.
Normal process: from DATA to DECISION to ACTION
By adding Big Data (300-400 Parameters) you can work directly toward actionable knowledge

Presentation Doris

Vision of the All-factory: very flexible space which can produce almost anything.
Question is how we can push the operator to the same 4.0 level
Adapt > Sense > Reason > learn > Adapt etc.

3 pillars to optimize to: Social, Service and Technical.

2 use cases: ground floor worker and the ‘cockpit’ supervisor

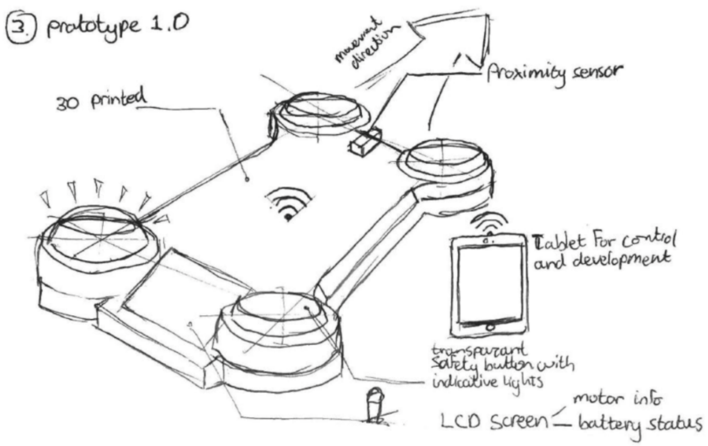
Robot arm on a (A)GV = Mobile Manipulator

First, Identify specific handling problems
Then, combine this with swarm robotics potential
To get, Interaction Potential

Presentation Gottfried
Goal: lift euro pallet.
Carrousel for storage integration.

They did field testing bringing parts from pre-assembly to main assembly. Testing in real environment with 14 forklifts was very successful. AGVs adapted real time to a changing environment. Testing was done in both the Mercedes Benz G-class and BMW area.

Prototype 1.0:

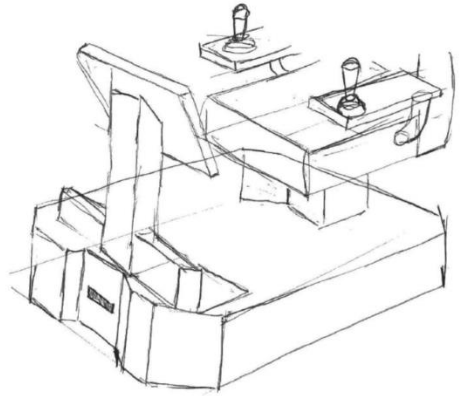


- 2 m/s
- Straight lines
- Using proximity sensors
- 95 kg own weight
- 150 kg load

3d printed Hull. LCD screen in the front will all types of status/error information etc. 4 large lights in the corners also act as safety buttons.
It was mainly tested for storeroom-retrieval. Prototype 1.0 had 3 subversions for the storeroom interaction with the AGV.
first version simply had buttons to order parts / products
Second version used e-paper to dynamically show product information. It could also show 'ordered' or 'in process'.
Third version used RFID chips.
Once ordered this way the AGV would know which products were needed where.

Camera on board is for safety, not for navigation.

Prototype 2.0

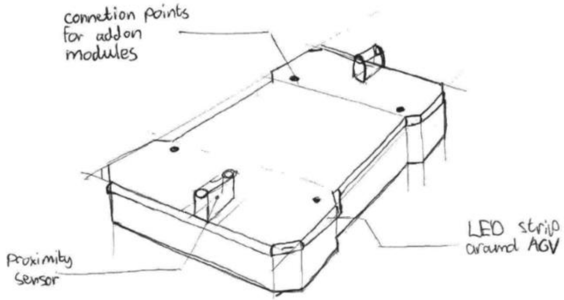


Was mainly used to test hardware like suspension, motor, stress-testing etc.
Has a chair on it and 2 joysticks for control (only 1 axis). The screen shows information about battery, state, safety area + obstacle area)

The joysticks control the speed of the vehicle and not the torque exerted by the drive. This makes the manual control rather difficult and sensitive to the input.

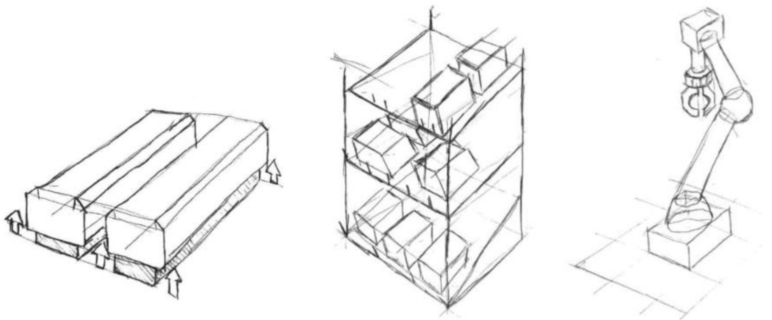
Prototype 2 provided a better understanding of the AGV behaviour and specific hardware such as the motor.

Prototype 3.0

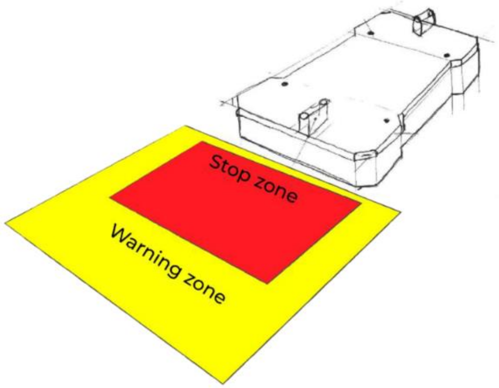


- 2 m/s
- Free navigation
- 200 kg own weight
- 500 kg load
- Safety sensors at both ends.
- Kinematic suspension
- 2 batteries, can be expanded to 4 batteries.
- It can charge at 60A, but they charge it at 20A
- 4 – 6 hours of use. But the use-cases right now are built in a way that the AGV always turns back to a charging station during short breaks in it's routine. It takes around 1 hour to charge. Design Challenge: where will these charging stations be most efficiently integrated.

Prototype 3.0 has a modular setup. Different addons can be put up the base unit.



For example, a dual set of bars that can lift euro pallets, a storage rack or in the future a robot arm (mobile manipulator)



Prototype 2 showed two zones in the interface. If an object is in the warning zone the AGV will slow down. Once an obstruction is found in the stop zone the AGV will quickly come to a complete stop. Warning lights on the AGV will flash red.

Light strip all around the vehicle, it can do the following things:

- Indicate start-up sequence (have the lights go on immediately when starting up to confirm to the user that the vehicle is successfully starting up, sometimes it can take 2 minutes until it can start moving etc.)
- Battery status, (battery charging and how much %)
- What is the back and the front (+ nice animation if the device starts switches direction).
- Turning direction.
- Error-state.
- Emergency stops.
- When there is an object in the Obstruction Area,
- etting in pre-position (MV: not sure what the animation was)

Interesting: no screen anymore on the product (compared to prototype 1.0). no status information can be given locally (only through the desktop software).

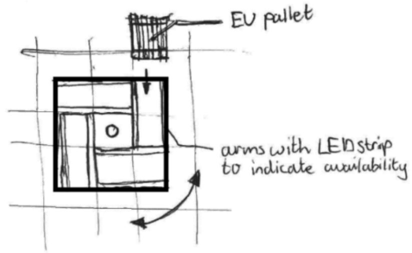
currently no auditory alarms or notifications are used. This could be an opportunity to expand (local) situation awareness. Apparently, tests were performed with AGVs that always have music running on the AGV as a way of notifying that the AGV is getting close.

A possible improvement chance is using sound. This would be useful for example when someone is in the way for the AGV to get into pre-position.

All devices have a blue light in front (the forklifts have these as well) so you can see them coming even around the corner. This builds on pre-existing safety training known by factory workers.

Carrousel

The carrousel improves the efficiency of loading and unloading pallets. The arms of the carrousel are fitted with LED strips to communicate if the tray is free for loading / unloading.



Currently it is not able to handle heavy loads due to large deflections.

CoCoAs Project

Cyber Physical Systems workshop will be held at the TU Delft with all partners.
One of the outcomes of the project is to create a new start-up from Magna and CharismaTec that will concern itself with the AGV development and also sell that technology to other companies.

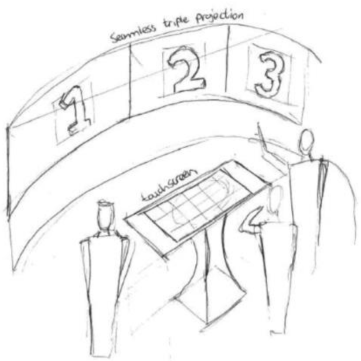
The project can be divided into two categories:

1. Swarm / Infrastructure use cases
2. Interaction use cases

Franz tells that a test was done comparing different modes of control for machinery (?)
Voice control was strongly preferred, even in loud environments (>60db). This was against expectations. (information missing)

Immersive Meeting Place

Magna has immersive high-tech meeting places inside production halls that are geared toward highly efficient, well informed meetings. A stand-up desk with a large touch screen is in the centre. Around is a 3-projector screen that will load the necessary information before the meetings starts.



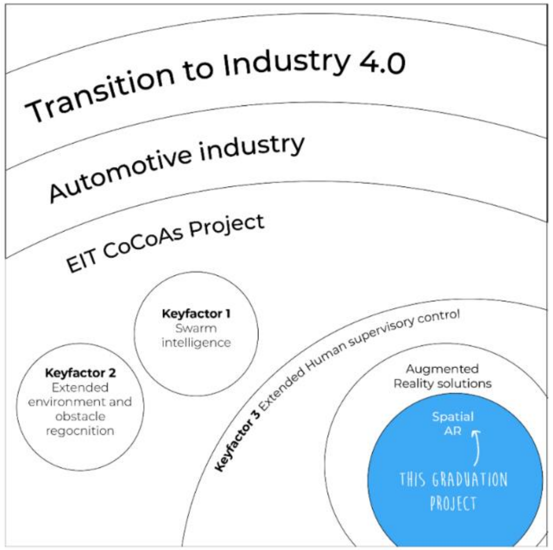
Software:

Incubed: http://www.incubedit.com/

The software makes a point map with all the data (SLAM) gathered by the AGVs. The AGVs constantly scan the area (green points) and compare this to what they already know. This way the map constantly gets updated.
In the software areas can be set that should not be entered, have only one direction or that are speed restricted. Goals are set and the closed available AGV will start working on it.

Breaking the paradigm

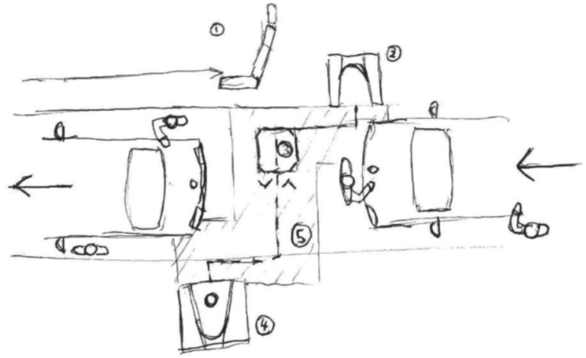
Reportedly every OEM is currently attempting to break the manufacturing paradigm and move toward industry 4.0. This consists of a broad package of innovations that need to be integrated and associated challenges that come with it. Examples: breaking the typical 'assembly line' model, flexible internal transport systems (AGVs) and integrated use of AR and VR.



The scope of the graduation within the context of the developments toward industry 4.0:

Current implementation AGV

Currently AGVs are being used for a simple but effective application of transporting car seats from one side of the assembly line to the other. The AGV acts alone and can be viewed as a separated system.



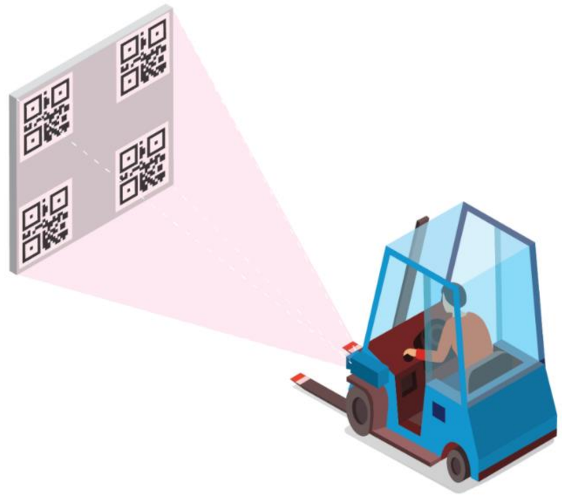
(1.) a conveyor belts delivers seats (2.) A pickup station hosts the seat until it is picked up (3.) by the AGV (4.) The AGV waits here until the seat is removed. The AGV is also charged here (5.) indicates the marked off zone in which the AGV operates.

The AGV will only move from (2) to (4) if there is a seat placed on it (the factory worker places the seats and presses a button to indicate that the seat is placed) and if the suspended car line is not moving. The assembly line will also not move if the AGV is not at one of its base stations.

This AGV was bought including its software (as opposed to prototypes 1.0 to 3.0, which were developed inhouse).

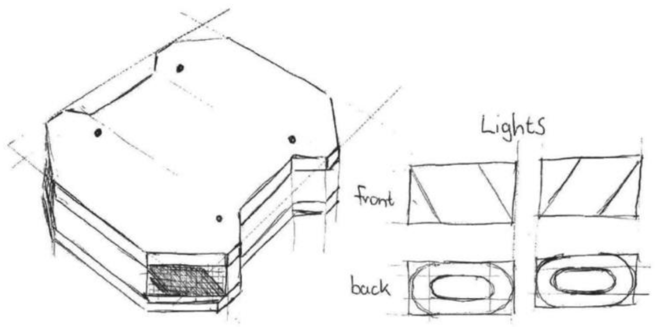
Forklifts

Currently internal transport between warehouses and assembly-lines is done by forklifts. These are driven by humans but directed centrally. Forklifts are fitted with an interface receiving directions. While driving the forklifts camera pick up QR codes that identify the location. This information is fed back to the system creating a real time map of all forklifts locations thus allowing monitoring of the completion of delivery tasks.



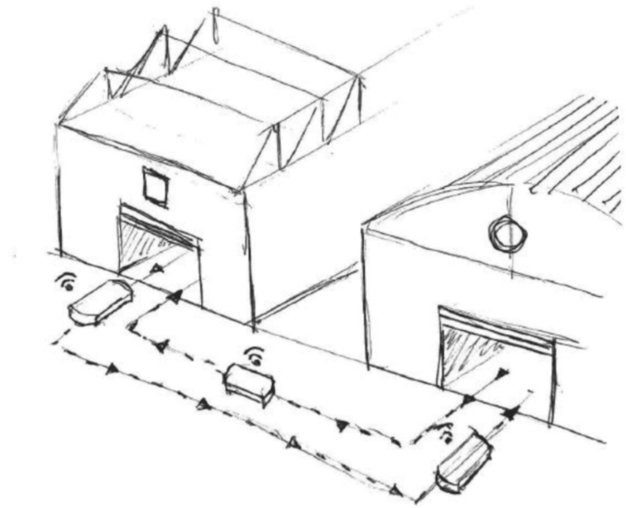
CharismaTec

CharismaTec is developing its own AGV. It has broader application case than Magna's prototype 3.0. It has a steel frame on the inside that can carry the addons. (4 connection points). The outside frame can be adapted to fit the clients need.
The AGV is outfitted with 4 small LED screens, these are used to show the front and back side but could in the future also be used to show more detailed information such as error-codes or indication of direction and task. They also flash red if the AGV encounters an obstruction it cannot circumvent. cost of the AGV is estimated at 100.000 euro including installation.
This AGV is equipped with a high precision LIDAR that enables mapping and localization with approximately 1cm accuracy. It can carry approximately 500 kg load. The design is modular, which enables customization according to application needs.



Parts are delivered externally (party unknown).

Dieter is sceptical about an application where an AGV goes outside and inside again and switches between coordination methods because it will bring dirt, water etc. inside.



Free coordination of an AGV currently isn't really needed. Because the factories work with 2-way streets you often do not want it to deviate from its current route because it might go into incoming traffic. In a vision of factory 4.0 this might chance because the layout of an assembly line might be flexible by having all machinery movable.

These requirements start to differ depending on the length of the cycle. If the cycle is very long (> 20 minutes for example) it does not matter if the AGV is waiting for an obstruction to be removed. As a rule, if a box is in the way in the factory-street it will always be removed within a minute. In smaller AGV cycles (<2 minutes) obstruction of the AGV might lead to delay in the entire production process, here it is useful if the AGV tries to go around an obstruction and otherwise trigger an alarm to prevent a delay in manufacturing.

If you are working with humans, accuracy isn't necessarily the biggest priority. Example If the AGV needs to deliver a box of supplies to a human it is better to define an area in which it can be deposited than an exact point. If the exact point cannot be reached a delay will occur although the human in need of the supplies wouldn't care if the box was deposited half a meter away from the point.

Appendix C

Full research questionnaire

Autonomous Ground Vehicle Questionnaire (v3A)

Thank you for contributing to our research.

During this questionnaire you will be shown videos of an **autonomous robot** and asked to imagine yourself in the situation depicted in the movies. After each video you will be asked a series of questions concerning your imagined response and experience.

This questionnaire is expected to take **30 minutes**.

Kind regards,
Martijn Verbeij
* Required

Consent form

In order to contribute you must agree the consent form below:

Consent for participation in the evaluation experiment of 'User Test'
1. I volunteer to participate in a product evaluation experiment conducted by University of Technology Delft, Faculty of Industrial Design Engineering.
2. My participation in this product evaluation experiment is voluntary. I understand that I will not be paid for my participation. I may withdraw and discontinue participation at any time without penalty.
3. Participation involves answering personal background questions, viewing several videos and answering questions regarding these videos afterward. This process will take around 30 minutes.
4. I understand that the results and gathered (anonymous) data from the experiment will be saved and stored for scientific processing.
5. I understand that the experiment doesn't want to measure my performance, but the performance of the product or design. No specific participant related performance measurement is transferred to any external source.
6. I have read and understand the explanation provided to me. I have had all my questions answered to my satisfaction, and I voluntarily agree to participate in this study.

For further information or questions, please contact:
Martijn Verbeij (m.m.verbeij@student.tudelft.nl)

1. *

Check all that apply.

☐ By checking this box I consent with the above.

Preliminary questionnaire

Thank you for contributing to our research.
We don't rate your personal performance, but the performance of our system.

This survey will be processed anonymously.
Please fill out this preliminary questionnaire, it helps us to classify the experiment data.

2. Age *

Mark only one oval.

- 25 years or younger
- 26-30 years
- 31-35 years
- 36-40 years
- 41-45 years
- 46-50 years
- 51 years or older

3. Gender *

Mark only one oval.

- Male
- Female
- Other

4. Do you work or study at the Delft University of Technology? *

Mark only one oval.

- Yes, student
- Yes, researcher
- Yes, worker
- Yes, other
- No

5. In which country are you living? *

6. In which country were you born? *

7. Highest achieved level of education *

Mark only one oval.

- ⬭ High school (middelbare school)
- ⬭ MBO (manual / practical training and education)
- ⬭ HBO (higher professional education)
- ⬭ University (bachelors)
- ⬭ University (Masters)
- ⬭ PhD

8. How comfortable are you with the use of a **smart phone**? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very

9. How comfortable are you with the use of a **desktop computer**? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very

10. How experienced would you rate yourself at playing **video games**? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Expert

11. How familiar are you with **production environments** (manufacturing factories / plants)? *

Mark only one oval.

	1	2	3	4	5	6	7	
None	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Expert

12. How much experience do you have with **Automated Ground Vehicles (AGVs)**? (If you do not know what that is choose: '1') *

Mark only one oval.

	1	2	3	4	5	6	7	
None	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Expert

13. How much experience do you have with the use of **Augmented Reality**? (If you do not know what that is choose: '1') *

Mark only one oval.

	1	2	3	4	5	6	7	
None	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Expert

14. If you have experience with using any of the following check the corresponding checkbox

Check all that apply.

- ☐ Augmented Reality goggles (such as Google Glass, Hololens, Magic Leap etc.)
- ☐ Projected Augmented Reality
- ☐ VR Goggles (such as Oculus Rift, HTC vive, Samsung gear VR etc.)

Instructions

You will now be shown 4 different scenario's through videos. You are asked to imagine yourself in the situation that is filmed. The footage is shot from your point of view. Listening to the audio is encouraged but not necessary.

For every scenario you will go through the follow steps:
1. Read the **task**. this is what you intend to do in the movie. Imagine yourself wanting to fulfill this task within the context presented in the movie.
2. Watch the **video**. Please pay attention, the videos are very short and you may only view each video once.
3. Fill in the **questionaires** after each video to the best of your ability.

15. *

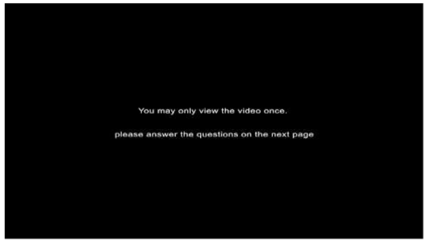
Check all that apply.

- [ ] I have read and understood the instructions above

Scenario 1

watch the video carefully, you may only view it once.

In this movie you want to walk straight ahead at the crossing. Your **task** is to make a decision in the moment the video stops: You need to plan your own path and predict the actions of the robot.



http://youtube.com/watch?v=Wlp3JHmdNJ4

1 - Response Questionaire

16. Overall, how difficult or easy was **the task** (planning your own actions and predict the actions of the robot) to complete? *

Mark only one oval.

	1	2	3	4	5	6	7	
Very Difficult	○	○	○	○	○	○	○	Very Easy

17. Describe what you think the robot will do at the end of the movie (please describe from the **robots perspective**) *

18. Describe the action you will take at the end of the movie. (please describe this from **your perspective**) *

19. How would you feel if you envision yourself in the situation shown in the movie? *

20. How certain were you of the robots next move? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very

21. How safe did you feel in the situation? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very

1 - SART

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability

22. 1. How changeable is the situation? Is the situation highly unstable and likely to change suddenly (high), or is it very stable and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

23. 2. How complicated is the situation? Is it complex with many interrelated components (high) or is it simple and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

24. 3. How many variables are changing in the situation? Are there a large number of factors varying (high) or are there very few variables changing (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

25. 4. How alert are you in the situation? Are you alert and ready for activity (high) or do you have a low degree of alertness (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

26. 5. How much are you concentrating on the situation? Are you bringing all your thoughts to bear (high) or is your attention elsewhere (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

27. 6. How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (high) or focused on only one (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

28. 7. How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (high) or nothing to spare at all (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

29. 8. How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	○	○	○	○	○	○	○	High

30. 9. How familiar are you with the situation? Do you have a great deal of relevant experience (high) or is it a new situation (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low								High

1 - TLX

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability.

IMPORTANT: these questions rate on a scale of 1 to 21. you may need to scroll sideways to see all (21) options.

31. 1. How mentally demanding was the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
–										

32. 2. How hurried or rushed was the pace of the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
–										

33. 3. How succesful were you in accomplishing what you were asked to do? *

Mark only one oval per row.

	1 - Perfect	2	3	4	5	6	7	8	9	10
–										

34. 4. How hard did you have to work to accomplish your level of performance? *

Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
–										

35. 5. How insecure, discouraged, irritated, stressed and annoyed were you? *

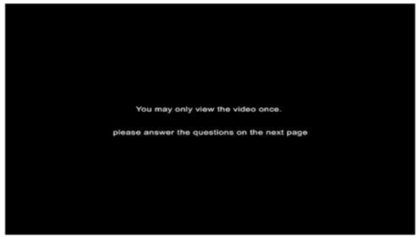
Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
–										

Scenario 2

watch the video carefully, you may only view it once.

In this movie you are walking diagonally behind the robot. You want to walk straight ahead at the crossing. Your **task** is to make a decision in the moment the video stops: you need to plan your own path and predict the actions of the robot.



http://youtube.com/watch?v=tsFw5GqYRrs

2 - Response Questionnaire

36. Overall, how difficult or easy was **the task** (planning your own path and predict the actions of the robot) to complete? *

Mark only one oval.

	1	2	3	4	5	6	7	
Very Easy	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very Difficult

37. Describe what you think the robot will do at the end of the movie. (please describe from the **robots perspective**) *

38. Describe the action you will take at the end of the movie. (please describe this from **your perspective**) *

39. How would you feel if you envision yourself in the situation shown in the movie? *

40. How certain were you of the robots next move? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very

41. How safe did you feel in the situation? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very

2 - SART

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability

42. 1. How changeable is the situation? Is the situation highly unstable and likely to change suddenly (high), or is it very stable and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

43. 2. How complicated is the situation? Is it complex with many interrelated components (high) or is it simple and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

44. 3. How many variables are changing in the situation? Are there a large number of factors varying (high) or are there very few variables changing (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

45. 4. How alert are you in the situation? Are you alert and ready for activity (high) or do you have a low degree of alertness (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

46. 5. How much are you concentrating on the situation? Are you bringing all your thoughts to bear (high) or is your attention elsewhere (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

47. 6. How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (high) or focused on only one (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

48. 7. How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (high) or nothing to spare at all (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

49. 8. How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

50. 9. How familiar are you with the situation? Do you have a great deal of relevant experience (high) or is it a new situation (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	High

2 - TLX

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability.

IMPORTANT: these questions rate on a scale of 1 to 21. you may need to scroll sideways to see all (21) options.

51. 1. How mentally demanding was the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
-	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

52. 2. How hurried or rushed was the pace of the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
-	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

53. 3. How succesful were you in accomplishing what you were asked to do? *

Mark only one oval per row.

	1 - Perfect	2	3	4	5	6	7	8	9	10
-	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

54. 4. How hard did you have to work to accomplish your level of performance? *

Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
-	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

55. 5. How insecure, discouraged, irritated, stressed and annoyed were you? *

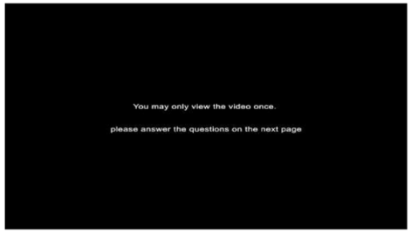
Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
-	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Scenario 3

Watch the video carefully, you may only view it once

You are in a factory hallway stacking boxes. Your **task** is to make a decision in the moment the video stops: You need to plan your own actions and predict the actions of the robot.



http://youtube.com/watch?v=8spmhCvgRTo

3 - Response Questionnaire

56. Overall, how difficult or easy was **the task** (planning your own actions and predict the actions of the robot) to complete? *

Mark only one oval.

	1	2	3	4	5	6	7	
Very Easy	◯	◯	◯	◯	◯	◯	◯	Very Difficult

57. Describe what you think the robot will do at the end of the movie. (please describe from the **robots perspective**) *

58. Describe the action you will take at the end of the movie. (please describe this from **your perspective**) *

59. How would you feel if you envision yourself in the situation shown in the movie? *

60. How certain were you of the robots next move? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very

61. How safe did you feel in the situation? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very

3 - SART

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability

62. 1. How changeable is the situation? Is the situation highly unstable and likely to change suddenly (high), or is it very stable and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

63. 2. How complicated is the situation? Is it complex with many interrelated components (high) or is it simple and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

64. 3. How many variables are changing in the situation? Are there a large number of factors varying (high) or are there very few variables changing (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

65. 4. How alert are you in the situation? Are you alert and ready for activity (high) or do you have a low degree of alertness (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

66. 5. How much are you concentrating on the situation? Are you bringing all your thoughts to bear (high) or is your attention elsewhere (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

67. 6. How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (high) or focused on only one (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

68. 7. How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (high) or nothing to spare at all (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

69. 8. How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low								High

70. 9. How familiar are you with the situation? Do you have a great deal of relevant experience (high) or is it a new situation (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low								High

3 - TLX

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability.

IMPORTANT: these questions rate on a scale of 1 to 21. you may need to scroll sideways to see all (21) options.

71. 1. How mentally demanding was the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
_										

72. 2. How hurried or rushed was the pace of the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
_										

73. 3. How succesful were you in accomplishing what you were asked to do? *

Mark only one oval per row.

	1 - Perfect	2	3	4	5	6	7	8	9	10
_										

74. 4. How hard did you have to work to accomplish your level of performance? *

Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
_										

75. 5. How insecure, discouraged, irritated, stressed and annoyed were you? *

Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
_										

Scenario 4

Watch the video carefully, you may only view it once.

In this movie you want to walk straight ahead at the crossing. Your **task** is to make a decision in the moment the video stops: You need to plan your own path and predict the actions of the robot.

[redacted]

http://youtube.com/watch?v=U11e_85fYWA

4 - Response Questionaire

76. Overall, how difficult or easy was **the task** (planning your own path and predict the actions of the robot) to complete? *

Mark only one oval.

	1	2	3	4	5	6	7	
Very Easy	◯	◯	◯	◯	◯	◯	◯	Very Difficult

77. Describe what you think the robot will do at the end of the movie. (please describe from the **robots perspective)** *

78. Describe the action you will take at the end of the movie. (please describe this from **your perspective)** *

79. How would you feel if you envision yourself in the situation shown in the movie? *

80. How certain were you of the robots next move? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very

81. How safe did you feel in the situation? *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very

4 - SART

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability

82. 1. How changeable is the situation? Is the situation highly unstable and likely to change suddenly (high), or is it very stable and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

83. 2. How complicated is the situation? Is it complex with many interrelated components (high) or is it simple and straightforward (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

84. 3. How many variables are changing in the situation? Are there a large number of factors varying (high) or are there very few variables changing (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

85. 4. How alert are you in the situation? Are you alert and ready for activity (high) or do you have a low degree of alertness (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

86. 5. How much are you concentrating on the situation? Are you bringing all your thoughts to bear (high) or is your attention elsewhere (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

87. 6. How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (high) or focused on only one (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

88. 7. How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (high) or nothing to spare at all (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

89. 8. How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

90. 9. How familiar are you with the situation? Do you have a great deal of relevant experience (high) or is it a new situation (low)? *

Mark only one oval.

	1	2	3	4	5	6	7	
Low	◯	◯	◯	◯	◯	◯	◯	High

4 - TLX

With the help of this standardized questionnaire, we want to understand how you experience the situation. As this is a standardized questionnaire, it is not fully adapted to this situation. Please still try to answer it with your the best of your ability.

IMPORTANT: these questions rate on a scale of 1 to 21. you may need to scroll sideways to see all (21) options.

91. 1. How mentally demanding was the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
-	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

92. 2. How hurried or rushed was the pace of the task? *

Mark only one oval per row.

	1 - Very Low	2	3	4	5	6	7	8	9	10
-	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

93. 3. How succesful were you in accomplishing what you were asked to do? *

Mark only one oval per row.

	1 - Perfect	2	3	4	5	6	7	8	9	10
–	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

94. 4. How hard did you have to work to accomplish your level of performance? *

Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
–	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

95. 5. How insecure, discouraged, irritated, stressed and annoyed were you? *

Mark only one oval per row.

	1 - Very low	2	3	4	5	6	7	8	9	10
–	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

5 Comparison Questionnaire

You have reached the last questionnaire!

During this research you have seen the vehicle project indicators on the floor. For this last questionaire I would like to ask you to compare the two videos shown side by side here:

You may view this video **multiple times** if it helps you answer the questions.

http://youtube.com/watch?v=E24lyNpX7lc

Please state to which degree you agree with the statements below.

96. The projected arrows help me to unterstand the situation. *

Mark only one oval.

	1	2	3	4	5	6	7	
Disagree	◯	◯	◯	◯	◯	◯	◯	Agree

97. I don't need the arrows to understand the situation. *

Mark only one oval.

	1	2	3	4	5	6	7	
Disagree	◯	◯	◯	◯	◯	◯	◯	Agree

98. The projected arrows give me confidence in the situation. *

Mark only one oval.

	1	2	3	4	5	6	7	
Disagree	◯	◯	◯	◯	◯	◯	◯	Agree

99. The projected arrows are distracting. *

Mark only one oval.

	1	2	3	4	5	6	7	
Disagree	◯	◯	◯	◯	◯	◯	◯	Agree

Appendix D

Midterm Evaluation Form

The Midterm Evaluation Form

>> Complete the form to prepare for the midterm evaluation, and send it to your supervisors, at least 3 days prior to your midterm evaluation session. <<

Name student	Martijn Verbeij
Student number	4150015
Name chair	Doris Aschenbrenner
Name mentor	Zoltán Rusák

Interim/In-between results

Short description of realised interim results:

The goal of the project is to identify (Spatial) AR solutions, that are suited to facilitate the interaction with an AGV (autonomous guided vehicle) swarm in a smart factory setting. The AR interface solution should improve the situation awareness of the user. Important outcomes of the analysis phase are:

- *deciding upon what operational role the user has within the factory ← 'Application Context'*
- *what the (future) factory is like (including the level of 'industry 4.0' technological integration) ← 'Industry State'*
- *What type of Augmented reality framework is to be used ← 'Technological Framework'*

The project has seen delay of approximately 1 month due to uncertainty surrounding the project; difficulties with the literature research and personal reasons.

These milestones were delivered:

- *Contextual Inquiry (visiting the Magna factory in Graz)*
- *Identification of industry states, application contexts and technological frameworks*
- *Stakeholder Map*
- *Made first steps toward a proof of concept using holographic glass as an Augmented Reality Device.*
- *Morphological chart with solution spaces. This includes initial concept directions.*
- *Morphological chart with existing AR solutions / state of the art overview (unfinished)*
- *Literature research (unfinished) including*
  - *Automated Ground Vehicles, their behaviour, functions and application in the industry (including the topics supervisory control and autonomy)*
  - *Augmented Reality and Spatial Augmented Reality, Including the different technological approaches, academic research and it's current integration level in the industry*
  - *Situation Awareness, it's relevance to the industry and the way it is measured*
  - *Fundamentals of human to machine communication (with focus on spatial intent and visual communication)*

Reaction on description interim results:

@Zoltan:

The supervisory team was very pleased with the results from the contextual inquiry. The student has a good insight into the project. In general, he follows a very structured approach, but he currently struggles with the theoretical side of the project and the literature analysis also due to family reasons. Coping with the complexity and uncertainty around the project creates a challenge that needs to be sorted out soon. Reporting the results could benefit from weekly updates.

Reflection[1]

<take the course's learning objectives as starting point when reflecting on the topics below [2]>

Reflection on quality	*The factory visit in Graz was insightful and gave an impression of the application context. However, we were unable to meet and speak to employees that work with the AGVs on a daily basis. In order to design for the future context of the factory I will need to build on justified assumptions and vision of the Smart factory shared by Magna.* *I have a proper basic understanding of all the key factors influencing the project assignment: AGVs, AR, (S)AR and the Industry 4.0 paradigm.* *I have put the complex matter of deciding on a specific direction for the project into a workable framework and structure, I have however struggled in communicating the framework properly.*	*<to be filled in by supervisory team>* The student shows strong design capabilities. His attempts to re-framing the project context is clearly one of the very strong points of his work, together with the high visual quality. Currently, he struggles to digest the academic literature which is involved in the project context. Quality of the work is on a good

[1] A short indication of your thoughts and considerations with regard to the graduation project up till now.
[2] Learning objectives are to be found in the Course Manual, and in the IDE Study guide.

		level, meaningful insights are created. The full potential of the student is not always reflected in the written material.
Reflection on planning	*The original planning was good but because of external and personal factors was not reached.* *The separate topics required more research than expected. It is challenging to decide on the depth of research required for each individual topic.* *Steady progress has been made but the planning will need to be revised for the remainder of the project.*	*<to be filled in by supervisory team>* The student did not take into account the amount of time needed for a structured literature analysis, especially regarding the external factors. We expect, that the planning within the practical part is better. The way of working needs adjustments, the focus should be on the strength of the student (visual communication and design).
Reflection on personal ambitions (if formulated in project brief)	*I learned a lot about the relevant topics: Situation awareness, AGVs, AR, SAR. I have obtained a proper understanding of the way these topics are interconnected and what the state of the art is regarding these topics.* *I have not been able to start programming a Unity simulation.* *I am not satisfied with the amount of progress made during the first part of the project.* *By reserving more time for the graduation and working in a more disciplined fashion I hope to pick up the pace*	*<to be filled in by supervisory team>* The student has high ambitions and suffers, if he is not able to meet them, especially with regards to timing and also in the context of academic literature research. We fear that this overreaction blocks him from further productivity and advise to search for coaching regarding this matter.
Reflection on supervision and/or project context	*The project is moving in a direction where I feel I can create something valuable for the client and the industry. Lessons from the project can hopefully be more broadly applied: the solution spaces morphological chart provides multiple directions for matching AR solutions to specific factory responsibilities.* *Information coming from the company has been limited.* *Support from the supervisory team has been good. Sometimes questions through email/WhatsApp need additional reminders to get answered.*	*<to be filled in by supervisory team>* The supervisor team encourages the student ask for help a bit more, in case he feels stuck. We want to motivate the student to continue bringing in his view on the project.
Decision supervisory team concerning progress graduation project at this moment		
☐ **Continue**	X **Adjust**	☐ **Discontinue**

Substantiate the decision:
<to be filled in by supervisory team>
The supervisory team sees a substantial delay of the project with regards to the original planning. Nevertheless, we think that the work of the student is valuable and can yield results, that are beneficial.

Adjustment of Project Brief: new arrangements

Proposal new arrangements based on this midterm evaluation:
<to be filled in by the student, based on the above reflection. If applicable: add appendices>

The contextual inquiry did not include interviews with workers. However, a good idea of the application context has been obtained. The ideation and conceptualisation phase will be based on the information we do have from the factory visit and a vision of the future smart factory.
We do also not expect to have access to Magna factory workers for the evaluation of the final concept. The evaluation will happen based on testing with students. Contextual info will be supplemented using expert interviews

The project has been delayed. The planning will need to be revised. A new planning is added in the appendix.
Final arrangements *<describe here the agreed on new arrangements, to be filled in during/after meeting>* The supervision team wants to continue the project with then new (attached planning). Weekly email updates will report on the progress toward a finished analysis report The student will start practical work such as unity development simultaneous to finishing the analysis report.

Signatures (name, date and signature of student, chair and mentor)		
Name student: Martijn Verbeij **Date:** 27-01-2020	**Name chair: Doris Aschenbrenner** **Date:** 27-01-2020	**Name mentor: Zoltán Rusák** **Date:** 27-1-2020

At the end of the Midterm Evaluation meeting: Please hand-in the filled-in form **on Brightspace,** upload to **'IDE Master Graduation Project'** organisation.

Research Data

ID name	C	Condition	Date:	C	TASK1	T1SEQ	T1Q2RAW	T1Q2CAT	T1Q2VERD	T1Q3RAW. Des	T1Q3CAT	T1Q3VERD	T1Q4RAW. How wo	T1Q4CAT	T1Q4VERD
A01	A	Projected Arrows	5/16/2020 19:38:59			5	He will mov	left	correct	Step to the left, I	step aside, I	desirable	A bit uncomfortable b	uncomfortable	negative
A02	A	Projected Arrows	5/18/2020 16:20:58			7	It will move	left	correct	Wait until the rob	wait	desirable	fine, because the rob	good, distrustful	neutral
A03	A	Projected Arrows	5/18/2020 17:58:04			6	The robot w	left	correct	stop at the inters	wait	desirable	A little ill at ease, for	uncomfortable, safe,	negative
A04	A	Projected Arrows	5/18/2020 18:01:27			7	I think the r	left	correct	There is not muc	wait	desirable	This depends: I feel lil	bad, doubtful	negative
A05	A	Projected Arrows	5/18/2020 19:18:01			5	Turn left	left	correct	Pause and wait t	wait	desirable	Hurried and confused	hurried, doubtful	negative
A06	A	Projected Arrows	5/18/2020 19:51:27			7	turn to the	left	correct	pause to give it ti	wait	desirable	quite confident	confident	positive
A07	A	Projected Arrows	5/18/2020 20:02:06			7	turn left	left	correct	turn left	turn, left	desirable	pretty confident	confident	positive
A08	A	Projected Arrows	5/18/2020 20:27:52			5	The robot is	left	correct	Wait until the rob	wait	desirable	The overlapping arrow	comfortable, confider	neutral
A09	A	Projected Arrows	5/18/2020 22:34:54			6	Turn left	left	correct	Turn right	turn, right	not desirable	Fielt secure what to d	confident	positive
A10	A	Projected Arrows	5/19/2020 10:34:19			6	The robot w	left	correct	I will stand still ur	wait	desirable	I was wondering what	other	neutral
A11	A	Projected Arrows	5/19/2020 12:15:11			7	I think the r	left	correct	Wait for the robot	wait	desirable	Its my first encounter	cautious	neutral
A12	A	Projected Arrows	5/19/2020 14:10:26			6	It will move	left	correct	I will step in betw	wait	desirable	I imagine I'd feel som	afraid	negative
A13	A	Projected Arrows	5/19/2020 15:02:24			6	turn left	left	correct	wait until the rob	wait	desirable	relaxed but allert	comfortable, cautiou	positive
A14	A	Projected Arrows	5/19/2020 15:13:29			6	The robot w	forward	incorrect	I would turn to th	turn, left	desirable	I would lift my arm up	other	neutral
A15	A	Projected Arrows	5/19/2020 16:47:59			5	Make a left	left	correct	Stop walking. Co	wait	desirable	Neutral	neutral	neutral
A16	A	Projected Arrows	5/22/2020 11:07:08			6	it will follow	left	correct	I will wait for the r	wait	desirable	a bit annoyed that i h	annoyed	negative
A17	A	Projected Arrows	5/22/2020 12:19:23			6	I think the r	left	correct	The robot will turr	wait	desirable	I would be a bit hesita	hesitant, trustful	neutral
A18	A	Projected Arrows	5/22/2020 12:47:07			7	Stoppen er	stop	incorrect	Stoppen en wach	wait	desirable	Neutraal	neutral	neutral
A19	A	Projected Arrows	5/22/2020 18:02:20			6	Go to the l	left	correct	Go to the left	wait	desirable	Sure and save	safe, confident	positive
A20	A	Projected Arrows	5/22/2020 18:40:01			6	Turn left	left	correct	Wait a couple of	wait	desirable	I would be surprised t	surprised	neutral
A21	A	Projected Arrows	5/25/2020 18:12:00			5	The robot w	left	correct	At first I thought,	wait	desirable	Uncertain at first...do	doubtful	negative
A22	A	Projected Arrows	5/26/2020 10:20:02			7	The robot w	left	correct	I will go a few ste	step aside, I	desirable	I would feel safe, bec	safe, confident	positive
A23	A	Projected Arrows	5/26/2020 11:55:02			5	Turn left	left	correct	turn left	turn left	desirable	quite ok, though I did	neutral	neutral
A24	A	Projected Arrows	5/27/2020 10:14:29			3	Well, the a	left	correct	I will stop for a m	wait	desirable	Not confident as there	doubtful	negative
A25	A	Projected Arrows	5/28/2020 8:45:54			4	turn left	left	correct	wait until the rob	wait	desirable	ok	neutral	neutral
A26	A	Projected Arrows	5/29/2020 7:36:23			7	turn left	left	correct	stop and wait	wait	desirable	indifferent	indifferent	neutral
B01	B	No Projection	5/16/2020 23:27:30			6	straight	forward	incorrect	go left or right	turn	don't know	afraid	afraid	negative
B02	B	No Projection	5/17/2020 16:02:02			5	Robot will s	stop	incorrect	Try to sidestep	step aside	don't know	Ok	neutral	neutral
B03	B	No Projection	5/18/2020 8:11:51			5	Stop and le	stop	incorrect	Wait and then pa	wait	desirable	Curious	curious	neutral
B04	B	No Projection	5/18/2020 9:54:59			2	Stop, beca	stop	incorrect	Stop and wait for	wait	desirable	Not confident, that th	doubtful	negative
B05	B	No Projection	5/18/2020 10:34:35			2	As a robot,	other	incorrect	I first stop and w	wait	desirable	Uncomfortable becau	uncomfortable	negative
B06	B	No Projection	5/18/2020 12:27:23			6	Sensed hu	stop	incorrect	I will go to the lef	neutral	don't know	a bit uncomfortable, b	uncomfortable	negative
B07	B	No Projection	5/18/2020 18:09:18			5	I expect th	stop	incorrect	I will either turn le	step aside	don't know	If the robot is new to i	doubtful	negative
B08	B	No Projection	5/18/2020 18:30:16			7	Rechtdoor	forward	incorrect	Recht of links ga	step aside	don't know	Ik zou vrezen dat het	afraid	negative
B09	B	No Projection	5/18/2020 21:02:58			5	He stops	stop	incorrect	I stop	wait	desirable	Worry	afraid	negative
B10	B	No Projection	5/19/2020 9:58:33			6	keep movin	forward	incorrect	move aside	step aside	don't know	Invisible	other	neutral
B11	B	No Projection	5/19/2020 12:07:27			2	I hope it wil	other	incorrect	Probably stop m	wait	neutral	A bit scared that I'll b	doubtful	negative
B12	B	No Projection	5/19/2020 16:33:41			5	It will conti	forward	incorrect	I would wait to se	wait	desirable	Uncertain	doubtful	negative
B13	B	No Projection	5/20/2020 17:09:29			3	I think it wil	stop	incorrect	I would back awa	step aside	not desirable	Anxious the first time	afraid	negative
B14	B	No Projection	5/21/2020 23:03:06			2	That depen	left or right	don't know	I would turn right	turn right	not desirable	Intrigued. Here is a ro	curious	neutral
B15	B	No Projection	5/21/2020 23:11:18			7	The robot w	stop	incorrect	I want to go strai	step aside	desirable	a bit stressed. The ro	stressed	negative
B16	B	No Projection	5/22/2020 11:29:21			5	He will stop	stop	incorrect	I will step aside ju	step aside	desirable	I would feel cautious	cautious	negative
B17	B	No Projection	5/22/2020 14:00:20			5	Automatica	stop	incorrect	Choose between	step aside	don't know	A bit intimidated...	afraid	negative
B18	B	No Projection	5/23/2020 10:58:12			4	Pause or s	stop	incorrect	Pause, observe,	wait	neutral	Comfortable	comfortable	positive
B19	B	No Projection	5/24/2020 12:18:49			5	Stop movin	stop	incorrect	quickly step side	step aside	neutral	Mildly irritated that th	annoyed	negative
B20	B	No Projection	5/24/2020 16:42:47			6	Stop movin	stop	incorrect	Move to the right.	step aside, r	not desirable	Like I should have tak	other	neutral
B21	B	No Projection	5/25/2020 16:12:29			3	Stop	stop	incorrect	Take a right, and	step aside, r	not desirable	Uncomfortable. I have	uncomfortable	negative
AVERAGE A						5,9									
AVERAGE B						4,6									
AVERAGE						5,3									

		How char	How com	How man	How alert	How muc	How muc	How muc	How muc	How fami	Average										
T1Q5	T1Q6	T1SAR	T1SAR	T1SAR	T1SAR	T1SAR	T1SAR	T1SAR	T1SAR	T1SAR	T1SART	Column2	T1TLX1	T1TLX1	T1TLX2	T1TLX2	T1TLX3	T1TLX3	T1NASA	T1NASA	T1NASA
5	6	6	3	2	7	5	2	5	5	3	5,1		15	70	17	80	3	10	5	20	14
7	6	2	2	2	4	2	2	6	5	4	6,0		2	5	2	5	10	45	2	5	1
7	4	2	3	3	7	5	6	4	6	1	6,3		16	75	14	65	3	10	11	50	10
7	6	6	5	3	5	6	1	6	6	2	3,8		9	40	6	25	8	35	5	20	10
5	4	3	3	4	6	5	2	4	6	2	4,9		15	70	18	85	3	10	15	70	15
7	6	2	1	1	4	5	4	6	7	1	7,4		2	5	1	0	1	0	3	10	2
7	7	4	2	3	4	5	3	5	4	1	3,8		4	15	5	20	8	35	5	20	1
5	7	3	3	3	2	4	5	6	6	5	6,8		2	5	3	10	3	10	3	10	4
6	6	5	1	2	5	5	4	4	2	1	3,3		3	10	12	55	4	15	5	20	5
7	7	6	2	2	7	7	3	6	6	1	5,9		2	5	1	0	1	0	1	0	2
6	7	2	2	1	5	2	2	7	7	6	8,8		4	15	3	10	2	5	2	5	1
7	5	2	2	3	6	6	2	4	3	2	4,7		9	40	11	50	4	15	6	25	6
5	6	1	2	2	4	3	2	6	2	5	5,6		8	35	7	30	3	10	4	15	5
2	4	6	3	2	2	4	2	6	2	2	1,8		3	10	3	10	3	10	3	10	3
5	4	4	4	4	3	3	2	4	5	6	4,5		5	20	5	20	15	70	5	20	10
7	6	2	2	3	4	2	3	6	4	2	4,4		7	30	14	65	1	0	5	20	9
6	6	4	3	2	6	5	1	6	5	3	5,5		12	55	7	30	2	5	3	10	14
7	7	6	3	3	5	5	2	5	2	6	4,3		4	15	14	65	17	80	3	10	1
6	6	5	2	2	6	5	2	5	2	2	3,5		6	25	8	35	4	15	6	25	7
6	7	2	2	2	3	5	2	4	2	2	3,5		4	15	3	10	7	30	1	0	5
6	5	4	3	2	7	6	2	2	5	1	4,3		13	60	17	80	1	0	11	50	14
6	6	2	2	3	6	6	5	5	6	6	9,2		7	30	5	20	9	40	5	20	6
5	3	2	2	2	6	3	3	6	4	2	5,5		7	30	7	30	12	55	13	60	5
3	2	6	2	2	7	7	7	5	3	1	5,2		4	15	9	40	6	25	4	15	10
4	4	3	3	4	3	4	2	5	4	2	3,2		3	10	2	5	3	10	3	10	1
5	6	2	1	1	2	2	2	5	4	3	4,9		3	10	1	0	3	10	1	0	1
3	2	3	2	2	4	4	1	4	6	5	6,4		2	5	4	15	4	15	6	25	10
3	4	6	3	4	3	6	3	4	4	2	2,7		2	5	2	5	4	15	3	10	3
3	5	4	5	3	5	6	3	5	3	1	2,8		9	40	10	45	16	75	9	40	9
3	3	2	2	2	4	5	2	4	2	5	5,3		4	15	2	5	4	15	2	5	5
2	4	2	2	2	5	4	5	4	2	1	4,0		9	40	8	35	10	45	15	70	13
3	5	5	2	1	5	5	6	7	6	5	8,6		7	30	5	20	6	25	7	30	5
3	5	3	3	5	7	6	4	5	3	5	5,8		15	70	13	60	1	0	9	40	13
4	4	5	2	2	5	6	5	3	3	1	3,8		4	15	11	50	10	45	6	25	7
4	3	5	2	3	7	7	6	5	3	6	7,4		3	10	3	10	2	5	4	15	3
6	7	1	3	2	2	6	6	5	2	1	4,3		4	15	15	70	4	15	3	10	7
2	1	7	4	2	6	5	3	4	2	1	1,7		10	45	16	75	16	75	7	30	15
2	6	3	3	2	6	6	2	4	2	4	4,8		4	15	5	20	8	35	5	20	7
7	4	7	1	1	2	2	3	2	4	1	1,8		5	20	3	10	18	85	3	10	3
1	3	3	1	2	3	6	2	4	2	5	5,3		4	15	8	35	4	15	1	0	17
1	3	1	4	2	5	6	2	4	4	1	4,4		7	30	11	50	11	50	3	10	6
5	5	2	2	2	5	4	2	6	2	1	3,8		5	20	5	20	8	35	5	20	5
3	2	3	1	2	5	6	1	4	2	6	6,0		4	15	17	80	4	15	1	0	18
4	5	4		4	5	5	3	4	3	3	3,3		4	15	4	15	6	25	6	25	3
4	6	2	3	3	6	6	2	3	3	3	4,6		15	70	14	65	10	45	5	20	17
4	6	1	1	1	2	2	1	7	5	2	5,5		6	25	7	30	13	60	5	20	6
1	6	2	3	3	5	4	5	6	3	1	4,3		5	20	5	20	7	30	4	15	7
5,7	5,5	3,5	2,4	2,4	4,8	4,5	2,8	5,1	4,3	2,8	5,1			27,5		32,5		21,2		20,0	6,2
3,2	4,2	3,4	2,5	2,4	4,6	5,1	3,2	4,5	3,1	2,9	4,6			25,5		35,0		34,5		21,0	8,5
4,6	4,9	3,5	2,4	2,4	4,7	4,8	3,0	4,8	3,8	2,8	4,9			26,6		33,6		27,1		20,4	7,3

																How chan	How com	How man	How alert
T1NASA	T1TLX	Column	TASK2	T2SEQ	T2Q2RA	T2Q2CA	T2Q2VE	T2Q3RAW. Desc	T2Q3CA	T2Q3VERD	T2Q4RA	T2Q4CAT	T2Q4VERD	T2Q5	T2Q6	T2SAR	T2SAR	T2SAR	T2SAR
65	49			2	Move to th	right	correct	Move to the left be	wait	desirable	A bit anno	annoyed	negative	6	6	4	2	2	6
0	12			1	the robot v	right	correct	I can continue wa	forward	desirable	happy, I h	happy	positive	7	7	2	2	2	2
45	49			1	The robot	right	correct	I will wait for the r	wait	desirable	Comfortab	comfortable, confident	positive	7	7	1	2	2	2
45	33			2	I think the	right	correct	I will again wait ur	wait	desirable	In this situ	bad	negative	7	6	3	4	3	5
70	61			2	Turn right	right	correct	Wait till he has cr	wait	neutral	Fine	good	positive	6	6	3	4	3	6
5	4			1	turn right	right	correct	pause to give the	wait	desirable	relaxed	comfortable	positive	7	7	1	2	1	3
0	18			3	turn right	right	correct	stop for a while (n	wait	desirable	pretty norr	neutral, safe	positive	6	5	3	4	3	4
15	10			2	It will turn	right	correct	I'll go straight (bu	slow down	desirable	Pretty cor	confident	positive	5	7	2	2	2	2
20	24			1	Turn right	right	correct	Walk straight ove	forward	desirable	Determina	determined	positive	6	6	2	2	2	2
5	2			1	It will turn	right	correct	I will walk slowly u	slow down	desirable	A bit anno	annoyed	negative	7	7	1	2	1	4
0	7			1	turn right a	right	correct	keep simular dista	wait	desirable	comfortab	comfortable	positive	6	7	1	1	1	2
25	31			1	It will drive	right	correct	I will go to my left	wait	desirable	I would pre	impatient	negative	7	5	2	2	3	4
20	22			2	turn right	right	correct	wait untill the robo	wait	desirable	relaxed	comfortable	positive	7	7	1	1	1	2
10	10			4	The robot	forward	incorrect	I will move diagon	other	neutral	I would slo	other	neutral	4	4	5	3	3	4
45	35			3	Make a rig	right	correct	Stop walking, cros	wait	desirable	A little bit	afraid	negative	5	3	4	4	4	5
40	31			4	It will mak	right	correct	I will keep on follo	wait	desirable	More com	comfortable	positive	7	7	6	2	3	5
65	33			2	The robot	right	correct	I will wait for the r	wait	desirable	Maybe a b	impatient, safe	neutral	7	7	2	3	2	4
0	34			1	Stop. Wai	stop	incorrect	Kgoed op de robo	other	neutral	Neutraal	neutral	neutral	6	5	3	4	3	6
30	26			3	go to the r	right	correct	go right behind th	forward	desirable	a little ins	insecure	negative	6	3	6	3	2	6
20	15			1	Turn right	right	correct	Continue slowly. T	slow down	desirable	Curious to	curious	neutral	5	5	2	2	2	5
65	51			2	the robot v	right	correct	I just keep behind	wait	desirable	In control,	confident	positive	7	7	1	2	1	4
25	27			2	The robot	right	correct	I will walk behind t	slow down	desirable	I will feel g	good	positive	6	6	2	2	2	4
20	39			4	turn right	right	correct	wait until the robo	wait	desirable	weird, not	uncomfortable	negative	5	5	2	2	2	6
45	28			6	No idea w	don't know	don't know	Probably nothing,	wait	don't know	waiting mo	other	neutral	1	2	4	2	2	6
0	7			5	I don't kno	don't know	don't know	waiting	wait	desirable	ok	neutral	neutral	1	5	5	6	4	5
0	4			1	turn right	right	correct	stop and wait	wait	desirable	held up	impatient	negative	7	7	1	1	1	1
45	21			2	continue s	forward	incorrect	continue walking s	slow down	desirable	relaxed; s	comfortable, impatient	neutral	5	4	2	2	2	5
10	9			2	Continue s	forward	incorrect	Walk parallel and	overtake	neutral	Ok	neutral	neutral	5	6	6	3	4	3
40	48			4	Move on (s	forward	incorrect	Wait if it takes my	overtake	don't know	Curious, n	curious	neutral	2	6	3	3	4	2
20	12			1	Go on in a	forward	incorrect	Wait until the robo	wait	desirable	Annoyed b	annoyed	negative	6	7	2	2	2	3
60	50			3	The robot	forward	incorrect	I want to overtake	overtake	neutral	Sure, sinc	certain	positive	3	6	2	3	3	3
20	25			4	Will go on	-	don't know	I don't know if the	overtake	don't know	I would be	annoyed	negative	2	6	3	2	2	2
60	46			2	It wil go st	forward	incorrect	I wil stay behind t	stay behin	desirable	Slightly ar	annoyed	negative	5	7	5	5	2	4
30	33			4	Rechtdoor	forward	incorrect	Rechtdoor gaan e	stay behin	desirable	Neutraal	neutral	neutral	5	6	2	2	4	2
10	10			3	Turn right	right	correct	Go straight ahead	forward	desirable	Safe	safe	positive	5	6	4	3	3	6
30	28			2	remain wit	forward	incorrect	go around it and s	overtake	neutral	impatient	impatient	negative	6	7	1	2	2	3
70	59			3	Continue s	forward	incorrect	I will keep on wall	-	neutral	Relaxed, f	comfortable, safe, afrai	positive	4	6	4	4	2	1
30	24			2	It will cont	forward	incorrect	Pass the robot on	overtake ri	not desirable	calculating	other	neutral	5	7	3	2	2	5
10	27			2	It will eithe	-	don't know	I will stop walking	wait	desirable	safe, fine,	safe, good	positive	6	7	6	2	2	2
80	29			2	It was mo	forward	incorrect	Maintain position	stay behin	desirable	Slightly ar	annoyed	negative	5	6	2	2	1	4
25	33			5	the robot v	stop	incorrect	I will wait behind	wait	desirable	a bit anno	annoyed	negative	1	5	1	3	3	4
20	23			3	He will go	forward	incorrect	I would walk strait	stay behin	desirable	Normal, m	neutral, alert	neutral	6	6	2	2	2	4
85	39			4	Stop to de	stop	incorrect	Wait to see what	wait	desirable	irritated	annoyed	negative	1	7	2	4	1	7
10	18			3	Go left	left	incorrect	Give it time to turn	wait	desirable	Savant	other	neutral	6	6	3	2	2	4
80	56			2	Continue s	forward	incorrect	at the crossing pa	forward	not desirable	A bit anno	annoyed	negative	3	5	5	2	2	3
25	32			2	Blieb blob	forward	incorrect	Get annoyed and	overtake, r	not desirable	Annoyed.	annoyed	negative	4	7	4	4	3	5
30	23			2	Keep goin	forward	incorrect	Overtake the robo	overtake, r	not desirable	Annoyed.	annoyed	negative	6	5	2	2	2	2
26,2	25,5			2,2										5,8	5,7	2,7	2,5	2,2	4,0
37,6	30,7			2,7										4,3	6,1	3,0	2,7	2,4	3,5
31,3	27,8			2,4										5,1	5,9	2,8	2,6	2,3	3,8

How muc	How muc	How muc	How muc	How fami	Average																	
T2SAR	T2SAR	T2SAR	T2SAR	T2SAR	T2SART	Column	T2TLX1	T2TLX1	T2TLX2	T2TLX2	T2TLX3	T2TLX3	T2NASA	T2NASA	T2NASA	T2NASA	T2TLX	Column	Column	TASK3	T3SEQ	T3Q2RA
5	3	6	6	4	7,3		7	30	4	15	6	25	6	25	15	70	33				6	Wait until
2	2	6	6	4	6,0		2	5	2	5	10	45	1	0	1	0	11				1	The robot
2	2	7	7	3	6,6		4	15	2	5	1	0	2	5	2	5	6				2	The robot
3	2	5	6	2	4,4		8	35	4	15	8	35	8	35	16	75	39				5	I think it w
5	2	4	5	2	4,4		16	75	18	85	4	15	15	70	17	80	65				6	Move to th
3	4	6	7	2	7,2		1	0	1	0	1	0	2	5	1	0	1				1	it will wait
4	4	3	3	1	2,4		5	20	5	20	4	15	5	20	1	0	15				2	wait until I
2	6	6	6	6	8,0		1	0	1	0	2	5	3	10	8	35	10				2	If I step as
3	3	5	5	1	4,3		3	10	3	10	3	10	2	5	2	5	8				2	Ride forew
6	2	7	3	6	7,9		1	0	1	0	1	0	1	0	3	10	2				1	The robot
1	1	7	7	6	8,3		2	5	1	0	1	0	1	0	1	0	1				3	It either w
6	2	3	3	2	3,9		12	55	4	15	17	80	10	45	10	45	48				5	It will wait
2	2	2	2	6	5,0		2	5	1	0	1	0	1	0	2	5	2				1	wait untill
4	3	3	4	3	3,3		3	10	3	10	2	5	2	5	2	5	7				5	The robot
5	1	2	3	5	3,3		10	45	5	20	15	70	10	45	15	70	50				4	Go straigh
2	3	6	6	3	4,8		11	50	8	35	1	0	9	40	5	20	29				1	It will wait
3	2	6	5	4	5,9		4	15	4	15	2	5	4	15	14	65	23				6	The robot
6	3	4	5	7	7,4		3	10	1	0	2	5	3	10	1	0	5				1	Wachten
4	3	5	4	2	3,8		9	40	7	30	5	20	11	50	9	40	36				6	go to the
4	2	3	2	2	3,5		3	10	3	10	6	25	6	25	2	5	15				6	Wait till I
3	5	5	6	1	6,4		7	30	4	15	1	0	4	15	6	25	17				4	I expect it
3	3	3	6	6	7,3		7	30	2	5	5	20	5	20	5	20	19				2	The robot
6	6	5	2	1	5,3		9	40	9	40	14	65	11	50	4	15	42				3	go straigh
5	2	6	2	2	4,1		3	10	2	5	6	25	6	25	9	40	21				2	go backwa
5	4	6	3	2	2,5		2	5	2	5	5	20	2	5	5	20	11				2	I think the
1	1	6	4	6	6,3		1	0	1	0	1	0	1	0	1	0	0				1	Do not mo
4	2	4	6	4	6,8		2	5	3	10	17	80	3	10	10	45	30				2	wait
2	3	2	3	2	0,7		2	5	2	5	5	20	3	10	1	0	8				2	Stay
3	2	3	1	1	0,2		9	40	10	45	11	50	4	15	5	20	34				6	Nothing. I
3	2	5	4	6	6,3		2	5	1	0	4	15	3	10	2	5	7				5	Wait
4	4	5	2	1	2,8		7	30	6	25	10	45	10	45	10	45	38				4	Since the
2	4	2	4	3	3,7		3	10	3	10	12	55	5	20	8	35	26				5	I stop and
5	3	6	4	6	5,5		5	20	14	65	3	10	4	15	10	45	31				6	The robot
2	4	4	3	1	2,3		3	10	2	5	18	85	3	10	2	5	23				1	Stil blijven
6	5	5	3	6	6,7		2	5	4	15	3	10	4	15	2	5	10				2	He will col
2	5	5	3	1	4,1		4	15	10	45	4	15	3	10	1	0	17				1	remain sti
3	2	4	1	1	0,2		5	20	5	20	14	65	3	10	1	0	23				5	I think it w
6	2	6	4	4	6,4		5	20	5	20	12	55	4	15	9	40	30				5	It wants to
3	3	6	4	2	3,2		3	10	3	10	19	90	4	15	2	5	26				2	It will wait
4	3	5	3	5	6,3		2	5	6	25	19	90	1	0	11	50	34				4	Wait for ol
2	5	4	2	6	5,4		4	15	5	20	11	50	4	15	14	65	33				2	I don't kno
3	2	6	2	1	3,3		5	20	4	15	7	30	7	30	4	15	22				5	stay still
4	1	4	2	6	5,7		5	20	15	70	5	20	10	45	16	75	46				1	Stop and
4	3	5	6	5	7,2		3	10	1	0	8	35	5	20	2	5	14				4	Wait for m
5	5	5	5	5	6,5		6	25	5	20	16	75	5	20	8	35	35				5	Wait till th
5	4	5	3	3	4,1		5	20	15	70	15	70	6	25	14	65	50				5	Two plaus
3	2	6	2	1	2,8		4	15	12	55	7	30	5	20	13	60	36				1	Stay still
3,7	2,8	4,9	4,5	3,4	5,4			21,2		13,8		18,8		20,2		25,2	19,8				3,1	
3,6	3,1	4,6	3,2	3,3	4,3			15,5		26,2		47,4		17,9		29,5	27,3				3,5	
3,6	3,0	4,8	3,9	3,4	4,9			18,6		19,4		31,6		19,1		27,1	23,2				3,3	

										How char	How com	How man	How alert	How muc	How muc	How muc	How muc
T3Q2CA	T3Q2VE	T3Q3RAW. Describe the action you	T3Q3CA	T3Q3VERD	T3Q4RA	T3Q4CAT	T3Q4VERD	T3Q5	T3Q6	T3SAR	T3SAR	T3SAR	T3SAR	T3SAR	T3SAR	T3SAR	T3SAR
wait and g	correct	Step back and wait until the robot ha	step away	desirable	Annoyed I	annoyed	negative	6	3	3	2	2	7	6	1	2	3
wait and g	correct	I can take a step aside, so that I am	step away	desirable	that I am a	afraid, annoyed	negative	7	7	4	4	4	5	5	5	5	5
wait and g	correct	I will step aside where possible to le	step away	desirable	irritated to	annoyed	negative	7	6	2	2	2	3	3	3	5	6
collide	incorrect	Because I am at work, I would not b	continue w	not desirable	I would fee	annoyed	negative	5	5	5	7	4	6	6	6	2	4
other	incorrect	Step away	step away	desirable	Ready doe	determined	positive	6	4	6	6	3	6	6	2	2	6
wait	correct	take a step back, so the robot can p	step away	desirable	a little ann	annoyed	negative	7	6	2	3	2	5	3	4	5	6
wait	correct	move backa nd wait for robot to pass	step away	desirable	mildly inco	annoyed	negative	7	5	1	1	2	3	3	2	2	4
wait and g	correct	I'll step aside, to let the robot operat	step away	desirable	Pretty con	confident	positive	5	4	3	3	4	4	3	3	5	5
go forwarc	incorrect	Step backward to allow the robot to	step away	desirable	A bit start	surprised	neutral	6	2	2	2	2	6	6	3	3	3
wait and g	correct	I will step aside or back and let the r	step away	desirable	A bit like \	surprised	neutral	7	7	2	1	1	3	3	3	5	3
wait and g	correct	This is dependent on my task specil	step away	desirable	little allert	alert, comfortable	positive	6	6	4	3	3	2	2	2	6	7
wait and g	correct	I will make room for the robot so it c	step away	desirable	A bit anno	annoyed, intimidating	negative	5	2	3	5	5	7	6	5	4	5
wait and g	correct	step to the side of the table and let t	step away	desirable	bored of s	other	neutral	7	6	3	1	2	1	1	1	4	5
other	incorrect	I would stabilze the two packages o	other	not desirable	Actually I	doubtful	negative	4	4	6	6	4	6	6	6	4	4
collide	incorrect	Move away from the table	step away	desirable	A bit anxi	afraid	negative	5	3	3	3	3	4	5	2	5	4
wait and g	correct	I would finish stacking my boxes, if t	step away	desirable	If this was	annoyed	negative	4	6	3	3	5	6	4	5	4	5
wait	correct	I will step out of the way to clear the	step away	desirable	good, I'd fe	annoyed	negative	7	7	2	2	1	5	2	4	6	6
wait	correct	Ik blijf staan	continue w	not desirable	Neutraal	neutral	neutral	5	5	3	3	2	2	3	3	5	6
right	incorrect	go backward	step away	desirable	not sure w	doubtful	negative	4	2	6	5	5	6	5	4	3	3
wait and g	correct	Step back to let the robot through, tl	step away	desirable	I would fee	annoyed	negative	6	4	5	4	4	6	6	6	3	4
wait and g	correct	Make sure I ended my task of stack	step away	desirable	If familiar \	neutral, trustful	positive	4	4	3	2	2	6	6	3	6	7
wait and g	correct	I will go a few steps backwards and	step away	desirable	I would fee	safe	positive	6	6	3	2	2	4	4	4	3	6
collide	incorrect	Go aside, may be a step back or to	step away	desirable	a bit unsa	unsafe,	negative	6	3	2	2	2	6	6	6	5	6
other	incorrect	go backward and let the other robot	step away	desirable	irritated as	annoyed	negative	1	6	2	2	2	7	6	1	2	1
wait	correct	step back	step away	desirable	I think it is	other	neutral	5	5	2	2	2	2	4	5	5	6
wait and g	correct	Continue my work, step aside eventi	step away	desirable	bothered	annoyed	negative	6	5	2	1	1	3	2	4	5	4
wait	incorrect	put boxes on robot	put boxes (	not desirable	afraid	afraid	negative	3	3	4	2	2	4	2	4	6	6
wait	incorrect	Continue to work	continue w	not desirable	Ok	neutral	neutral	5	6	5	2	3	2	2	3	2	4
wait	don't know	I don't see a necessary interaction \	continue w	not desirable	Neutrale	neutral	neutral	1	6	5	6	6	4	3	3	5	1
wait	incorrect	Clear the way for the robot	step away	desirable	Interruptec	annoyed	negative	2	4	2	3	3	4	4	4	5	2
wait and g	correct	I let the robot drive by me	step away	desirable	I'd feel goo	good	positive	4	5	4	3	4	2	3	4	4	4
wait and g	correct	I go away so the robot can pass anc	step away	desirable	I would be	surprised, annoyed	negative	3	5	2	2	2	5	5	3	3	4
wait and g	correct	I step aside	step away	desirable	Fine	good	positive	2	5	2	2	5	6	6	2	5	4
wait	incorrect	Uit de weg gaan zodat de robot zijn	step away	desirable	Kalm, neu	neutral	neutral	6	6	2	2	1	2	1	4	6	2
other	incorrect	Make side steps	step away	desirable	Helping	other	neutral	2	6	5	6	5	5	7	6	4	3
wait	incorrect	Go about my box-stacking business	continue w	not desirable	bored	other	neutral	7	7	1	1	1	3	2	4	6	6
wait and g	correct	Step out of the way to let the robot p	step away	desirable	I envision	comfortable	positive	6	7	2	1	2	3	1	4	2	4
other	correct	Step back and let it pass	step away	desirable	Puzzled	doubtful	negative	6	3	5	4	3	6	6	2	5	4
other	incorrect	I will stack boxes on top of the robot	step away	desirable	Like a me	other	neutral	6	7	7	1	2	6	4	5	6	5
wait and g	correct	I was out of boxes. The robot seems	step away	desirable	Frustrated	annoyed	negative	2	6	4	1	1	1	6	2	5	1
don't know	don't know	I don't know I already stacked boxes	don't know	don't know	neutral	neutral	negative	1	7	1	1	1	2	3	4	7	1
wait	incorrect	take a step back and look up	step away	desirable	suprised	surprised	neutral	3	4	5	4	3	2	3	3	5	2
wait and g	correct	See if there's a place to move so the	step away	desirable	A bit intim	afraid	negative	2	3	2	2	2	5	4	3	5	2
wait and g	correct	Go onto my next task, walk away	continue w	not desirable	Productive	good	positive	5	6	3	2	2	4	3	4	3	4
wait and g	correct	I would step aside and see if the rob	step away	desirable	A bit unce	doubtful	negative	2	6	6	5	3	5	5	2	2	2
wait and g	correct	Move to the right of the cart I'm curre	step away	desirable	if it's the fi	neutral, annoyed	neutral	2	6	5	6	6	6	3	5	5	2
wait	incorrect	Keep stacking boxes	continue w	not desirable	Confident	confident	positive	7	7	1	2	1	2	2	2	1	5
								5,5	4,7	3,2	3,0	2,7	4,7	4,3	3,6	4,1	4,8
								3,7	5,5	3,5	2,8	2,8	3,8	3,6	3,5	4,4	3,2
								4,7	5,1	3,3	2,9	2,7	4,3	4,0	3,5	4,2	4,1

How fami	Average																			
T3SAR	T3SAR	Column	T3TLX1	T3TLX1	T3TLX2	T3TLX2	T3TLX3	T3TLX3	T3NASA	T3NASA	T3NASA	T3NASA	T3TLX	Column	Column	TASK4	T4SEQ	T4Q2RA	T4Q2CA	T4Q2VE
1	3,7		4	15	5	20	15	70	10	45	21	100	50				5	Stop and	stop	correct
4	5,5		3	10	2	5	10	45	4	15	6	25	20				3	the robot	stop	correct
3	6,0		6	25	16	75	3	10	4	15	16	75	40				4	The robot	stop	incorrect
1	2,2		18	85	13	60	15	70	17	80	20	95	78				6	I feel like t	stop	correct
1	2,5		16	75	18	85	3	10	3	10	20	95	55				1	Go in a st	forward	incorrect
1	5,4		2	5	3	10	1	0	2	5	2	5	5				2	the robot	stop	incorrect
1	3,7		2	5	2	5	7	30	2	5	5	20	13				3	Continue g	forward	incorrect
5	5,4		3	10	6	25	5	20	4	15	8	35	21				5	He will stc	stop	correct
1	4,5		4	15	9	40	6	25	6	25	9	40	29				6	Go straigh	forward	incorrect
6	6,7		1	0	2	5	1	0	1	0	1	0	1				3	The robot	stop	incorrect
6	6,2		4	15	1	0	3	10	2	5	4	15	9				1	It will stop	stop	correct
1	4,2		15	70	21	100	15	70	12	55	15	70	73				5	It will wait	stop	incorrect
2	3,3		1	0	6	25	2	5	1	0	2	5	7				3	stop at the	stop	correct
4	4,2		6	25	4	15	8	35	8	35	8	35	29				6	I don't kno	don't know	don't know
4	5,0		10	45	18	85	10	45	10	45	10	45	53				2	Go straigh	forward	incorrect
3	5,1		14	65	7	30	1	0	12	55	12	55	41				6	I think it w	stop	incorrect
3	7,1		4	15	12	55	2	5	2	5	15	70	30				6	I think the	stop	correct
2	4,6		3	10	3	10	4	15	3	10	1	0	9				3	Rechtdoor	don't know	don't know
2	1,7		13	60	14	65	12	55	12	55	16	75	62				5	stop	stop	correct
3	4,4		14	65	4	15	7	30	4	15	10	45	34				2	Stop and	stop	incorrect
1	6,9		9	40	16	75	5	20	7	30	15	70	47				6	I am not s	don't know	don't know
6	7,4		7	30	2	5	5	20	5	20	5	20	19				2	The robot	stop	correct
2	7,8		7	30	10	45	5	20	7	30	6	25	30				6	go straigh	forward	incorrect
2	3,5		6	25	10	45	6	25	6	25	10	45	33				2	go straigh	forward	incorrect
2	6,0		2	5	2	5	6	25	2	5	4	15	11				2	maybe stc	don't know	don't know
4	6,2		4	15	10	45	1	0	1	0	13	60	24				1	stop and	stop	correct
5	6,8		7	30	3	10	16	75	3	10	7	30	31				2	go ahead	forward	incorrect
2	1,9		3	10	2	5	3	10	4	15	2	5	9				2	Continue s	forward	incorrect
1	-0,9		15	70	13	60	20	95	6	25	16	75	65				2	Stop	stop	correct
5	5,1		3	10	5	20	4	15	4	15	3	10	14				2	Go straigh	forward	incorrect
1	2,1		10	45	10	45	9	40	9	40	11	50	44				4	I as a robc	other	incorrect
5	6,5		8	35	11	50	9	40	6	25	7	30	36				6	I will go or	other	don't know
5	6,3		10	45	3	10	12	55	8	35	9	40	37				1	It will cros	forward	incorrect
1	3,1		2	5	13	60	1	0	3	10	2	5	16				2	Rechtdoor	forward	incorrect
1	2,2		1	0	1	0	1	0	1	0	1	0	0				1	It does no	forward	incorrect
1	6,3		3	10	8	35	3	10	3	10	1	0	13				1	keep mivir	forward	incorrect
1	3,3		3	10	6	25	1	0	2	5	1	0	8				3	He will co	forward	incorrect
4	4,8		6	25	14	65	17	80	5	20	16	75	53				5	Go forwarc	forward	incorrect
3	5,9		2	5	2	5	19	90	2	5	1	0	21				2	I think the	stop	correct
4	4,0		2	5	6	25	1	0	1	0	19	90	24				1	No obstac	forward	incorrect
1	4,0		2	5	1	0	1	0	3	10	1	0	3				4	I expect th	slow down	incorrect
1	0,8		7	30	10	45	9	40	7	30	8	35	36				4	He will go	forward	incorrect
4	5,3		17	80	16	75	10	45	10	45	16	75	64				1	Stop	stop	correct
4	5,2		3	10	4	15	5	20	5	20	4	15	16				1	Go ahead	forward	incorrect
4	1,8		16	75	6	25	11	50	6	25	8	35	42				3	Continue s	forward	incorrect
2	1,1		15	70	15	70	8	35	14	65	16	75	63				4	I don't thin	forward	incorrect
2	3,9		4	15	5	20	1	0	2	5	2	5	9				6	Continue f	forward	incorrect
2,7	5,0			29,2		36,5		25,4		23,3		43,8	31,7				3,7			
2,7	3,8			28,1		31,7		33,3		19,8		31,0	28,8				2,7			
2,7	4,4			28,7		34,4		28,9		21,7		38,1	30,4				3,3			

								How char	How com	How man	How alert	How muc	How muc	How muc	How muc	How fami	Average
T4Q3RAW. Describe the action	T4Q3CA	T4Q3VERD	T4Q4RA	T4Q4CAT	T4Q4VE	T4Q5	T4Q6	T4SAR	T4SAR	T4SAR	T4SAR	T4SAR	T4SAR	T4SAR	T4SAR	T4SAR	T4SAR
Move straight through the cross	forward	desirable	Unsecure	doubtful	negative	3	1	4	2	1	7	5	2	3	5	1	4,9
I would wait until the robot stops	wait	not desirable	a bit unce	doubtful	negative	5	4	3	4	3	5	5	4	4	4	4	5,2
I will continue going straight as	forward	desirable	A little ins	doubtful, confident	neutral	5	5	2	4	2	5	5	4	4	6	3	6,3
I would hesistantly try to start c	forward	desirable	I would fee	doubtful, hesitant	negative	3	3	6	7	5	7	7	7	1	3	2	2,0
Wait till it bas crossed	wait	not desirable	Fine, only	fine, annoyed	neutral	7	7	2	2	2	4	4	2	5	6	1	5,3
keep going as I was	forward	desirable	a little ner	afraid	negative	7	6	3	2	1	5	4	5	4	7	1	6,5
stop and wait for it to pass me	wait	not desirable	mildly imp	impatient	negative	6	6	3	4	3	5	3	4	4	3	1	2,7
I will stop to make sure the robc	wait	not desirable	Pretty cor	confident	positive	2	5	4	4	3	4	4	3	5	5	5	5,3
Stand still and wait till the robot	wait	not desirable	Inspectie,	other	neutral	2	1	6	5	5	6	6	2	3	3	1	0,9
The robot is coming from the rig	wait	not desirable	I knew wh	doubtful	negative	3	4	5	4	2	6	6	2	7	3	6	6,1
continue on, but make sure it dc	forward	desirable	somewhat	cautious	neutral	6	7	2	1	2	4	2	3	5	7	6	8,3
I will continue walking forward, r	forward	desirable	I bit insec	doubtful	negative	3	3	6	3	3	6	6	3	5	3	1	3,0
walk straight across the crossin	forward	desirable	a little bit	cautious	negative	4	5	3	2	2	4	2	1	7	4	2	4,2
I would stop my motion and wai	stop	not desirable	I feel inse	doubtful	negative	1	1	7	5	6	7	7	2	4	2	2	1,0
Stop walking	stop	not desirable	Unsure	doubtful	negative	1	2	6	6	4	6	5	1	1	1	1	-1,1
I would continue watching the rc	slow down	neutral	I am wond	doubtful	negative	3	5	6	5	3	6	6	6	2	4	2	3,3
I will wait for the robot to come t	wait	not desirable	Hesitant, I	hesitant	neutral	3	5	5	5	3	6	5	1	3	5	2	2,9
Voorrang geven	wait	not desirable	Lichtelijk (	doubtful	negative	2	4	6	3	3	6	7	2	4	2	6	4,8
Go straigt and over the crossing	forward	desirable	stressed b	afraid	negative	2	2	2	2	2	6	6	5	3	3	2	5,5
Continue walking, but be mindfu	forward	desirable	SLightly h	hesitant	negative	4	4	4	4	4	6	6	2	3	3	2	2,8
I would wait until the robot will s	wait	not desirable	Unsure an	doubtful	negative	2	6	7	3	3	5	4	5	6	6	1	4,2
I will go straight over the crossir	forward	desirable	When i an	fine, doubtful	neutral	5	5	5	3	4	6	5	4	5	5	6	6,5
stop and let the robot go first	wait	not desirable	unsecure,	unsafe	negative	6	3	1	2	2	5	6	6	4	5	1	6,6
go straight on	forward	desirable	confident	confident	positive	6	4	1	2	2	6	5	4	5	6	6	9,3
wait	wait	not desirable	OK	neutral	neutral	2	5	2	2	3	4	3	5	5	5	2	5,4
move on	forward	desirable	unfazed	neutral	neutral	6	6	2	1	1	2	2	2	6	6	5	7,2
wait until robot passes	wait	not desirable	ok	neutral	neutral	4	5	4	2	2	4	4	2	6	6	5	6,8
Stop and wait until bot pass	wait	not desirable	Ok	neutral	neutral	7	7	6	3	2	1	1	2	3	2	2	0,1
Move on	forward	desirable	Secure	safe	positive	6	7	2	2	2	1	2	2	1	2	2	1,5
Wait for the robot to clear the ju	wait	not desirable	The robot	other	neutral	3	4	5	4	4	5	5	3	3	2	4	2,7
I reduce my walking speed and	slow down	neutral	Fine.	good	positive	4	5	5	4	5	5	5	4	4	3	1	1,8
I don't know where the robot is g	step away	not desirable	I would fee	uncomfortable	negative	1	4	6	5	3	6	6	5	6	2	5	4,6
I will wait until the robot has pas	wait	not desirable	Ok	neutral	neutral	6	6	6	5	5	6	5	5	6	4	5	4,7
Speen, wachten tot de robot voc	wait	not desirable	Kalm	calm	positive	5	6	2	1	2	4	5	2	6	3	1	4,6
I stop	wait	not desirable	Responsit	other	neutral	6	5	3	3	3	6	6	3	4	3	2	4,3
wait for the robot to pass then c	wait	not desirable	awkward	uncomfortable	negative	3	7	3	1	3	5	3	2	3	4	1	3,4
Assuming he will keep moving I	wait	not desirable	In danger	unsafe	negative	1	1	7	4	3	7	6	5	4	4	1	3,3
Wait and see where the AGV is	wait	not desirable	Uncertain	doubtful	negative	2	5	5	2	2	6	6	2	5	2	3	4,3
I will continue walking	forward	desirable	Alert, kee	cautious	neutral	3	2	6	2	1	5	4	5	5	3	2	4,3
Wait until robot has passed.	wait	not desirable	I would fee	other	neutral	7	6	1	1	1	5	3	4	5	6	4	8,8
I will stop to let the robot pass.	wait	not desirable	neutral	neutral	neutral	2	7	3	5	5	6	6	6	3	4	4	4,9
I will stop and let the robot pass	wait	not desirable	normal	neutral	neutral	5	6	3	3	2	4	4	2	5	3	3	4,1
Stop	wait	not desirable	Careful	cautious	negative	1	4	7	4	2	6	6	2	2	4	6	4,7
Wait for the robot, then go straiç	wait	not desirable	Confident	confident	positive	7	7	3	3	3	4	4	4	5	5	5	6,3
Wait for the robot to pass and c	wait	not desirable	A bit anno	annoyed	negative	6	6	2	2	3	2	3	3	6	5	4	5,7
I'll wait to see which way the rot	wait	not desirable	Annoyed t	annoyed	negative	5	6	4	3	4	6	5	2	6	6	2	5,1
Wait	wait	not desirable	Insecure c	doubtful	negative	1	3	5	5	5	6	4	2	5	2	2	1,3
						3,8	4,2	4,0	3,3	2,8	5,3	4,8	3,3	4,2	4,3	2,8	4,6
						4,0	5,2	4,2	3,0	3,0	4,8	4,4	3,2	4,4	3,6	3,0	4,1
						3,9	4,6	4,1	3,2	2,9	5,1	4,7	3,3	4,3	4,0	2,9	4,4

	Mental		Temporal Demand		Performance		Effort		Frustration											
Column	T4TLX1	T4TLX1(	T4TLX2	T4TLX2(	T4TLX3	T4TLX3(	T4NASA	T4NASA	T4NASA	T4NASA	T4TLX	Column	Column	COMPA	PTQ1	PTQ2	PTQ3	PTQ4	PTQ5Raw. Ple	Age	Gender
	6	25	17	80	9	40	18	85	21	100	66				7	2	6	3	The projection help	36-40	M
	5	20	4	15	7	30	5	20	8	35	24				7	1	7	1	The arrow projectio	<25	F
	13	60	8	35	3	10	7	30	5	20	31				7	1	7	5	The arrows provide	26-30	M
	17	80	9	40	11	50	15	70	17	80	64				7	2	6	1	For the case on the	<25	F
	9	40	14	65	2	5	8	35	13	60	41				7	2	6	1	I like the arrow way	31-35	F
	2	5	1	0	1	0	1	0	2	5	2				7	2	7	1	I think the projecte	26-30	F
	4	15	5	20	8	35	6	25	3	10	21				6	2	4	1	Side by side The a	<25	M
	3	10	6	25	6	25	4	15	7	30	21				7	1	7	2	Don't know if this is	26-30	M
	5	20	3	10	13	60	5	20	17	80	38				7	1	7	1	The one with the ar	>51	F
	4	15	5	20	6	25	6	25	6	25	22				7	1	7	1	I think the arrow is	36-40	F
	5	20	2	5	2	5	2	5	8	35	14				7	2	7	2	I would like a bit of	26-30	M
	13	60	14	65	13	60	6	25	15	70	56				7	2	6	3	The robot which is	<25	M
	5	20	5	20	1	0	1	0	4	15	11				7	4	7	1	the arrows make it	26-30	M
	12	55	14	65	12	55	4	15	18	85	55				7	1	7	1	I highly prefer the v	>51	F
	15	70	5	20	15	70	5	20	20	95	55				7	2	7	1	Non arrow variation	26-30	M
	16	75	11	50	1	0	18	85	12	55	53				7	2	7	1	I am comparing an	<25	M
	12	55	14	65	6	25	14	65	16	75	57				7	1	7	1	The variation with tl	26-30	F
	10	45	6	25	4	15	4	15	15	70	34				7	1	7	1	Met pijl is vele mak	<25	M
	15	70	16	75	5	20	15	70	16	75	62				6	2	6	2	hey are the same b	>51	M
	14	65	10	45	7	30	8	35	9	40	43				7	2	7	1	The arrows make it	26-30	M
	7	30	9	40	10	45	10	45	13	60	44				7	2	6	2	The arrow simply is	36-40	M
	5	20	2	5	7	30	5	20	5	20	19				7	1	7	1	In the situation with	<25	M
	7	30	7	30	5	20	5	20	5	20	24				7	1	6	1		31-35	F
	3	10	9	40	6	25	6	25	3	10	22				7	1	7	1	with arrows is clear	>51	M
	1	0	2	5	5	20	2	5	4	15	9				6	1	6	1		36-40	F
	1	0	1	0	1	0	1	0	2	5	1				7	3	6	1		36-40	M
	3	10	1	0	3	10	4	15	5	20	11				7	3	7	1	arrows are very hel	31-35	M
	3	10	2	5	2	5	2	5	2	5	6				7	3	7	1	Arrows support-> L	31-35	F
	5	20	5	20	12	55	4	15	1	0	22				7	2	7	1	It is much easier to	31-35	F
	3	10	4	15	7	30	5	20	3	10	17				6	4	5	2	Easier to understar	36-40	M
	10	45	8	35	10	45	10	45	11	50	44				7	2	7	2	The indication of th	41-45	F
	17	80	13	60	18	85	12	55	18	85	73				7	2	7	3	The arrows make it	<25	F
	13	60	10	45	7	30	7	30	9	40	41				7	5	6	3	It's convenient to s	>51	M
	5	20	5	20	3	10	1	0	1	0	10				7	1	7	1		26-30	M
	2	5	2	5	3	10	2	5	1	0	5				7	1	7	1	Left one is more sa	>51	M
	7	30	4	15	3	10	4	15	1	0	14				7	1	6	1	They illustrate diffe	26-30	M
	17	80	21	100	1	0	13	60	14	65	61				7	1	7	1	I would feel far mor	26-30	F
	6	25	10	45	13	60	5	20	15	70	44				6	2	7	1	In both scenarios I	26-30	M
	2	5	2	5	19	90	3	10	2	5	23				7	1	5	2	With the arrow its i	26-30	M
	1	0	7	30	17	80	2	5	12	55	34				7	1	5	5	Left version gives n	<25	M
	11	50	2	5	11	50	4	15	10	45	33				7	1	7	3	It really helps that t	26-30	F
	5	20	5	20	5	20	6	25	4	15	20				6	3	6	1	The arrows make it	26-30	F
	16	75	10	45	10	45	4	15	15	70	50				7	2	7	1	With the arrow is s	41-45	M
	4	15	3	10	7	30	4	15	3	10	16				7	2	7	1	The left variation is	26-30	M
	5	20	4	15	15	70	5	20	10	45	34				6	3	6	2	The augmented rea	26-30	M
	8	35	3	10	15	70	5	20	18	85	44				7	1	7	1	That the arrows giv	26-30	F
	13	60	12	55	13	60	8	35	14	65	55				7	2	7	2	Arrow is a major im	31-35	M
		35,2		33,3		26,9		29,8		45,8	34,2				6,9	1,7	6,5	1,5			
		32,1		26,7		41,2		21,2		35,2	31,3				6,8	2,0	6,5	1,7			
		33,8		30,3		33,3		26,0		41,1	32,9				6,9	1,8	6,5	1,6			

	PQ1. Do y	PQ2. In w	PQ3. In w	PQ4. High	PQ5. How	PQ6. How	PQ7. How	PQ8. How	PQ9. How	PQ10. Ho	PQ11
Column	PQ1	PQ2	PQ3	PQ4	PQ5	PQ6	PQ7	PQ8	PQ9	PQ10	PQ11
	No	Germany	Germany	PhD	7	7	6	2	2	3	AR, VR
	Researche	The Nethe	The Nethe	MsC	7	7	4	1	3	4	AR, PAR, VR
	No	The Nethe	The Nethe	MsC	6	6	4	6	3	4	AR, PAR, VR
	Student	The Nethe	The Nethe	BsC	6	6	5	4	3	4	AR, VR
	No	The Nethe	The Nethe	MsC	7	6	4	2	2	2	VR
	Student	The Nethe	The Nethe	BsC	6	7	2	3	1	2	PAR
	Other	The Nethe	Cape Verc	BsC	7	7	4	3	2	2	VR
	No	Italy	Italy	MsC	7	7	3	5	5	3	AR, VR
	No	The Nethe	The Nethe	HBO	4	5	2	1	1	1	VR
	No	The Nethe	The Nethe	MsC	4	6	1	1	1	1	PAR
	Student	The Nethe	The Nethe	BsC	7	7	7	2	3	3	VR
	Researche	The Nethe	The Nethe	MsC	7	7	6	5	6	5	AR, VR
	No	The Nethe	The Nethe	MsC	7	7	4	3	2	4	AR, VR
	Yes	The Nethe	The Nethe	MsC	5	5	1	2	2	2	
	No	The Nethe	The Nethe	MsC	6	7	4	2	1	2	AR
	Yes	The Nethe	Belgium	High scho	7	7	7	2	2	3	VR
	No	The Nethe	The Nethe	MsC	7	7	2	3	2	2	VR
	Yes	The Nethe	The Nethe	High scho	7	7	5	1	1	2	VR
	No	The Nethe	The Nethe	MsC	4	4	3	2	2	2	
	No	The Nethe	The Nethe	MsC	7	7	4	5	1	2	
	Yes	The Nethe	The Nethe	MsC	7	7	4	2	2	2	
	No	Austria	Austria	BsC	7	7	5	6	7	5	AR, PAR, VR
	Yes	The Nethe	Russia	MsC	7	7	5	4	1	6	AR, VR
	No	The Nethe	The Nethe	MsC	7	7	2	7	1	3	
	No	Germany	Germany	PhD	7	7	5	4	4	5	
	No	Germany	Germany	PhD	6	7	6	2	2	3	AR, PAR, VR
	No	Germany	Germany	MsC	7	7	7	4	2	5	AR, PAR, VR
	No	Germany	Germany	MsC	6	6	4	5	2	4	PAR
	No	Germany	Germany	BsC	7	5	2	1	1	2	PAR
	No	Germany	Germany	MsC	7	7	5	3	5	4	AR, VR
	No	Germany	Germany	MsC	5	5	1	2	1	2	PAR
	No	Germany	Germany	MBO	6	5	2	2	1	4	AR, PAR, VR
	Researche	The Nethe	Nl	HBO	7	7	3	5	5	5	AR, PAR, VR
	No	The Nethe	Netherlanc	MsC	7	7	5	2	1	1	AR
	No	The Nethe	The Nethe	MBO	5	5	1	1	1	1	AR
	Student	The Nethe	Brazil	MsC	6	7	5	3	1	3	AR, VR
	No	The Nethe	Netherlanc	MsC	6	6	2	1	1	2	
	Student	The Nethe	The Unite	BsC	7	7	6	5	2	2	VR
	Researche	The Nethe	The Nethe	MsC	7	7	7	5	5	5	VR
	No	The Nethe	The Nethe	MsC	7	7	6	4	6	3	VR
	No	The Nethe	South-Afri	MsC	7	7	4	3	2	1	VR
	No	The Nethe	Netherlanc	High scho	5	6	2	2	2	2	VR
	No	The Nethe	Netherlanc	MsC	6	7	3	4	2	3	AR, VR
	Student	The Nethe	Nederland	High scho	6	7	5	4	3	4	
	No	The Nethe	Netherlanc	MsC	6	6	5	5	5	4	PAR, VR
	Student	The Nethe	the Nethe	BsC	6	6	4	3	2	2	VR
	No	The Nethe	Netherlanc	HBO	7	7	7	5	3	4	AR, PAR, VR
					6,4	6,6	4,0	3,1	2,4	3,0	
					6,3	6,4	4,1	3,3	2,5	3,0	
					6,4	6,5	4,1	3,2	2,4	3,0	