The Implementation of autonomous agents into aircraft turnaround operations:
A wheel chock robot case study

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Background picture: Mark Wagtendonk

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Preface

From the start of my educational journey, I always was more geared towards the technical aspects of Industrial Design Engineering. This gradually shifted towards the use of the Internet of Things to do ‘A’ over here, and then ‘B’ happens somewhere else, and it somehow made me very excited for all the possibilities that came with this.

But I never could have imagined that this interest would in the end help me end up creating an actual physical robot during my master's thesis, that you can control remotely. I would therefore like to thank Roy and Eric for introducing me to this challenge, and Roy especially for his guidance throughout the project. I would also like to thank Peter, the supervisor from KLM, for his guidance, new and interesting perspectives, and the possibility to work on this project.

I could also not have done this without the support from the people closest to me during the many setbacks throughout the project.

Thank you for taking the time to read this thesis!

- Robert

Abstract

The increasing difficulty of recruiting personnel and increased awareness towards the physical health implications of repetitive and physical tasks combined with the exposure to harmful fumes led to the exploration into the use of autonomous agents during aircraft turnaround operations. These autonomous agents will be used to alleviate some of the workload from the ground personnel. The use of autonomous or automatic systems has increased over the years, but a common misconception about the use of these systems is that this will always improve performance. More often than not the human operators are not replaced, but left with other tasks, like monitoring, which require a different set of skills and when done improperly, could negatively influence performance. This thesis looked into the challenges regarding the implementation of autonomous agents into aircraft turnaround operations concerning localization and human interaction. This resulted in the creation of a framework to cater for the information requirements of the autonomous agents and allow communication between themselves and the ground personnel as well as the integration of synthetic map-based localization. Situation awareness was found to be a significant factor that influences the performance of human autonomy teams. A workflow was created for designers which included situation awareness-oriented design steps to help guide the addition of situation awareness aspects into the design of autonomous agents during their development. This workflow was used during a case study to guide the development of an autonomous wheel chock robot and showed its use by integrating several situation awareness aspects into the design. As well as showing the possible functionalities of the robot concerning the placement and removal of wheel chocks, and the localization capabilities.

Table of contents

Abbreviations

AMR:	Autonomous Mobile Robot
AO:	Autonomous Operations
ERA:	Equipment Restrain Area
EUR:	European
FOD:	Foreign Object Debris
FPU/GPU:	Fixed or Ground Power Unit
GDTA:	Goal-directed Task Analysis
GNSS:	Global Navigation Satellite System
GSE:	Ground Service Equipment
HAT:	Human Autonomy Team
IATA:	International Air Transportation Association
ICA:	Intercontinental
ICAO:	International Civil Aviation Organization
IMU:	Inertial Measurement Unit
IP:	Interaction Point
KLM:	Koninklijke Luchtvaart Maatschappij N.V.
MLG:	Main Landing Gear
NLG:	Nose Landing Gear
RFID:	Radio-Frequency Identification
ROS2:	Robot Operation System 2
SA:	Situation Awareness
SAGAT:	Situation Awareness Global Assessment Technique
SAT:	Situation Awareness-based Transparency
SAOD:	Situation Awareness-Oriented Design
SLAM:	Simultaneous Localization And Mapping
TC:	Team Coordinator
TM:	Team Member
TOF:	Time-Of-Flight
VDGS:	Visual Docking Guidance System
UWB:	Ultra-Wideband
WCR:	Wheel Chock Robot

1. Introduction

An increasing amount of tasks have been automated over the years, such as automated production lines, the cruise control functionality in cars and plannable thermostats. However, recently, this trend has changed into making things autonomous, meaning that these systems have the capability of making decisions without relying too much on user input, thus being more independent. Examples of these systems include autonomous mobile robots (AMRs), capable of autonomous navigation or autonomous vehicles that are already being limitedly deployed in some parts of the world. This thesis will be about making another task more autonomous, namely aircraft turnaround operations.

This thesis project is done on behalf of KLM, a Dutch airline company, that provides both continental and intercontinental destinations. This is done according to a 'hub-spoke' model, which is designed to bring passengers from all over Europe to the main hub, Amsterdam Airport Schiphol. From there these passengers are transferred to bigger aircraft, bringing them to intercontinental destinations such as North-America or Asia. This means that a significant portion of the activities of KLM revolve around transferring passengers from one aircraft to another, while still upholding passenger satisfaction.

This project is about introducing autonomous agents into the aircraft turnaround operations that KLM performs at Amsterdam Airport Schiphol.

1.1. KLM turnaround operations

Because a significant portion of KLM's activities are about transferring passengers from gate to gate, to cater for as many passengers as possible, a quick and smooth 'turnaround' is required. Turnaround operations for an aircraft are the operations that are performed to properly receive, handle and send out the aircraft at the aircraft stands in front of the airport gates. This involves refuelling, baggage handling and connecting the passenger bridge for example. Figure 1 shows a picture of turnaround operations being performed. If delays arise during these operations, costs can build up significantly. According to a study from the University of Westminster and Eurocontrol, each minute of delay costs around €100 [1].

Figure 1: Picture of the turnaround operations around a KLM aircraft, by Mark Wagtendonk

1.2. Problems with turnaround operations

Several problems have been emerging over the past few years that could influence the ability to perform turnaround operations sufficiently, in its current form.

According to IATA, staff shortages are one of the main problems that could influence turnaround operations in the near future [2]. There are fewer people available and willing to do that kind of work, which in turn affects the ability to fill all the labour hours that are required to perform turnaround operations without causing too many delays.

The increased attention to physical strain for ground personnel during turnaround operations has also caused KLM to look for improvements or changes in these operations to reduce this strain.

Most recently, the Dutch labour inspection has asked Amsterdam Airport Schiphol to create plans for a ‘green zone’ around the aircraft, because aircraft emissions can be harmful for the ground personnel working near it [3]. This caused the phasing out of APU usage on aircraft stands, and increasing the amount of aircraft that is towed towards the landing strip, to reduce the amount of emissions near the aircraft stands. Another way would be to move the ground personnel away from the aircraft stand or to reduce the amount of ground personnel required to perform the turnaround operations.

1.3. Autonomous turnaround operations

KLM intends to find solutions to these problems, by looking into the use of autonomous agents for aircraft turnaround operations. These autonomous agents should alleviate some of the workload from the ground personnel and make their working environment healthier, smarter, easier and future-proof. This is all organised under the Autonomous Operations project (AO) from KLM, which will be explained in more detail in Section 2. In that same section, potential challenges associated with the use of autonomous agents will also be addressed, emphasizing that their implementation often does not immediately reduce the workload of human operators.

1.4. This thesis project

This thesis project will explore how to correctly implement autonomous agents to alleviate some of the workload from the ground personnel, while addressing the challenges that are associated with the use of autonomous agents. As previously mentioned, this is done under the umbrella of the AO Project by KLM. The contribution of this thesis project to AO is to focus on the localization of autonomous systems on an aircraft stand, as well as the interaction between ground personnel and autonomous agents. In addition to this, a case study will be conducted to test the findings of the research done towards these two directions.

1.4.1. Localization

All below-wing turnaround activities require some kind of interaction with the aircraft at specific points around the aircraft. This means that for future autonomous agents, localization on the aircraft stand to be able to know where they are with regard to the aircraft is necessary to do their tasks. For this reason, different localization technologies and methods are researched and compared to determine which ones are best suited for use in the context of the turnaround activities.

1.4.2. Human interaction

It is expected that not all turnaround activities will be performed by autonomous agents instead of human ground personnel at once, this means that there will be a period where human ground personnel and autonomous agents need to work together for a successful turnaround. As will be explained in Section 2.3, it is not a simple matter of ‘replacing’ human personnel with autonomous agents. The inclusion of autonomous agents into any operation can have a great influence on the performance, but if done incorrectly, this influence will be negative. Therefore, research into human interaction with autonomous agents was conducted for this thesis, to search for possibilities to minimize this effect.

1.4.3. Wheel chock robot case study

From KLM the question was to create a wheel chock robot prototype to show the people at KLM what is possible regarding autonomous operations, because the concept of using autonomous systems for turnaround operations is quite new. As well as to see what hurdles could be encountered during the development of such a system. For this thesis, the design and development of the wheel chock robot will act as a case study to test the workflow that will be created using the results from the aforementioned research directions. The results of this case study could then be used to validate the effectiveness of the workflow and also advise KLM on what to look out for during the development of autonomous agents for turnaround operations.

2. Autonomous Operations Project

As explained in the previous section, this project falls under the Autonomous Operations project of KLM. The goal of this project is to explore various solutions related to autonomous systems to reduce the workload of ground personnel during turnaround operations, thereby safeguarding turnaround times that may otherwise be compromised due to the issues outlined in Section 1.2. Alongside this, the AO project has the following purpose:

“Creating a healthy working environment to make the work of our employees easier, smarter, more fun and future proof”

The mission is as follows:

“Automate and robotize repetitive, heavy, potential unsafe and complex work of our employees in order to utilize manpower in a more effective way”

This also emphasizes the alleviation of the workload of the ground personnel, with a focus on the experience of the ground personnel.

This section will first go over the industry context of this project, looking at what things are currently in motion regarding autonomous airport operations and how this project aligns with them. The state of the art of autonomous systems and general misconceptions about automation and autonomous systems are explained next, to better understand how this project can contribute to solving these problems.

2.1. Industry context

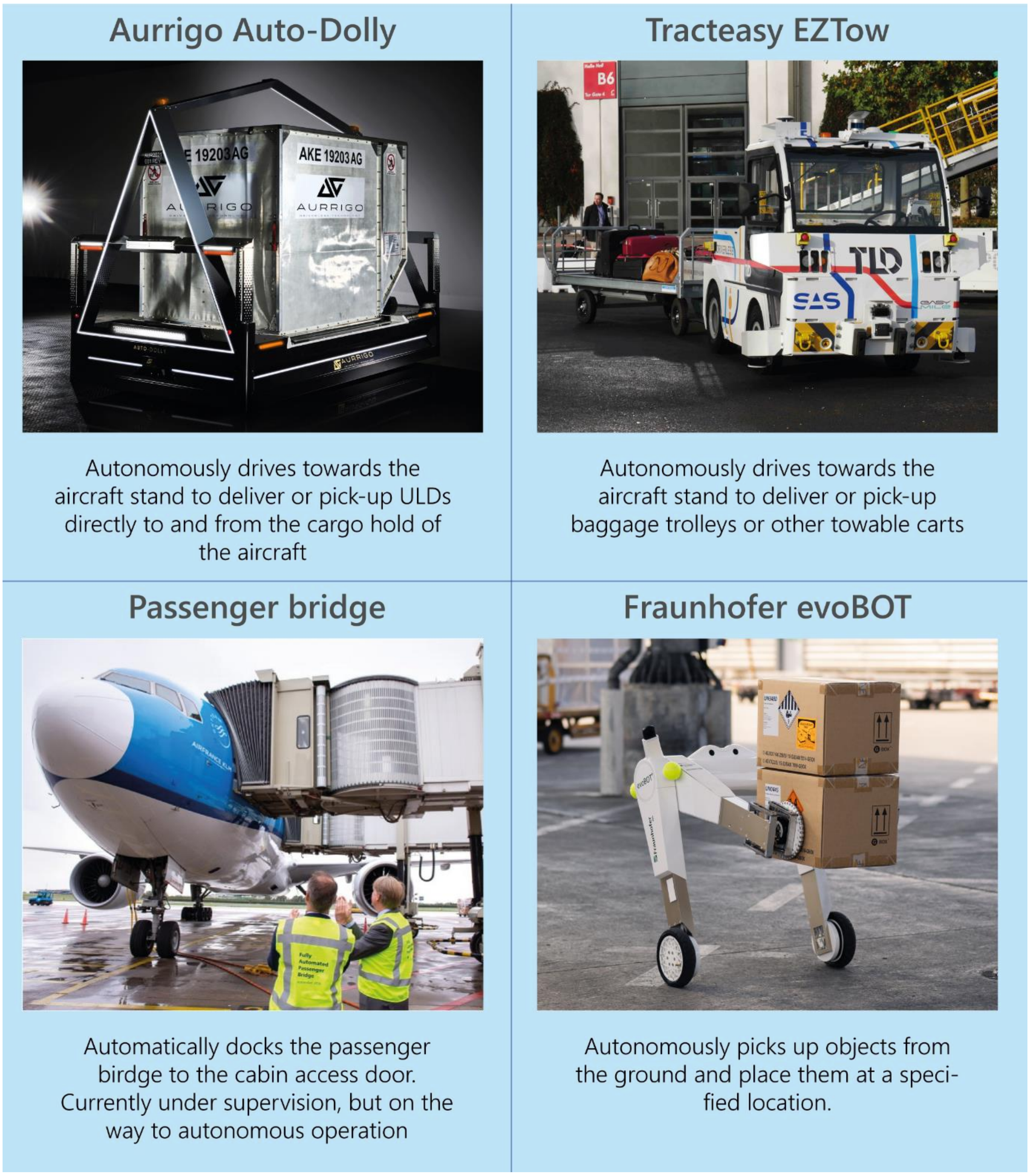
The three main entities that influence what and how flights are handled on airport grounds are: the airports, the airlines and the regulatory bodies. For this project, these three are Amsterdam Airport Schiphol, KLM and IATA respectively. KLM is the biggest ground services provider at Schiphol, not only handling their aircraft, but also that of other airlines, contributing to around one-third of the total ground handling activities at the airport. Schiphol is one of the biggest airports in Europe, facilitating millions of passengers each month, with KLM as its primary airline customer. This often means that when one of these parties wants to implement changes, the other wants to have some say in it. They both have aspirations of implementing autonomous agents into their operations. Schiphol has the ambitious goal of being a 100% autonomous airport by 2050, according to its Autonomous Airside Project [4]. And KLM is looking into this through the aforementioned AO project. This means that autonomous ground operations are gaining some traction. In the near future, Schiphol wants to test the concept of ‘Autonomous Docking’ with KLM, where the tasks of attaching the passenger bridge, placing the wheel chocks and cones, and connecting the GPU/FPU are all performed by autonomous systems.

The AO project from KLM will look into implementing autonomous agents into different divisions within KLM, ‘Engineering & Maintenance’, ‘Cargo’ and ‘Ground Services’. This project will be part of the ‘Ground Services’ division, looking into turnaround operations specifically.

IATA is not strictly a regulatory body, like ICAO, however, it sets standards and provides recommendations for airlines to follow, ensuring efficient and safe operations. IATA publishes the “Airport Handling Manual” each year, where they explain the new rules and recommendations regarding ground operations. In the most recent version, they have already outlined some recommendations regarding autonomous Ground Service Equipment (GSE), splitting the implementation of these systems into 3 phases. Phase 1, ‘Mobility’, accounts for the ability of the GSE to autonomously move from point A to B. Phase 2, ‘Manoeuvring’, explains the recommendations regarding the autonomous movement in busy areas, like the baggage halls or aircraft stands. Phase 3, ‘Operations’, applies to autonomous agents which would be able to perform turnaround activities. However, the recommendations outlined in those phases are not extensive and specific, with phase 3 not elaborated on yet. When more autonomous agents meant for ground operations start to be developed, IATA will most likely start to add to and specify these rules and recommendations, based on the results of these developments.

2.2. State of the art

Various autonomous and automatic systems are currently being developed, that can be used for aircraft turnaround operations or in the context of the airport. This section explores a selection of these systems, to explain what is already being done concerning autonomous agents on airport grounds and what functionality gaps still exist in this context. Below, in Figure 2, four of these systems can be seen, along with a short description of their functionalities.



Aurrigo Auto-Dolly

Autonomously drives towards the aircraft stand to deliver or pick-up ULDs directly to and from the cargo hold of the aircraft

Tracteasy EZTow

Autonomously drives towards the aircraft stand to deliver or pick-up baggage trolleys or other towable carts

Passenger bridge

Automatically docks the passenger birdge to the cabin access door. Currently under supervision, but on the way to autonomous operation

Fraunhofer evoBOT

Autonomously picks up objects from the ground and place them at a specified location.

Figure 2: A tiled overview, showcasing the main functionalities of the Aurrigo Auto-Dolly [5], the TractEasy EZTow [6], the automatic passenger bridge by KLM and Schiphol [7], and the Fraunhofer evoBOT [8]

The listed solutions could all achieve a single goal for the turnaround operations. The passenger bridge could be connected automatically, the Auto-Dolly will bring baggage or cargo from and to the cargo hold and the EZTow could to this for bulk-loaded aircraft baggage. However, this does all happen without any interfaces between these systems, they work individually, with no or limited communication to external systems.

In terms of human interaction, the evoBOT does provide human interaction, in the form of handing objects over to humans or back, according to their product video. However, similar to the other solutions, little is known about the monitoring or information transfer between the system and the operators.

The aforementioned shortcomings will be addressed in this thesis, by proposing a system architecture as a basis for multiple autonomous agents to work together and by exploring methods that cater for the design of the right interfaces for human interaction.

2.3. Autonomy and automation misconceptions

A common misconception about implementing autonomous or automatic systems to replace human personnel is that this will always increase performance and reduce the workload that is associated with that specific task. As pointed out by Bainbridge, L. in her letter ‘Ironies of Automation’ [5], this is not always the case. She explains that there are still tasks left after the task is taken over by an automation, such as monitoring and possible interventions. For these things, you also still need to have an operator who is knowledgeable about the automated task, to intervene when things go wrong, or first recognize when things go wrong. The type of skill necessary will change as well, because to understand the automation, the operator needs to be more skilled than before. During the monitoring of these automated tasks, the operator could also lose vigilance, because of the decrease in activity, making it more difficult for the operator to see problems and act quickly. Endsley verified Bainbridge’s observations in [6], saying that they still hold today, also discussing why the same, and more, challenges hold for implementing autonomous systems. This means that implementing automatic or autonomous systems should be done with care, otherwise it could result in a situation worse than before.

3. Analysis current operation

To understand how to implement autonomous agents into the turnaround operations at KLM, it is important to know how these operations are currently done. An analysis of the current operations, focussing on the steps involved in the various activities of the operations, the aircraft stand where these operations are being performed and the team interaction during the operations, will enhance this understanding. This section will elaborate on this analysis of the current operation. The following conclusions came forth out of the 'Ground Operations Manual', visits to the aprons at Schiphol and internal talks with KLM staff.

3.1. Turnaround activities

Each turnaround activity, like the attachment of the GPU or the water service, contributes something to completing the turnaround of an aircraft. Figure 3 contains a schematic overview of a typical aircraft turnaround, listing all the turnaround activities and their approximate duration and order. The depicted relative starting points are an approximation, however, the blocks that start or end precisely after each other, indicate tasks that have to be done consecutively.

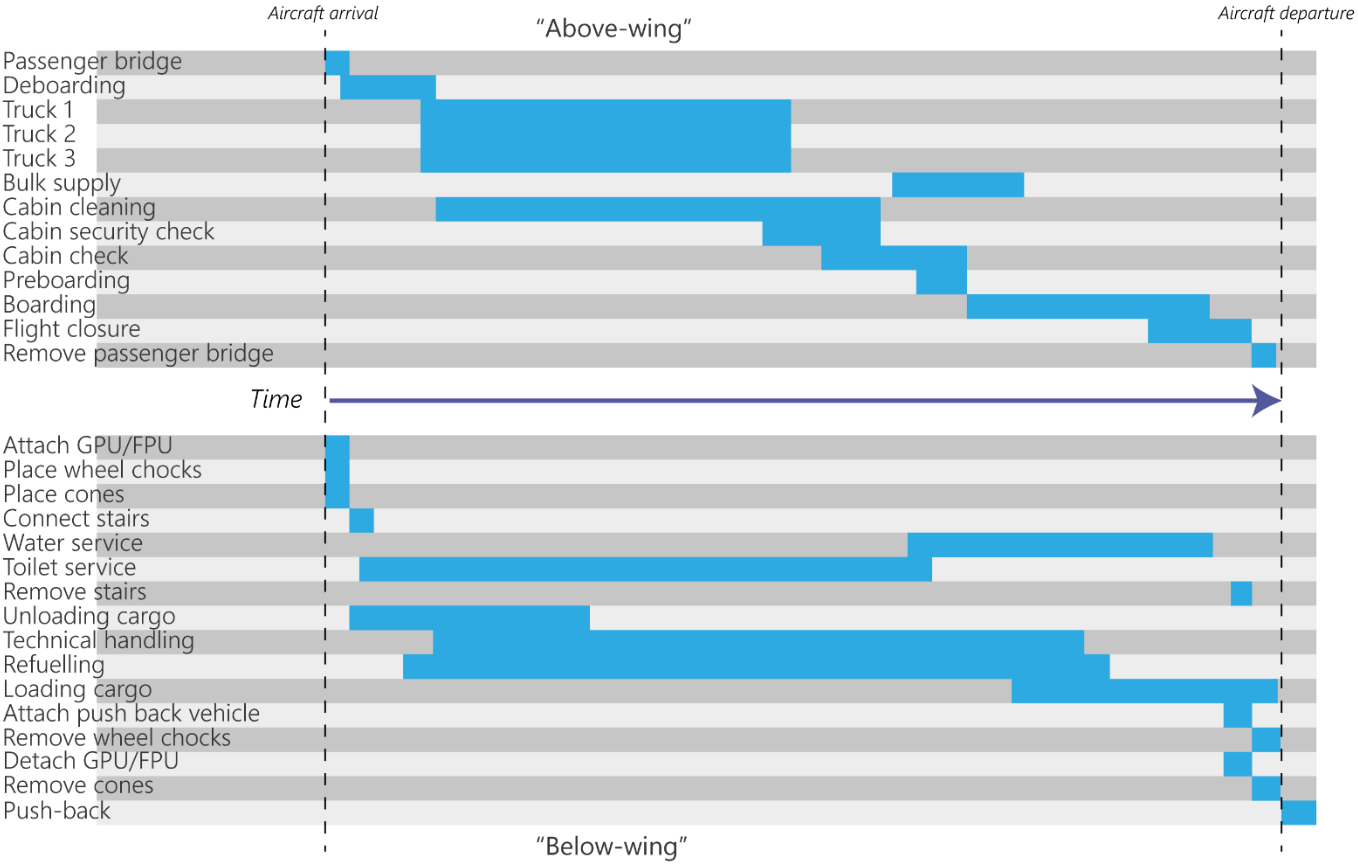


Figure 3: Block schedule of the turnaround activities, ordered in 'Above' and 'Below' wing

The top half of the figure shows the operations that are done "above-wing", which are all the activities connected to the passengers and cabin. The bottom half indicates the "below-wing" activities, which include most of the servicing activities of the aircraft, like refuelling or baggage handling, these activities are the focus of this project. As can be seen in Figure 3, Some of these activities have to be done consecutively, and some can be done in parallel.

3.2. Aircraft stand

The aircraft stand is the place in front of the airport gate, where the aircraft arrives for the passengers to deboard/board, either using a passenger bridge or passenger stairs, taking them to the gate. This is also the context where the turnaround operations take place and will thus be the context for the autonomous agents that will be implemented into those operations. During the turnaround operations, the aircraft stand is a dynamic environment, with GSE driving around and people walking around to do their part of the operation. Figure 4 shows a top-down view of an aircraft stand, also including the trajectories of some GSE to showcase this dynamic nature.

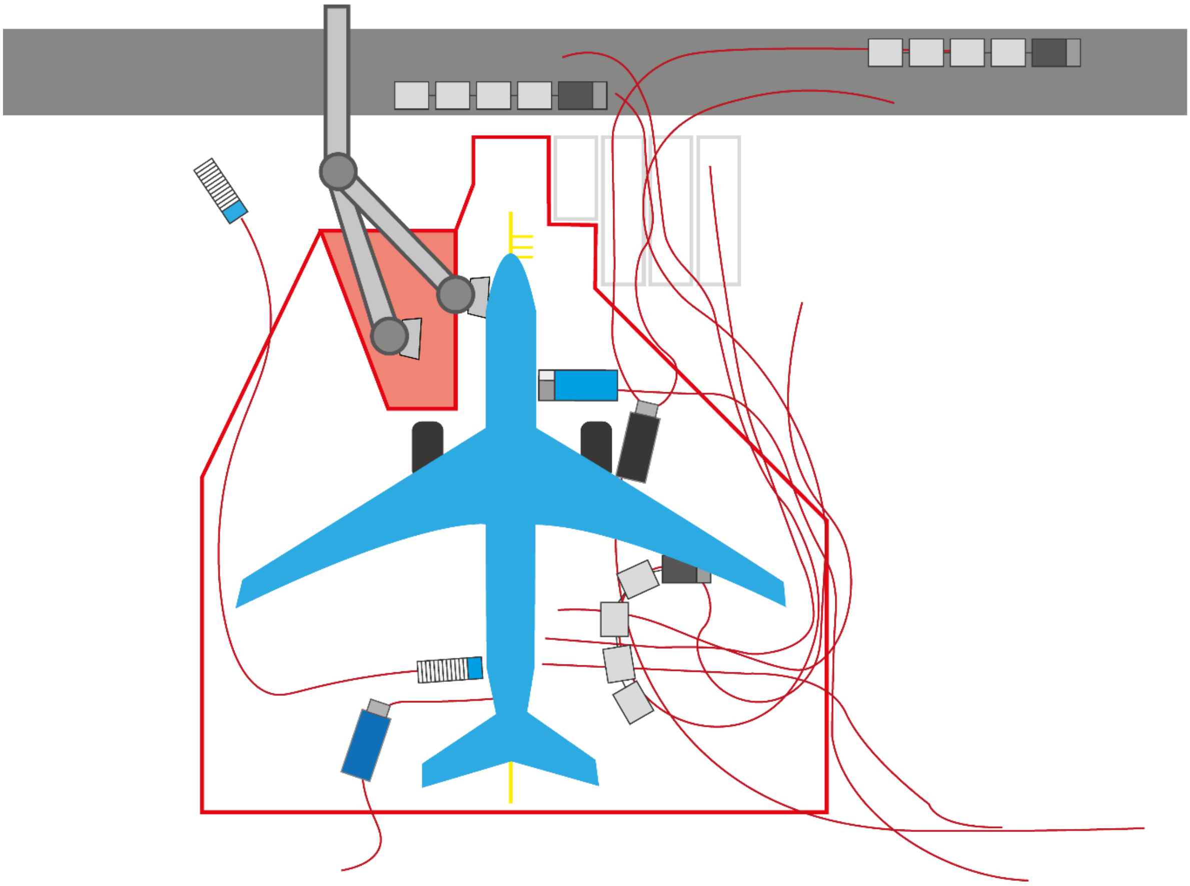


Figure 4: Schematic overview of an aircraft stand, where the curved red lines indicate the possible paths that the GSE can take. Adapted from [7]

The thick red line around the aircraft stand denotes the Equipment Restrain Area (ERA). When an aircraft arrives, for safety reasons, all GSE and personnel have to be outside of this area, until the engines are spooling down and the wheel chocks are placed. The yellow line in the middle is the centreline, which indicates the possible position of the aircraft, depending on the aircraft type. The aircraft remains a static component on the aircraft stand during the turnaround operations.

What could also be derived from Figure 4, is that it can be quite busy on the aircraft stand, which could cause congestions. This is also something that came forth from a visit to an aircraft stand, where a catering truck arrived and a trolley driver had to drive the trolley away to make place for it.

Before the engines of the aircraft are spooling down, the area surrounding the engines should also be avoided, since the inlet is still sucking in air with a significant amount of force, which could cause things to get sucked into the engine.

Figure 5 illustrates the size of this intake area for the engines of a Boeing 787, during idling. This indicates that the dangerous area around the intake is quite large and should be taken into account for the autonomous agents to avoid.

The ground personnel is also required to wear ear protection when the aircraft arrives and departs, because the noise from the engines could cause ear damage.

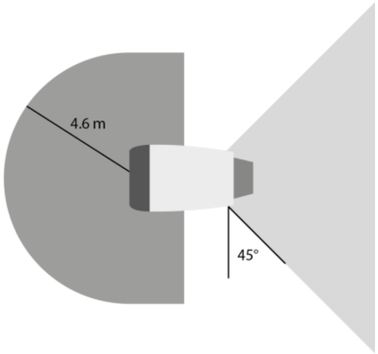


Figure 5: Illustration of the intake area of the engines from a Boeing 787 during idling.

3.3. Generalized functions

The turnaround operations all follow approximately the same pattern, as illustrated in Figure 6. This pattern of generalized functions will serve as a basis for understanding how the activities that the autonomous agents will perform will look like. These generalized functions were derived by comparing the tasks from the current operation and looking for similarities.

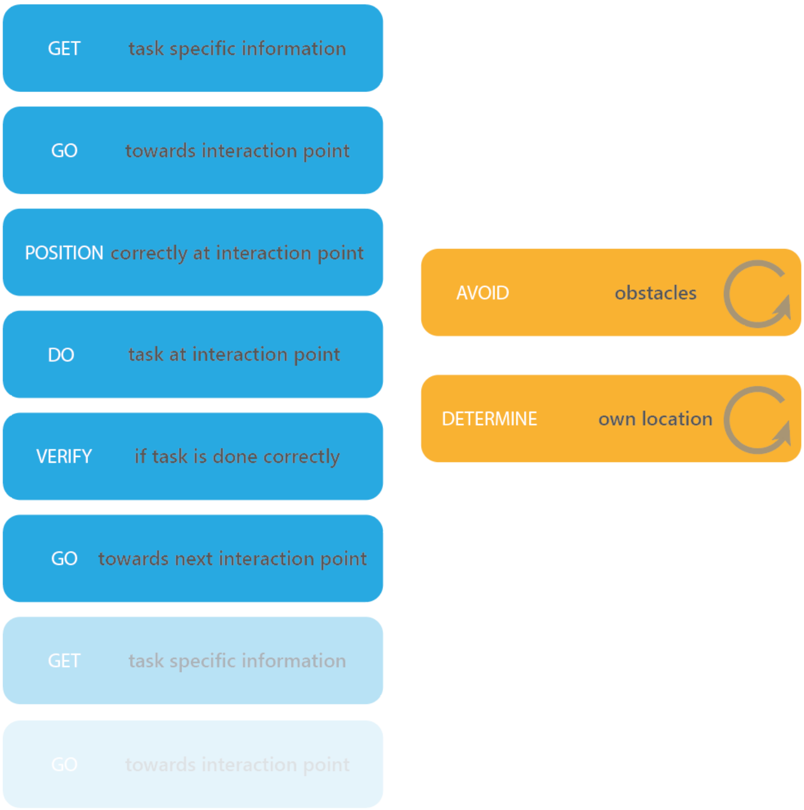


Figure 6: Overview of the generalized functions of a turnaround task. The left shows the consecutive steps, the right shows the continuous steps

To illustrate how this overview could be used to describe turnaround operations, it has been specified for the GPU attachment, as shown in Figure 7.

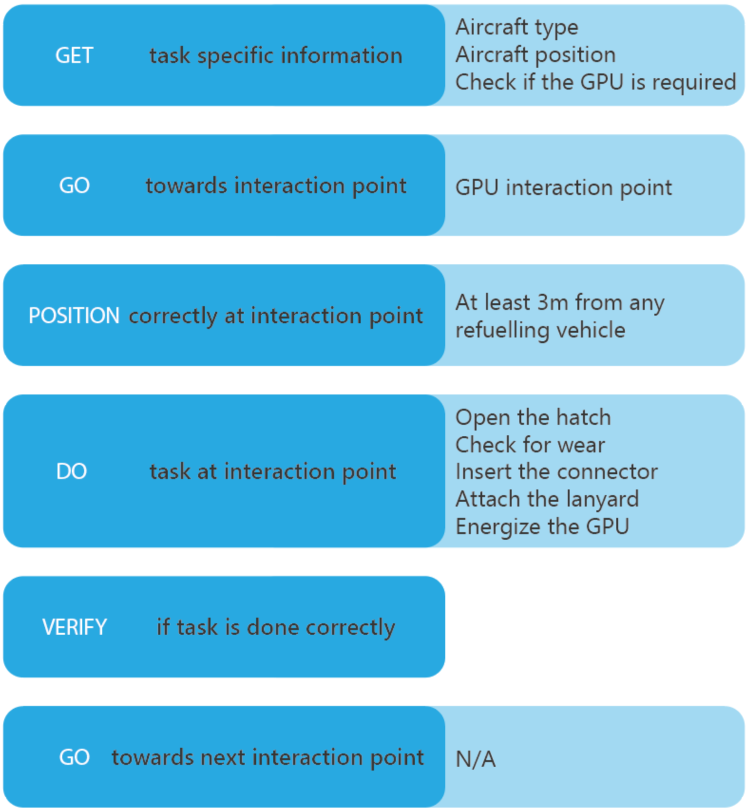


Figure 7: Overview of the consecutive steps for the attachment of the GPU during turnaround operations

3.4. Interaction types

To inform decisions regarding the selection of localization methods or human interaction design choices, the turnaround tasks are categorized into three types of interaction. These types could then be linked to specific requirements or recommendations regarding these two topics.

Placement

The placement of cones and wheel chocks falls under this type of interaction, where objects are placed near or around the aircraft, without directly interacting with it.

Interactive

An example of this type of interaction is the insertion of the GPU/FPU for ground power. To do this, a hatch on the aircraft has to be opened and a connector needs to be inserted. This requires a more direct interaction with the aircraft.

Inspection

During the turnaround, several inspections are done, one after arrival and one before departure, to make sure there are problems with the aircraft which could make it dangerous to fly with. This is done by walking around the aircraft and looking for discrepancies.

3.5. Interaction points

Almost all turnaround operations are executed at specific points around the aircraft, the GPU is attached at the GPU attachment point, and the wheel chocks are placed at the Nose Landing Gear (NLG) and Main Landing Gear (MLG) for example. In this thesis, these points are specified as ‘interaction points’, the points where the specific turnaround operations are carried out. These points can now also be used to differentiate between ‘going to interaction points’ and ‘positioning at interaction points’, which is already done in the current operation. For example, the belt loader is first driven towards the cargo door of the aircraft, after which it needs to position itself straight in front of the cargo door, to be able to move towards it in a straight line. This is done to create an uncomplicated way of moving towards the cargo door, to prevent damage as much as possible. These interaction points are located on the aircraft stand, based on the position of the incoming aircraft.

3.6. Verification

Verification of the actions performed during turnaround operations is crucial to ensure that the aircraft is handled both safely and efficiently. As described in the GPU procedure, illustrated in Figure 7, the receptacles, leads and plugs should be checked before attaching the cable. Similar things should also be checked when attaching the water or waste hose for example. Another example of verification in the current procedure is that the pushback driver will also verify whether the cabin access doors have been closed correctly by the cabin crew, before proceeding with the pushback procedures of the aircraft. Assuming that the verification of these steps is something that should still be done by human operators, autonomous agents should be designed to cater for this verification while they are performing their tasks.

3.7. Aircraft type and position

The autonomous agents that will be present on the aircraft stand after they have been implemented into the turnaround operations, should be able to adapt to different types of incoming aircraft and work on different aircraft stands. Each turnaround the type of the arriving aircraft could be different, this means that the layout of the aircraft stand changes as well because the attachment points and cargo doors are at different places. However, the centreline of the aircraft stand indicates where each aircraft type stops, to make sure that at least the interaction points approximately stay the same per aircraft type. A simplification of these markings is shown in Figure 8. To ensure that the aircraft stops at the same position each time, the VDGS (Visual Docking and Guidance System), shown in Figure 9, guides the pilots, indicating which direction to go and how far. The VDGS at Schiphol uses radar technology to sense where the aircraft is, to be able to guide it to the right spot. Although the aircraft position and orientation are relatively the same each time, it is almost impossible to position the aircraft exactly at the same spot each turnaround. This changing orientation, position and type of aircraft on the aircraft stand could have implications for the autonomous agents to localize themselves on the aircraft stand, because some localization methods make use of reference points, and this way, these reference points keep changing.

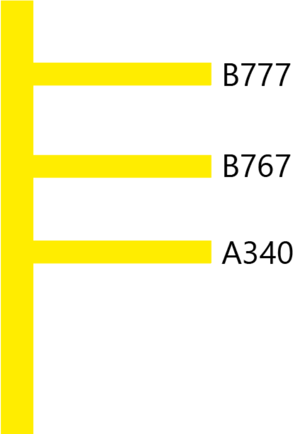


Figure 8: Illustration of the centreline markings for the aircraft on the aircraft stand

Figure 9: Picture of a VDGS, *from [8]*

3.8. Task division

The current task division for the turnaround activities is examined to gain an understanding of what kind of team the autonomous agents will be part of in the future. The size of the teams that handle a turnaround depends on the size of the aircraft. For most European (EUR) and some intercontinental (ICA) destinations, narrowbody (single-aisle) aircraft are used like the Boeing B737-900. For other ICA destinations, the larger wide-body aircraft (double-aisle) are used like the Boeing 787-10. Narrowbody aircraft turnarounds require 2-3 Team Members (TM) and 1 Team Coordinator (TC), while for the wide-body aircraft, this is 4-6 TM and 1 TC. The TM are responsible for the placement of the wheel chocks and cones, attachment of the GPU and the baggage handling. Figure 10 shows the task division during the arrival service of a wide-body aircraft.

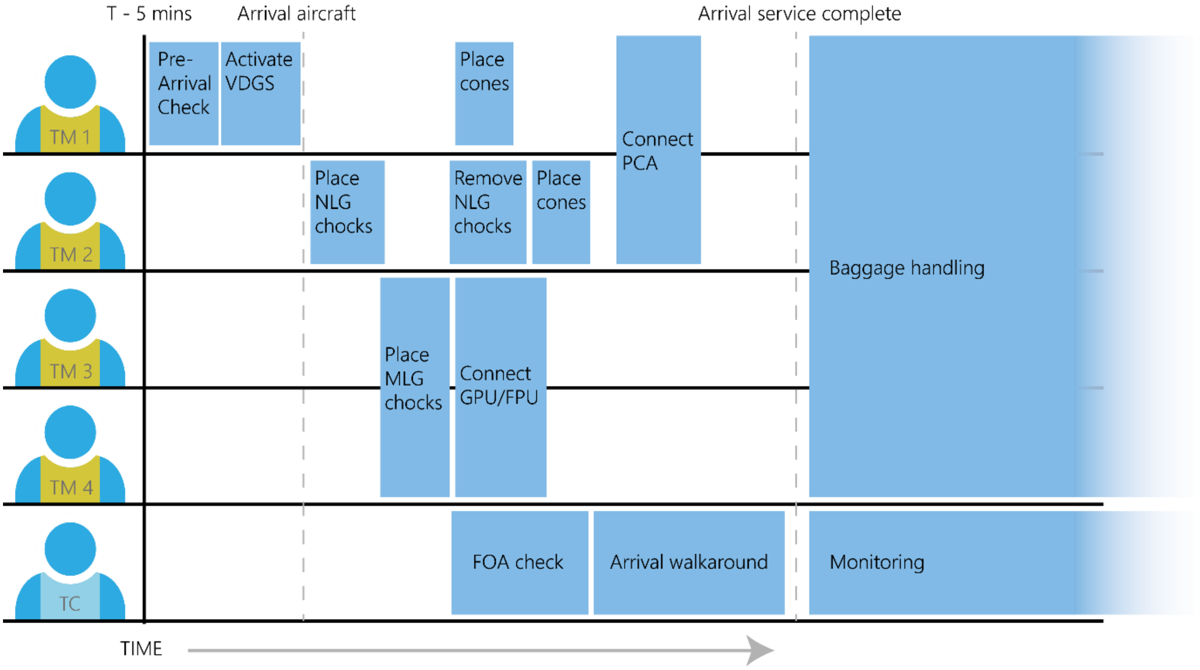


Figure 10: Schematic overview of the task division during the arrival service of a wide-body aircraft

It shows how before baggage handling every TM has distinct tasks, after which they all work together in the baggage handling. For the other tasks, like refuelling or water service, other, external ground personnel is used. Most of these ‘external’ tasks are done individually, for example, the water service personnel comes in with the water service truck, replenishes the water tanks, and leaves without much interaction towards the other ground personnel on the aircraft stand. The TC checks if these tasks are done correctly and tracks the progress of the turnaround operation. As well as keeping track of additional information, like safety conditions for the ground personnel, sometimes for multiple flights at the same time. The arrival walkaround is also done by the TC. The TC also has a tablet on hand to keep track of this information in real time. It is important to keep in mind what tasks need to be performed by multiple people and which do not, because this can influence how much and how the autonomous agent needs to work together with the ground personnel.

3.9. Communication

The current means of communication between the ground personnel are analysed to understand what could be applied for the communication between the ground personnel and the autonomous agents. This communication is important, as will be explained in Section 6.

Communication between ground personnel is mostly visual, since the noise on the aircraft stand requires them to wear ear protection, especially when the aircraft arrives or leaves. Some tasks also require communication between the ground personnel and the cockpit, this is done with hand signals, to for example indicate if the wheel chocks have been placed. During the pushback of the aircraft, the pushback driver communicates verbally with the cockpit using a headset to ensure that both parties are aligned in their actions.

To identify what kind of information is communicated between ground personnel and eventually between autonomous agents as well, an information requirements analysis will be conducted in the following section.

4. Information requirements analysis

It is expected that in the future, there will be more than 1 autonomous agent active on the aircraft stand, for example with the plan from KLM and Schiphol, to perform autonomous docking of arriving aircraft, as mentioned in Section 2.1. The autonomous agents that will perform these tasks, will all require or produce different kinds of information. For instance, it could need information regarding the task it needs to perform and produce information derived from its onboard sensors. This analysis is meant to map this information, to look at what information is required and produced per task of the turnaround operation and at what step in the process. This information subsequently allows for the identification of similarities between the information requirements and production per agent. These similarities lay the foundation of the framework that will be explained in Section 7, which will aid in the fulfilment of the information requirements for autonomous agents.

The aforementioned map of produced and required information per step of the turnaround operation can be found in Appendix A. It should be noted that for the creation of this information map, no distinction was made between which task is done manually and which task is done autonomously, since this information is required in both cases. For instance, both the human operator and the autonomous agent require knowledge of the aircraft's location to interact with it. However, the human operator can quickly determine the aircraft's position simply by looking at it.

Figure 11 shows a generalized version of what information each subsystem can produce and what information it needs during the turnaround operations.

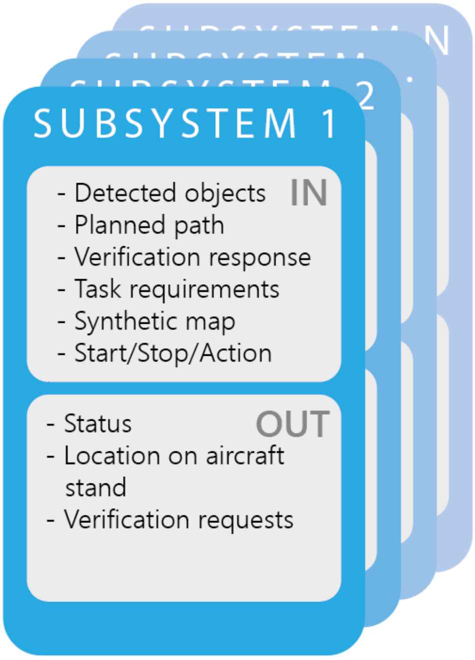


Figure 11: Generalized overview of the required (IN) and produced (OUT) information per subsystem

The generalized overview from Figure 11 indicates that the location of other subsystems is not required for the subsystems to be available at all times. For example, for the refuelling activity, the knowledge about where the cargo loading is being done is not required, except for obstacle avoidance. However, the location of the aircraft is important, since its location is required for the subsystems to interact with it to perform their specific tasks at the interaction points.

As explained in Section 3.5, these interaction points are based on the location of the aircraft, and because the aircraft is a static component during the turnaround operations, the localization could be based on the location of the aircraft on the aircraft stand.

For path planning, it might be beneficial to know the locations of each subsystem, to avoid congestio by planning the paths accordingly. Verification of each task is also important, for the subsystems to know whether they are performing the task correctly and if the ground personnel has to intervene.

The following section will explore different localization technologies and methods, and determine which methods can be used to cater for these information requirements.

5. Localization

For autonomous agents to localize themselves, a broad range of technologies and subsequent methods are available. The following section will explain what these technologies and methods entail, and if and how they could be employed in the context of an aircraft stand. As mentioned before, the localization of the autonomous agent can be split up into two parts: the localization in between the interaction points, and the localization at the interaction points. The latter of which needs to be more accurate and the agent needs to be able to recognize the objects/features, like wheel chocks or hatches, which it needs to interact with as well. Because it is expected that more than one autonomous agent will be present on the aircraft stand in the future, multiple robot localization is researched as well, to look at what best practices should be taken into account. As explained in Section 4, the autonomous agents do not always need to know where the other agents are on the aircraft stand, but for path planning to avoid congestion, an approximate location should be available.

5.1. Key takeaways from the context

From the context of the aircraft stand, the following key takeaways are taken into account that could influence the localization method and/or technology. These takeaways each come back later in this section to explain why certain localization technologies or methods can or cannot be used.

5.1.1. ‘Semi-controlled’ environment

Since an aircraft stand is structured and the GSE are all moving towards approximately the same interaction points each time, the environment is quite predictable. As well as there being strict safety precautions in place on the aircraft stand to protect the ground personnel. However, the GSE can also be in the way of one another and this could create congestions, which makes the aircraft stand chaotic. The GSE are also constantly moving around, creating a dynamic environment. On top of this, because the aircraft stand is located outdoors, the weather can also have an influence, for example, rainfall, fog or different lighting conditions during day and night. This is why for this thesis, the environment of the aircraft stand will be called ‘semi-controlled’.

5.1.2. Aircraft

As mentioned in Section 3.2, the aircraft will be a static component on the aircraft stand during the turnaround operations, this could be beneficial to base localization on. But the aircraft also brings some challenges. Some interaction points are located underneath or near the aircraft, which could break the line of sight and may cause problems for some localization technologies. When the aircraft engines are still spooling down, an ‘invisible’ keep-out zone should also be taken into account, to prevent agents from being damaged by the engines.

5.1.3. Interaction types

The turnaround operations all interact with the aircraft in different ways, as mentioned in the functional analysis, these interaction methods can be divided into 3 types: placement, interactive, and inspection. Each of these methods could need its type of localization method.

5.2. Localization technologies

This next section explains the main types of localization technologies that are used, how they can be used and if they can be used in the context of an aircraft stand for autonomous operations. These localization technologies are divided into three types: external, exteroceptive and proprioceptive technologies. The technologies are compared based on their approximate accuracies according to the literature, as well as their limitations and strengths when applied to the context of the aircraft stand. The results will inform the decision of which localization technologies are best suited for use by autonomous agents during the turnaround operations.

5.2.1. External sensors

External localization technologies use external sensors to locate a system, which gives the absolute position of the system in a reference frame. The Global Navigation Satellite System (GNSS) is the most popular example of this. It uses signals from satellites to triangulate the position of the receiver and has an accuracy of around 2 meters, which can be improved to a few centimetres by adding an extra receiver to a fixed position for reference. Since the receiver requires a direct line of sight with the transmitting satellites to work best, accuracy would degrade if the sensor goes under the aircraft body or wings for example [9].

Besides using satellites for external localization, it is also possible to use transmitters or beacons that are in closer proximity to the receiver. A grid of RFID (radio-frequency identification) tags could be placed on the ground to localize the system based on that. According to [10], this would give an accuracy of around 0.02 meters, but it would require a dense grid of RFID tags because the tags need to be close to the sensor to be detected.

Another option would be to install UWB (Ultra-wideband) beacons around the aircraft stand. Using the ‘time distance of arrival’ method, [11] managed to achieve an accuracy of 0.15 meters, or using sensor fusion with a lidar sensor as mentioned in [12], to achieve a better accuracy of around 0.08 meters. WiFi or Bluetooth could also be used similarly, but the accuracies would be worse. All of these methods also require line-of-sight with the beacons or transmitters to work best, just like with the GNSS. Since the aircraft stand is a dynamically changing environment with many possible obstacles, a great number of beacons would need to be installed for the system to continuously perform as expected. These technologies, except for the GNSS, also require the aircraft stand to be altered in some way, either by adding UWB beacons, or installing RFID tags.

5.2.2. Exteroceptive sensors

Sensors on a robotic system that acquire data from the environment of the system are exteroceptive, and the two main types that are used for localization, are ranging-based and vision-based sensors. These sensors, on their own, can only be used to detect the relative position of the surroundings of the sensor.

A popular ranging-based sensor used for localization is the lidar scanner. This sensor emits and detects light and measures the TOF (time-of-flight) between emission and detection to determine the distance to the reflected surface. The lidar sensors used for localization are often spinning 360 degrees to be able to detect objects all around the sensor in 1 plane. Some of these sensors also tilt up and down to be able to detect objects in multiple planes, which are 3D lidar sensors.

The resolution of such a sensor can be around 0.0013 meters [13], but with just the ranging data no location is found. [13] Used SLAM (Simultaneous Localization and Mapping) and sensor fusion with an IMU (Inertial Measurement Unit) to get the absolute position of the sensor in GNSS-denied urban environments, with an accuracy of 0.01 meters. [14] Also managed to achieve 0.01 meters of accuracy but without sensor fusion. There are some downsides to lidar sensors, according to [15], if there are too few features to detect, is harder to perform SLAM, because scan matching is more difficult with fewer features. Possible weather conditions on an aircraft stand, such as rain or fog can also interfere with lidar readings because the light rays from the sensor can bounce off the water droplets [15].

Cameras are exteroceptive sensors that can be used for localization as well. The difference between the frames captured by the camera can be used for visual odometry (VO), where the motion and orientation of the camera are calculated. [16] Used a camera in combination with an IMU, to perform visual inertial odometry, using the IMU to counteract the unreliability of the visual data, which resulted in centimetre level accuracy. In [17], they included a lidar sensor as well, to further reduce the information completeness deficiency and increase the localization accuracy, specifically for complex dynamic environments. Visual SLAM can also be performed using cameras, the process can be compared to visual odometry, but loop closure detection is used as well, decreasing the localization drift [18].

Compared to lidar sensors, cameras are relatively cheap, but it is more difficult to extract depth from the images and an external light source is needed for consistent imaging. Changes in light intensity could also negatively influence the accuracy, for example when going under the fuselage of an aircraft. Lidar sensors are superior for depth measurement, but using them, it is more difficult to recognize features than from camera images. According to [18], lidar sensors are better suited for performing SLAM in larger open and dynamic environments, because visual SLAM can be too inaccurate for this, possibly making it a better candidate for use on an aircraft stand.

5.2.3. Proprioceptive technologies

Proprioceptive technologies are sensors that measure the internal state of a system. The rotation of the wheels can be measured using motor encoders for example. This can be used to calculate the travel and rotation of the entire system, giving the position of the system relative to its starting point. However, wheel slippage and other errors can accumulate and will cause drift over time.

An IMU can be used to calculate the travel and rotation of the system relative to its starting point as well, also suffering from the same error accumulation, although it is not influenced by wheel slippage. To reduce this error accumulation, [19] fused the IMU data with a predicted path, achieving a 1 to 5-meter accuracy. Adding more degrees of freedom that the IMU can measure, also increases the accuracy of the localization [20].

These kinds of technologies are cheap and in some cases already integrated into other components. An Intel RealSense already has an IMU built into it, or the ODrive Pro motor controllers provide built-in encoders to perform wheel odometry. This is also the reason why these are often used in combination with exteroceptive sensors, since they provide added accuracy and redundancy, for no significant additional investment.

5.3. Synthetic map-based localization

As mentioned before, the pose and type of the aircraft on the aircraft stand differs each turnaround. For map-based localization to work, the aircraft stand would have to be mapped each time after an aircraft has arrived, which is not ideal. Using SLAM, this problem is averted, but in that case, the map has to be created in real-time, and the absolute position of the agents in the reference frame of the aircraft stand will be unknown for the start of the operations because no complete map has been created yet.

Synthetic maps are maps created from synthetic data, and can also be used by the autonomous agents for localization. This means that instead of having to map the aircraft stand manually after an aircraft has arrived, the map can be synthetically created by using the aircraft type, from the flight data, and aircraft pose, from the VDGS. The VDGS system is suited for this purpose, because of its fixed position relative to the aircraft stand, which means that when it measures the location of the aircraft, this location is known within the reference frame of the aircraft stand.

In recent years, synthetic map-based localization has been done in multiple contexts. [21] Used, sometimes incorrect, 3D models of famous buildings from the internet, to do visual localization using a camera that is pointing towards the specific building. In [22], [23] and [24] they used synthetic maps made using ‘building information model’ data for localization inside of buildings, either using 2D or 3D lidar scanners. Using 2D lidars for synthetic map-based localization, with multiple systems to localize, means that either the 2D lidar should mounted on the same height as each system, or that the synthetic map should be tailored to each system. These papers also mentioned the possible big difference between the as-designed and as-built, but they showed that localization was still possible. It was shown in [25], that it is possible to localize using a synthetic map, even though significant changes were made to the environment. In the context of an aircraft stand, this type of localization has already been tested, in [26] and [27], they used a 3D model of an aircraft and a 3D lidar to localize a de-icing truck around the actual aircraft. Caselitz et al. [28] showed that it is possible to localize a system using a monocular camera, against a 3D lidar map, indicating that it is not necessary to use the same type of map for a specific type of sensor.

5.4. Multiple robot localization and path planning

The localization of multiple robots in a single reference frame can be done in different ways. One of the main considerations for multiple robot localization is between having a central system do all the calculations to for example perform SLAM with, or have each robot perform these calculations itself. Sasaoka et. al. [29], argue that it is better to distribute these calculations over the different systems, making more use of the capacities of all the systems. In this method, each system independently calculates its location, which is then transmitted to a central system. The central system subsequently updates a global map with the locations of all systems.

Another reason for using the decentralized approach is because of the dependency on a connection between the central system and the autonomous agents on the aircraft stand. If the connection were severed, the individual agents would have no way of localizing themselves on the aircraft stand when using the centralized approach. This is also something that came forth from tests using a smaller robot, when the internet connection was severed between the host and the robot, the robot stopped moving altogether. This is not desired when such a system is implemented on an aircraft stand, where it can also be in the way of other systems or GSE, possibly creating dangerous situations.

As well as possibly creating congestions on the aircraft stand, which would negatively impact the performance of the turnaround operations. For path planning, a central system remains necessary, as outlined in Section 4.

In this case, the central system generates paths for the autonomous agents to follow independently after they receive the path, even if the connection is lost. This also implies that if the connection were to be severed before any paths have been sent out, the autonomous agents would not receive a path. This would require these agents to have means of independently returning to their starting point.

5.5. Object localization

As explained in the analysis of the turnaround operations, most operations have some interaction with either the aircraft, like the ground power hatches, or the objects that need to be placed around the aircraft, like the wheel chocks or cones. To be able to do this, the subsystems eventually responsible for these interactions should be able to recognize and locate these hatches or objects.

This section explains the main methods of object localization that are currently available, which could be used in the context of an aircraft stand.

By object localization, it is meant that after the object is recognized, the pose of the object is also known, not just being able to tell a cone from a wheel chock for example, but also being able to tell where this cone is and what its orientation is, relative to the sensor. The methods of doing object localization can be divided into two main categories: marker-based and markerless.

5.5.1. Marker-based object localization

Marker-based object localization works by using fiducial markers that are added to a known location near or on the object to be recognized. Once this marker is recognized, the location and orientation of the object can be determined because the location of the marker with respect to the object is known beforehand. In [30], they achieved a 0.47 cm average error within 80cm distance of the markers to be detected. Using more and bigger markers improved the results. The use of a stereo camera and a deep neural network for the interpretation of the video, [31] achieved accuracies with less than 1 mm error. Markers that are made specifically to be used for the docking of automated GSE to aircraft have already been explored by Alonso in [32], see Figure 12.

Figure 12: Illustration of the markers that are made specifically for GSE docking, adapted from [32]

5.5.2. Markerless object localization

It is not always possible to attach something to the objects that need to be recognized, in which case you can use markerless object recognition and localization. This can be done quite accurately, as done in [33], where the pose of objects like a bowl or laptop could be estimated with an error of around 0.1 cm, using a 3D camera. Nvidia also created software for pose estimation of household objects, specifically for the manipulation of these objects by a robotic gripper and showed that the accuracy for this was sufficient [34]. Figure 13 shows the objects being recognized, localized, and manipulated by the gripper. However, the computational burden and costs of markerless object recognition and localization are significantly higher than that of marker-based object localization. In [31] they state that marker-based object localization is often more accurate than markerless object localization.

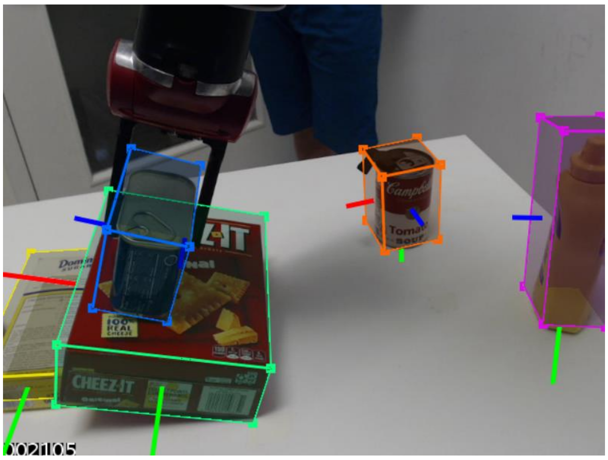


Figure 13: Example of markerless pose estimation being used to manipulate the detected objects using a gripper, from [34]

5.6. Conclusions

The localization technology and method that should be used for autonomous agents on an aircraft stand, depends on the required accuracy and the interaction method.

For each interaction method, a camera sensor is needed, either for inspection, verification or the recognition of hatches or wheels for example. Since the required accuracy for the different possible autonomous agents is not yet clear, as well as the performance of each localization technology in the context of the aircraft stand, tests should be done on whether or not additional sensors like lidars are necessary. It can be deduced from Section 5.2 that the addition of these sensors should increase the accuracy by using sensor fusion, as well as adding redundancy and making the localization more robust. The use of external sensors is not recommended, since it would require additions or modifications to the aircraft stands.

Synthetic map-based localization seems to be the best option for localizing the autonomous agents in the reference frame on the aircraft stand. These maps should be created using the pose and type of the arriving aircraft. It is however not clear from literature whether synthetic map-based localization using a camera sensor is sufficiently accurate for use on the aircraft stand by autonomous agents. Synthetic map-based localization would also enable the possibility of including the ‘invisible’ keep-out zones, to prevent the autonomous agents from moving into the engine intake areas for example.

A central system is necessary for path planning, but each autonomous agent should localize themselves on the aircraft stand, to create a more robust system where the agents can still localize themselves, even when the connection to the central system is severed. However, severing the connection to the central system would still mean that the paths cannot be sent to the individual agents. To solve this, the autonomous agents should be able to recognize when this connection is severed, to then either finish their tasks or return to their starting position.

To be able to recognize and interact with objects or features on and around the aircraft, marker-based pose estimation should be used. This method is currently more accurate, especially for the recognition of the hatches that are flush with the fuselage of the aircraft, which are harder to spot using markerless pose estimation because of the lack of features.

The following information is still necessary to be able to provide best practices for the localization of autonomous agents on the aircraft stand:

Accuracies:

It is not yet clear what accuracies are necessary for the autonomous agents on the aircraft stand. It is assumed that for the positioning at the interaction points, the accuracy needs to be higher than in between interaction points, but no hard requirements are known. These accuracies will depend on the task that the autonomous agent should be able to do. For example, the accuracy of the cone placement would not need to be as high as the positioning of the belt loader in front of the cargo doors. The cones do not have to be placed at the exact same place every time, but the belt loader needs to be in a straight line in front of the cargo doors.

Sensor types:

Because the concrete accuracies are not known, it is also not clear what sensor types are required for each interaction method or in between/at interaction points. Future tests using different types of sensors to localize autonomous agents on an aircraft stand using synthetic map-based localization should be executed to determine which sensor combination is best suited for these agents.

Besides the ability to localize themselves on the aircraft stand, the autonomous agents should also be able to correctly interact and work together with the ground personnel, and vice versa. The factors that influence the ability to correctly do so are explored in the next section.

6. Human interaction

The turnaround operations will not become 100% autonomous overnight, changes in the operations will most likely be gradual, shifting the balance to autonomy slightly. This means that the ground personnel during this time, have to work together with the autonomous agents and vice versa. As explained in Section 2.3, this interaction is not always beneficial for the performance and the amount of workload associated with a task. The following section will go over how to identify these points and design these interactions in such a way that it does not increase the workload of the turnaround operations.

6.1. Human Autonomy Teaming

Because the autonomous agents and ground personnel have to work together in a team, one of the focus points of this thesis will be on human autonomy teams and how to implement them. According to O'Neill et. al. [35], a human autonomy team (HAT) is specified as a team where "*Each human and autonomous agent is recognized as a unique team member occupying a distinct role on the team, and in which the members strive to achieve a common goal as a collective*". In [36] they specified further, that for the team to constitute as a HAT, the following criteria have to be met:

1. The team has to consist of at least 1 autonomous agent and 1 human team member.
2. The agent automation level [37] should be equal to or greater than 5.
3. The role of the agent should be interdependent with the rest of the team.

The goal of the AO project is to implement autonomous agents into the turnaround operations, which have the common goal of a successful aircraft turnaround, while also depending on each task to be completed to be successful. According to the autonomy scale from KLM, the autonomous agents will be at least 'semi-autonomous', which translates to automation level 5-7 from [37]. This means that the future teams containing autonomous agents for turnaround operations can constitute as a HAT.

6.2. Interdependence and reliability

Interdependence is an important aspect of HATs because it positively impacts the performance of them. This is because, with more interdependence, the human teammates see the autonomous agents as more similar to themselves, cooperate more and are more open to change [36]. In [38], they also argue that this has a positive effect, because of the increase in shared responsibility to finish the task. The reliability of the autonomous agent also plays an important role in HAT, since a lower reliability is often associated with lower trust and performance from the human operators [35]. Information about why the reliability is lower seemed to increase this trust and performance again [35], meaning that the information transfer or transparency between the ground personnel and autonomous agents is an important aspect as well.

6.3. Situation awareness

People who perform tasks in a dynamic environment, like an aircraft stand, need to have sufficient situational awareness (SA) to be able to make informed and quick decisions about their actions. SA is defined by Endsley as: *“The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.”* [39]. In [40] she created a model of SA, dividing it up into three different levels:

- **Level 1 SA: Perception of the elements in the environment**
  This could be the location of GSE around you on the aircraft stand, or what the weather conditions are at that moment.
- **Level 2 SA: Comprehension of the current situation**
  This is an understanding of what the elements around you mean to you. For example, are the GSE around you on the aircraft stand obstacles? Or is the wind so strong, that it requires changes in the turnaround operations?
- **Level 3 SA: Projection of future states**
  This means that you understand how the situation can change in the future, and how these future states can have an influence on your actions. For example, you know that in 5 minutes the catering truck arrives on the aircraft stand, so some room needs to be made around its interaction point.

For people to perform their tasks properly, all levels of SA need to be achieved. In [41] it was shown that SA is predictive of human performance, which means that it is important to keep the SA of the team members in the turnaround operations at the same level when autonomous agents are added. SA can also be viewed from a team perspective, where each team member needs to have the SA required to do their tasks. If this is not the case, the information required for this SA needs to be transferred between the team members. The addition of autonomous agents can reduce SA if the ground personnel is ill-informed about what these agents can and will do. If the role of the team members is reduced to monitoring, instead of active participation, the SA will also be reduced, because the human operator becomes more ‘out-of-the-loop’ [42].

6.4. Transparency

To cater for the team SA in HATs, Chen et. al. [43] created a transparency model based on the SA model from Endsley, indicating different levels of transparency (Situation Awareness based Transparency: SAT) the autonomous agent can provide.

- SAT Level 1: What is the agent doing?
- SAT Level 2: Why is the agent doing this?
- SAT Level 3: What is the probability of success for the future actions of the agent?

Contrary to the SA levels, not every transparency level is always necessary for the team to gain sufficient SA. These levels of transparency are only a means to an end to achieve the right level of SA. In [44], they found that increasing the level of transparency, also increased SA on all levels, but this does not mean that this is always better. According to [35], too much transparency could also increase complacency, increasing the risk of something being overlooked. [45] Also noted that increased transparency can lead to increased decision latency and mental workload due to the larger amount of information presented to the human operator.

Increasing SAT is therefore not always necessary or the best option. It is more important to know the right amount of transparency for the right ground personnel. For example, someone who is refuelling the aircraft might need less information about an autonomous wheel chocking robot, than somebody who has to check if the wheel chocks are placed correctly.

To achieve different SAT levels, in [46] they showed that user displays can be a suitable tool for this and that a good display can reduce the cognitive workload of the human team members working with autonomous agents. In the context of turnaround operations, this is not always possible, because some tasks, like refuelling, could require too much attention from the ground personnel to also be able to look at and interpret displays regarding other tasks of the turnaround operation. Other communication modalities for conveying the right amount of transparency should be used in these cases, such as coloured lights or simple signals on the agent itself. Unfortunately, research on the use and effects of these other modalities is still lacking, [46, 47].

For better transparency, the information from the agents should be 'pushed' to the ground personnel, instead of needing to ask for information [35]. However, this should not be done in excess, to prevent information overload for the human operators [48]. If in some cases it seems better not to push specific information, it should be easily available, and not behind complex drop-down menu structures for example.

It is also important to communicate the agent's situational model, which is the way the agent perceives the world around it, this makes it more straightforward for the human operator to be able to find mistakes in the reasoning and actions of the agent [42]. But this also means that the human operator should be able to correct these mistakes, making the communication essentially go both ways.

6.5. SA Oriented Design

From the former sections it can be concluded that for good performance in HATs, the right amount of SA for the ground personnel is critical. This section will explain a method of how to include SA in the design process of autonomous systems for HATs.

Endsley [42], introduced a design method for creating interactions that cater for SA, called Situation Awareness Oriented Design (SAOD). It is meant to be integrated into the development of autonomous systems and consists of the following three steps:

6.5.1. SA requirements analysis

This analysis is meant to find the information that is required to make certain decisions to complete specific tasks. It is done using Goal-directed task analysis (GDTA) [49], where the goal of the task is split up into subgoals, each requiring different pieces of information to be able to make the decisions for these subgoals. Figure 14 illustrates how these decisions are built up with the different levels of SA.

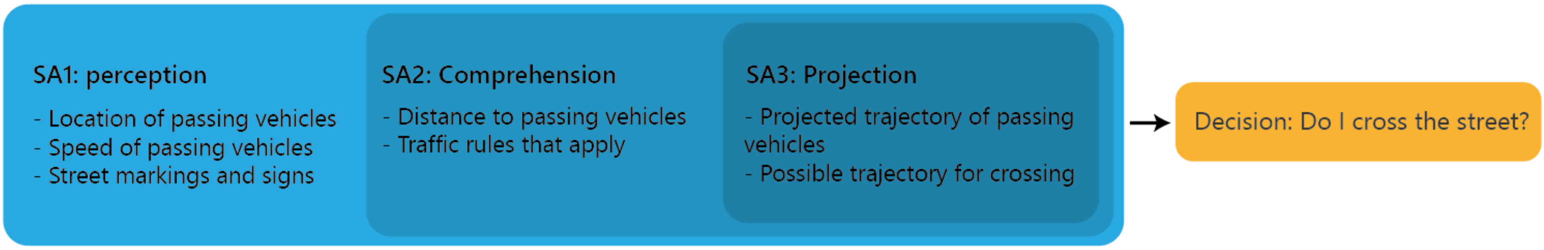


Figure 14: Illustration of how each SA level builds to a decision

6.5.2. SA design

The SA requirements form the basis of the design of the interfaces that should cater for the SA of the human operators. During the SA design part of SAOD, interfaces should be designed according to these requirements and the 50 SAOD design principles from [50], which indicate guidelines for these designs.

6.5.3. SA Evaluation

According to Endsley [42], the Situation Awareness Global Assessment Technique (SAGAT) should be used to assess how well the interfaces that were designed in the SA design step, cater for SA. Salmon et. al. [51] also found SAGAT to be best suited to measure SA.

The SAGAT tests are done in realistic scenarios with the human operator and autonomous agent. These scenarios are frozen at specific points during the operation, during which the operators are probed with questions regarding their SA at that moment. For example: ‘What is Agent X doing at this moment?’ or ‘Does the position of Agent X pose any difficulties for the next task?’. This results in knowledge about which SA requirements are fulfilled and which are not and should be used in the next iteration of SA design.

Although SAOD is not tested in the context of turnaround operations specifically, it is created and tested specifically for complex domains to increase SA [42]. However, it should be noted that the interfaces that are currently designed and tested using SAOD consist mostly of conventional touchscreen interfaces. Interaction with these interfaces happens within controlled environments, which is not the case for turnaround operations, where the autonomous agents could be somewhere else on the aircraft stand. This means that an additional step to evaluate the type of interactions and the influence of the environment on these interactions should be conducted to better inform the creation of the SA requirements.

Section 8 will go into more detail on how the steps from SAOD should be used for this context.

6.6. Explainability

A part of transparency and HAT in general, is being able to explain why the autonomous agent is behaving in a certain way, or ‘explainability’. The explainability of a system can increase trust in a system and is one of the key aspects of good HAT according to experts [42, 52]. Explainability can also solve the problem of mode confusion, where the human operators are not sure about how the agent will react in a specific situation [53].

One of the methods that is hypothesized to improve the explainability of a system, is the use of behaviour trees, according to [54, 55]. Behaviour trees provide an overview of the high-level tasks that the autonomous agent has to perform. They dictate the behaviour of a system by splitting it up into different nodes, each representing a different task or action. The hierarchy of the tree then determines which task or action is done at a specific moment [56, 57]. By familiarizing the ground personnel with the behaviour trees of the autonomous agents, the actions of the agents could be more explainable. This familiarization could be implemented into the training program that will teach the ground personnel how to work together with the autonomous agents. The next section will explain why training is important for the implementation of autonomous agents.

6.7. Training

As explained in Section 2.3, the skills of the ground personnel working with the autonomous agents also have to change to be able to successfully implement autonomous agents into the turnaround operations. According to [58], knowledge about the task that is taken over by autonomous agents is required to be able to verify whether these agents are working correctly. However, it is also necessary to know how the autonomous agents work and why they will do certain things in addition to knowledge about the task that is taken over. Knowledge about the inner workings of the autonomous agents could come from the aforementioned behaviour trees and the transparency between the autonomous agents and human operators. But training also plays an important role in this, especially by training in realistic scenarios with the autonomous agents. This will build prototypical situations in memory, which can be used to base future decisions on, when performing the actual turnaround operations, improving the SA of the ground personnel [40]

6.8. Conclusions

When implementing autonomous agents in turnaround operations, it is important to maintain the SA level of the ground personnel at the same level as before. The right amount of SAT between the autonomous agent and the ground personnel can enable this, by keeping the ground personnel in the loop of the actions, reasoning and fault/success probabilities of the autonomous agents. Interdependence also plays a role in good HAT, since it positively impacts the team performance when increased.

It is expected that an increased amount of interdependence between the autonomous agent and ground personnel would also require more transparency between them because more coordination is required, which in turn demands more SA. The specific amount of transparency required for different levels of interdependency is not yet clear from the literature.

To aid with the design of the interfaces and interactions between the ground personnel and autonomous agents, SAOD can be used to optimize the design for SA. To support the GDTA for the SA requirements, an interaction analysis should be done, looking at the possible encounters and interactions between ground personnel and autonomous agents. As well as looking into what environmental factors can influence these encounters. Section 8.2. will elaborate more on this analysis.

Ground personnel working with the autonomous agents should be knowledgeable of the task that is taken over by the agents, as well as about the inner workings of these agents, which means that more knowledge is required than in the current operation. The explainability of the autonomous agents could positively influence this, which is why behaviour trees should be used for the development and implementation of the behaviour of the autonomous agents. Training will also be an important factor in increasing this knowledge and assuring that the SA of the ground personnel does not decrease because of the implementation of autonomous agents.

The following knowledge gaps were identified, that should be covered in the future to successfully design and implement autonomous agents for turnaround operations.

Implementing transparency on an aircraft stand

As stated in Section 6.4, the effectiveness of communication modalities other than text in enhancing transparency between autonomous agents and ground personnel has not yet been confirmed. The outcomes of the SA evaluation using SAGAT will determine whether or not these other modalities are effective, in the context of an aircraft stand.

Increased explainability through behaviour trees

The positive effect of behaviour trees on the explainability of a system is not yet confirmed by literature. This should be confirmed to definitively say that they should be used for the development of autonomous agents and the training of ground personnel.

7. Framework

In this section, the framework that will be the backbone for the autonomous agents on the aircraft stand will be laid out. It could be used to add the autonomous agents to in the future and build up the system that will enable the autonomous agents and ground personnel to share information and control between them. The information requirements analysis and the localization research from Sections 4 and 5 primarily determined the layout of the framework.

As discussed in Section 4, for path planning, a central system that collects and uses the locations of the agents and the aircraft is required to prevent congestion on the aircraft stand. For the agents themselves, the generalized overview from the information requirements analysis informed what information they require and generate. This, along with the information requirements from the ground personnel, determined the layout of the framework, which will be explained in more detail below. This framework is shown in Figure 15.

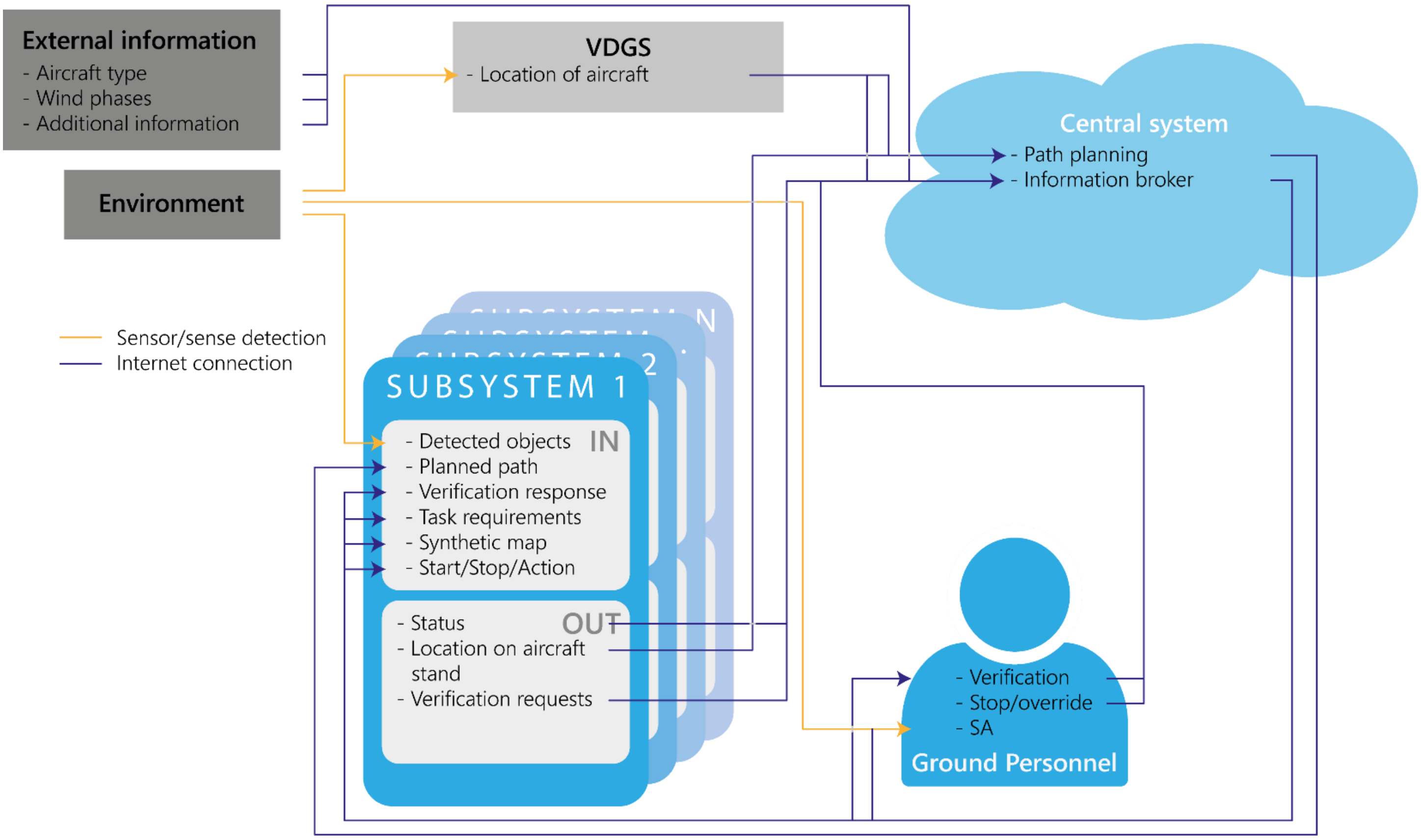


Figure 15: Schematic overview of the framework, showing the directions in which the information flows between the different parts.

7.1. Example scenario

To illustrate the flow of information, a scenario is described in this section, explaining the possible flow of information during the start of a turnaround.

1. An aircraft arrives at the aircraft stand.
2. The VDGS determines the position of the aircraft after it has stopped moving.
3. The central system uses the aircraft location it got from the VDGS and the aircraft type from external sources, to create a synthetic map of the aircraft stand.
4. The synthetic map is available for the subsystems for localization through the information broker.
5. The subsystems localize themselves and send their location to the information broker.
6. The central system determines the paths for the subsystems towards their respective interaction points, avoiding possible congestions.
7. The subsystems move to their specific interaction points while avoiding obstacles, using onboard sensors to detect objects or obstacles in their immediate environment.
8. After the autonomous agents finish their tasks, they send out a verification request to the information broker, which can be accepted or declined by the ground personnel.
9. The ground personnel that is still present could intervene when something goes wrong, sending a stop signal through the information broker, or remotely controlling the autonomous agents.

7.2. Subsystems

As illustrated in Figure 15, the subsystems generate information in the form of their: current status, current location on the aircraft stand, and verification requests. The types of information they require are: detected obstacles, planned paths, verification, task requirements, the synthetic map and start/stop/action commands for remote control of the autonomous agents. Note that this is different from the information requirements as outlined in Section 4, where the ‘location of the aircraft’ was noted instead of ‘synthetic map’. This change is because the subsystems now do not include the ground personnel anymore.

The autonomous agents can detect the objects or obstacles themselves in the environment using onboard sensors, but the other pieces of information come from the central system through the information broker. The subsystems use the synthetic map to localize themselves in the reference frame of the aircraft stand, and subsequently send their location to the information broker.

It should be noted that the subsystems in the framework do not only mean autonomous agents but could also be other, non-autonomous, GSE that also send out their location to the central system, which could also be used for path planning.

7.3. Ground personnel

The information that the ground personnel requires from the autonomous agents, is used to cater for the right amount of transparency between them, improving their SA, as explained in Section 6.4. The ground personnel also receives verification requests from the autonomous agents through the information broker and sends them back through the broker as well. In case of an emergency, or when the autonomous agents act faulty, the ground personnel should also be able to stop and/or override the autonomous agent. This connection also goes through the information broker.

7.4. VDGS

As explained in Section 5.3, the location of the aircraft should be determined by a system with a fixed position relative to the aircraft stand. Ideally, this should be done by the VDGS system that is already present on most aircraft stands on Schiphol. The VDGS will then send the location of the aircraft to the central system, which creates a synthetic map of the aircraft stand, also including the aircraft type. This map is sent to the subsystems to use for map-based localization.

7.5. Central system

Not all information requirements from the individual systems can be met by observation alone. For example, the synthetic map that will be used by the subsystems to localize themselves relative to the aircraft, cannot be generated by themselves. The same is true for other information, like the status, task requirements or verification commands. This information will come from external sources which are already in use by KLM. The central system acts as a path planner and information broker to cater for these information requirements of the subsystems and ground personnel.

8. Workflow

The conclusions from the former research sections determined the required steps for the development of autonomous agents into turnaround operations. This workflow is depicted in Figure 16 and should be used by the developers of the autonomous agents to ensure that the autonomous agents being developed will uphold the SA of the ground personnel that will be working with these agents.

The following section will go over these steps individually and explain what should be done there to design an autonomous agent for the turnaround operations. These steps will be followed during the case study in Section 9 and will act as an example of how these steps are carried out.

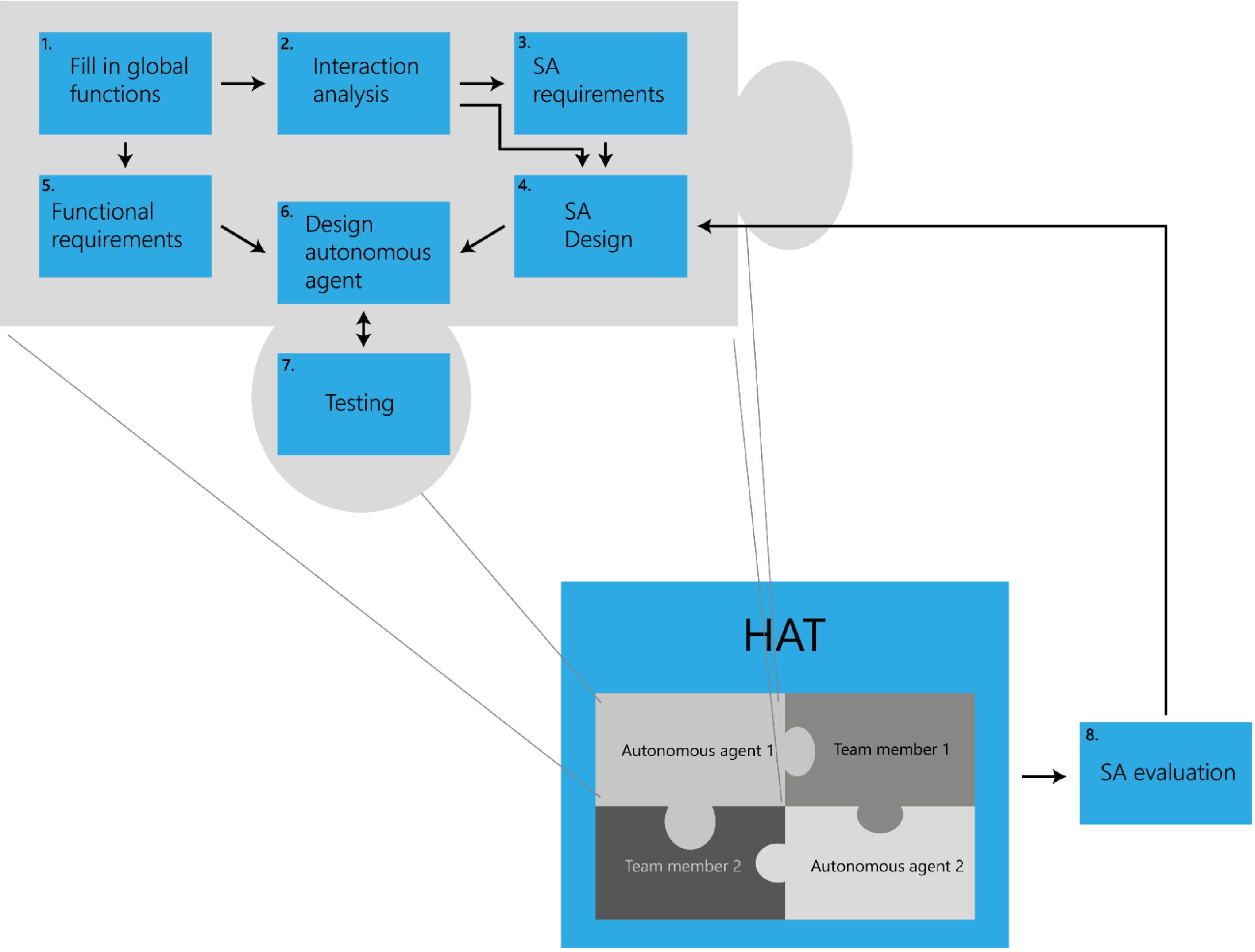


Figure 16: The workflow that caters for the inclusion of SA into the design of autonomous agents. The arrows indicate in which step the results of each step should be used.

8.1. Global functions

The first step of the workflow will be filling in the global functions concerning the task that the autonomous agent will perform during the turnaround operations. This should be done in the format that is provided in Section 3.3. This will provide the designer with an overview of the global functions that the autonomous agents will perform on the aircraft stand, and it will act as a base for the rest of the steps in the workflow.

8.2. Interaction analysis

Based on the global functions from the last step, the interaction analysis should be done, by filling in the possible interaction the autonomous agent could have with the ground personnel. The global functions will help with this, by already splitting the task up into different subtasks, and thus being able to determine the possible interactions per function. After this, the environmental factors that can influence these interactions should be analysed, by going over hypothetical situations of environmental factors that could occur during these interactions. Examples of these kinds of factors could include weather conditions or obstructions of view. After this analysis, the difference in interdependence for the specific ground personnel should be identified, to determine which SA requirements fit each type in the next step.

8.3. SA Requirements

To find out what information is needed in the team to complete all the subgoals of a specific task, concerning all three different SA levels, the results of the interaction analysis should be used to create the SA requirements, using Goal-Directed Task Analysis (GDTA) [49]. This is normally done by conducting interviews with the specific human operators, expert elicitation and desk research into the written protocols of the current operation. These requirements should be technology-independent, by focussing on what the ground personnel needs to know per goal and subgoals, not about what technology is needed for it. For example, the task ‘navigate to point’ could be done using different methods and tools, but the things that need to be known are still the same, which are ‘What is the best route?’ or ‘What is my current location?’. The same is true for that it should be agent-independent, the focus should be on what information the whole team needs to complete a task. Only after this step should this information be split up per operator, or in this case, type of ground personnel.

8.4. SA Design

The SA requirements from the last step inform what interfaces should be created to cater for the required SA per operator. Creating these interfaces should be done according to the SA design principles which are provided by Endsley in [50]. This should result in design requirements for the overall design of the autonomous agent, which will be done in step 6 of the workflow.

8.5. Functional requirements

For designing the more technical part of the autonomous agent, the global functions that are made during the first step should be split up into subfunctions, to provide a clearer understanding of the autonomous agent’s capabilities, in order to complete its task. In addition to this, the technical functions that will enable the SA design requirements should also be included here. This will result in a complete list of functions for the autonomous agent, that can be used for the design of the autonomous agent.

8.6. Design autonomous agent

This step combines the SA design requirements and the functional requirements into the design of the autonomous agent. This should result in a design of the autonomous agent that caters to upholding the SA of the ground personnel and that allows it to perform its task during the turnaround operations.

8.7. Individual testing

Before being able to test the autonomous agent within the aircraft turnaround operations, its functionalities should be tested to ensure a safe and efficient integration into the operation. When these tests conclude that the system cannot meet the desired functionalities, the design of the autonomous agent should be adapted and tested again.

8.8. SA evaluation

To determine whether the SA requirements are met, SAGAT should be used to assess the level of SA of the operators during a simulated scenario, preferably with other TM, TC and maybe even other autonomous agents. The scenario is frozen at specific points during the test, to then probe the operators by asking them specific questions concerning SA. This scenario should also be tested without any autonomous agents, to present a base measurement for comparison. The results of these tests should be used to iteratively improve the design of the interfaces of the autonomous agent.

9. Wheel chock robot case study

The following case study will examine the utility of the workflow by guiding the development of an autonomous wheel chocking robot (WCR) and evaluating whether it was successful in aiding the inclusion of beneficial SA aspects into the design of the autonomous agent. Where possible, the case study will also present the findings on the knowledge gaps that were still present, which were detailed in Sections 5.6 and 6.8. The required sensor type for localization of the autonomous agents is one of these gaps, which influenced the design of the WCR to allow for the use of different types of localization technologies for testing.

9.1. Current wheel chocking procedure

The current wheel chocking procedure is described below, to help understand what task the wheel chocking robot will perform during the turnaround operation. After which the global functions of the wheel chocking procedure will be filled in according to the workflow. It should be noted that the WCR should only be able to fulfil the task of placing and removing the wheel chocks, no other turnaround tasks. For autonomous agents that could fulfil multiple tasks during the turnaround operations, it is not possible to fill global functions using solely the current procedures. The order and/or combination of these tasks should be determined to do this.

The wheel chocks are placed at the aircraft landing gear wheels to prevent the aircraft from making sudden movements because the brakes of the aircraft are disengaged when it is standing still. This is because the brakes are still hot from the landing, and cooling them is preferred with the brakes disengaged.

After the aircraft has arrived and its engines are turned off and spooling down, wheel chocks are placed at the NLG of the aircraft. This enables the ground personnel to already attach the GPU/FPU, while the other chocks are placed at the MLG. After the chocks are placed at the MLG, the chocks at the NLG can be removed and a signal is given to the cockpit, indicating that the chocks are placed and that the aircraft brakes can be disengaged. The NLG wheel chocks are removed, for the pushback vehicle to be attached. Removal of the MLG wheel chocks is done after the pushback vehicle is attached to the NLG and all other turnaround operations are finished. The pushback vehicle driver then uses a headset to communicate with the cockpit about the removal of the wheel chocks and further coordination of the pushback procedure.

9.2. Possible discrepancies

The increase in weight of the aircraft after refuelling and cargo loading can cause the wheel chocks to be stuck under the wheels, which incurs difficulties in the removal of these chocks. In most cases, this can be solved by prying the wheel chocks loose using a pole that the pushback driver has access to. But in some cases, this is not possible, and the pushback driver then has to move the aircraft a bit to clear the wheel chocks, which are then removed by other ground personnel. This requires coordination between the pushback driver and the ground personnel who are removing the chocks.

To decrease the chances of the chocks getting stuck under the aircraft wheels, the ground personnel is currently required to not kick or push the chocks under the wheels after placing the chocks. The chocks should be placed against the wheels, but not forcefully. During periods of increased wind, it is also required to place more wheel chocks, depending on the amount of wind and type of aircraft as well.

9.3. Preliminary requirements from KLM

For the development of the wheel chocking robot, KLM provided preliminary requirements to guide the project towards creating a demonstration that would inspire colleagues to think about the potential applications of autonomous agents in ground operations.

Wide-body aircraft:

The WCR should be developed to place the wheel chocks during the turnaround of a wide-body aircraft. This means that the scale of the operation is significantly larger and that the layout and amount of wheels is different compared to that of narrow-body aircraft.

Skip NLG chock placement:

To show how operations could be done differently, instead of placing the NLG wheel chocks first, the MLG chocks should be placed directly by the WCR, skipping the NLG. Since the placement of the chocks at the NLG is mostly done to keep the ground personnel safe before the anti-collision lights have been turned off.

Place the chocks in between the wheels:

Again, to show how operations could be done differently, instead of placing the wheel chocks in front and behind the MLG wheels, the wheel chocks should be placed in between the MLG wheels. Figure 17 shows what this means.

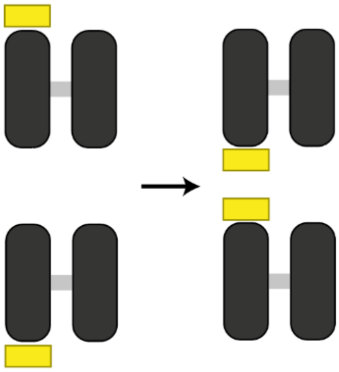


Figure 17: A schematic description of how the wheel chocks (yellow) are currently placed, left, and how they should be placed by the WCR, right.

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9.4. Procedure with WCR

The following section will explore how the wheel chocking procedure will look like when it is performed by the WCR. The current wheel chocking procedure and the information map from Appendix A determined how the global functions from Section 3.3 were filled in, which is shown in Figure 18. This is the first step of the workflow from Section 8, also indicated by the indicator that can be found on the top left side of this page, which will also indicate the other steps of the workflow throughout the case study.

The information map from Appendix A was used to determine the required task-specific information for the WCR. The interaction point will be the MLG, as explained in Section 9.3, and the task for the WCR will be the placement and removal of the wheel chocks. The continuous task 'provide transparency' was added to include the SA aspect.

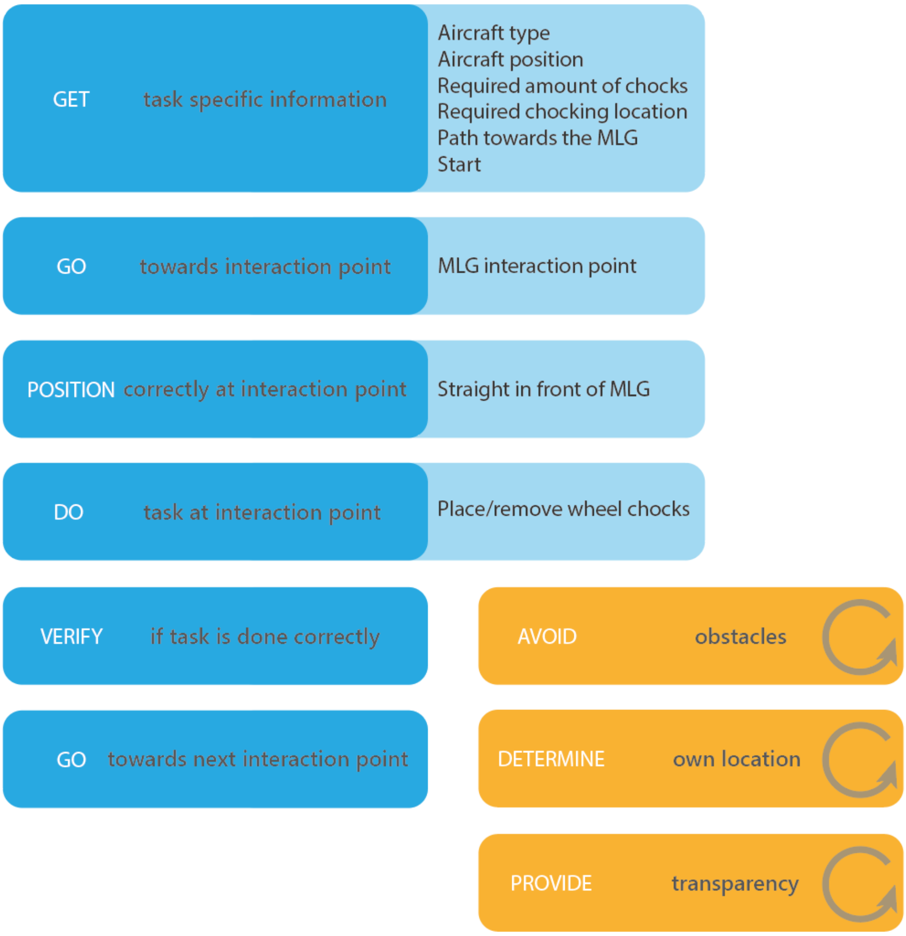

Figure 18: Schematic overview of the main functions during wheel chocking procedure

9.5. Interaction analysis

Following the workflow, for step 2, the interaction analysis will explore the possible interactions between the wheel chock robot and ground personnel. The global functions from Section 9.4 act as a starting point to identify what interactions could happen between the ground personnel and the WCR per step. By reviewing these steps and envisioning the possible interactions, the table below was filled in.

9.5.1. Possible interactions

Get task-specific information	
	Ground personnel could add task-specific information, like a last-minute wind phase increase, increasing the required amount of wheel chocks that should be placed.
Go towards the MLG	
	Ground personnel could glance over to the WCR.
	Ground personnel could be actively monitoring the WCR.
Position correctly in front of the MLG	
	Ground personnel could glance over to the WCR.
	Ground personnel could be actively monitoring the WCR.
Place the wheel chocks	
	Ground personnel could glance over to the WCR.
	Ground personnel could be actively monitoring the WCR.
Verify if the wheel chocks are placed correctly	
	Ground personnel verifies if the wheel chocks are placed/removed correctly and take action if not.
	If the wheel chocks are stuck under the wheels, then the ground personnel needs to help the WCR to remove the wheel chocks.
Leave the MLG	
	Ground personnel could glance over to the WCR.
	Ground personnel could be actively monitoring the WCR.
Avoid obstacles	
	Ground personnel, either walking or driving GSE, could encounter the WCR, who then should avoid each other.
Determine own location	
Provide transparency	
	Ground personnel could need information regarding the WCR to gain sufficient SA.

Interdependence level

From the aforementioned list, a distinction between ‘glancing over’ to the WCR or being actively monitoring the WCR can be found. This difference depends on the role of the ground personnel. For this project, the decision was made that the TC will have the monitoring role over the wheel chocking robot during the turnaround operations, because they currently already have this role over the other ground personnel. This means that the TC will have a higher level of interdependence with the WCR and thus requires more transparency with the WCR.

9.5.2. Environmental factors

The environmental factors that could influence the aforementioned interactions are listed below. These factors are derived from analysing hypothetical scenarios of the aforementioned interactions and listing the potential environmental factors that could occur. Figure 19 provides a schematic overview of these environmental factors.

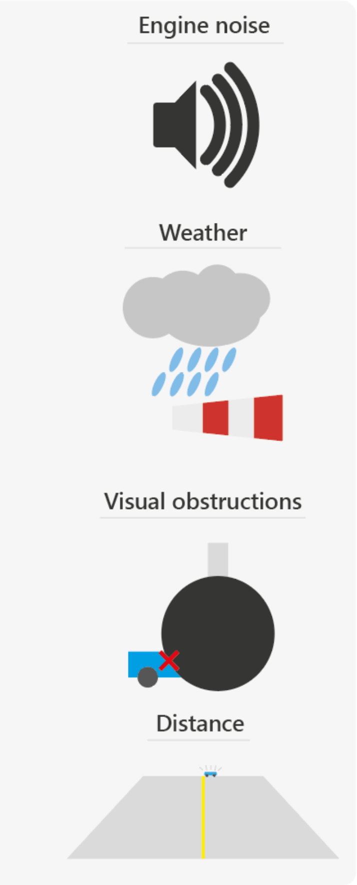

Figure 19: Schematic overview of the possible environmental factors

WCR moves towards MLG after or when the aircraft arrives, meaning the engines make a lot of noise. This means that audio communication is not possible, reinforced by the fact that human operators need to wear ear protection.

Weather conditions on the aircraft stand could obstruct the view of the WCR or change the behaviour of the WCR, because of the different wind phases. The reliability of the WCR could also change, which could cause it to need more help.

The view to the WCR could be obstructed by parts of the aircraft, including the NLG and MLG. Since the WCR is used at the beginning and end of the operations, this obstruction could not be caused by other GSE, since they would already have finished their task.

The aircraft stand is large to account for the size of the aircraft, this means that the WCR can move far away from the ground personnel, who have to wait outside of the ERA, which could be around 35 meters. This will make details on the WCR less visible.

9.5.3. Conclusions of the interaction analysis

The conclusions of the interaction analysis are listed below, including two requirements that came from these conclusions.

1. **Use visual communication.**
   This requirement originates from the fact that no audio communication is possible during the first minutes of the turnaround. As well as the fact that if the WCR moves quite far away, this audio should have to be quite loud to be comprehensible.
2. **The TC requires more transparency than the TM.**
   This was concluded from the increased interdependence that the TC will have compared to the TM, since they have the added responsibility of monitoring the whole operation, including the WCR. This will influence the division of SA requirements in the next step.
3. **Limited interaction**
   Since this is the first task after arrival and almost the last task before pushback, there will not be much interaction between the WCR and ground personnel or GSE. This changes when the wheel chocks are stuck, and the WCR requires help to remove them.

9.6. SA Requirements

The following section describes step 3 of the workflow, which is the creation and division of SA requirements.

9.6.1. Goal-directed task analysis

The SA requirements for the goal “Monitor the placement of the wheel chocks” are listed below and are based on the subsequent subgoals, decisions and information influencing those decisions, as explained in Section 6.5.1. While this goal is not the only goal associated with the placement and removal of the wheel chocks, it encompasses a significant portion of the interactions with the ground personnel. This analysis is based on the GDTA from [49], as explained in Section 8.3. Behind these decisions and pieces of the required information, the associated level of SA is stated.

Main goal: Monitor the placement of the wheel chocks

Subgoal 1: Verify whether the WCR is behaving normally:			
1.	Does the **location/pose** of the WCR correspond to the current action of the WCR?		SA 2
a.	Current action of the WCR	SA 1	
b.	Location of the WCR	SA 1	
c.	Goal location of the WCR	SA 1	
2.	Does the **speed** of the WCR correspond to the [action] of the WCR? (SA 2)		SA 2
a.	Current action of the WCR	SA 1	
b.	Speed of the WCR	SA 1	
c.	Goal speed of the WCR	SA 1	
3.	Does the **amount of chocks** that is being carried by the WCR correspond to its current action?		SA 2
a.	Current action of the WCR	SA 1	
b.	Amount of chocks being carried by the WCR	SA 1	
c.	Desired amount of chocks being carried by the WCR	SA 1	
4.	Does the future state of the WCR bring any problems? (SA 3)		SA 3
a.	Next action of the WCR	SA 3	
b.	Next goal location of the WCR	SA 3	
c.	Next goal speed of the WCR	SA 3	
d.	Future amount of desired chocks being carried by the WCR	SA 3	

Subgoal 2: Verify if wheel chocks are placed correctly:			
1.	Are the wheel chocks placed at the correct LG?		SA 2
a.	Current location of the chocks with regard to the aircraft	SA 1	
b.	Desired location range of the chocks with regard to the aircraft	SA 1	
2.	Are both wheel chocks placed correctly against the wheels?		SA 2
a.	Current pose of the chocks with regard to the wheels	SA 1	
b.	Desired pose range of the chocks with regard to the wheels	SA 1	
3.	Is the **amount of chocks** that is placed at the LG correct?		SA 2
a.	Current amount of wheel chocks at the LG?	SA 1	
b.	Desired amount of wheel chocks at the LG	SA 1	
4.	Are there any discrepancies?		SA 2

Subgoal 3: Resolve the incorrect behaviour of the WCR		
1. What is the cause of the abnormal behaviour of the WCR?		SA 2
a. Observed discrepancies with the WCR	SA 1	
b. Observed obstacles around the WCR	SA 1	
2. Could the current behaviour of the WCR cause damage or unsafe situations?		SA 2
a. Current location of the WCR	SA 1	
b. Current speed of the WCR	SA 1	
c. Current heading of the WCR	SA 1	
d. Current state of the WCR	SA 1	
3. Should the WCR be removed from the aircraft stand?		SA 2
a. Answer from the last decision	SA 1	
4. How can the WCR be removed from the aircraft stand?		SA 3
a. Possibility for the WCR to remove itself from the aircraft stand	SA 2	
i. Answer from decision 1	SA 2	
b. Current amount of available TM	SA 1	

Subgoal 4: Resolve the incorrect removal of the wheel chocks:		
1. What is the reason for the incorrect removal of the wheel chocks?		SA 2
a. The wheel chocks are stuck under the LG wheels	SA 1	
b. Possible EM malfunctioning	SA 1	
c. Mechanical damage	SA 1	
d. Other discrepancies	SA 1	
2. Does the incorrect removal of the wheel chocks pose any problems or safety issues?		SA 2
3. How can the wheel chocks still be removed?		SA 3
a. Possibility for the WCR to still remove the wheel chocks	SA 2	
b. Possibility for a TM to remove the wheel chocks	SA 2	
i. Amount of TM that are free to help	SA 1	
ii. Amount of TM that are needed to help	SA 1	
c. Possibility for the WCR to still remove the wheel chocks	SA 2	
d. Possibility for a TM to remove the wheel chocks	SA 2	
4. **Initiate new removal sequence**		

9.6.2. SA Requirements division

Compared to the TM, the TC require an additional amount of information, because they share an increased amount of interdependence with the WCR, as explained in Section 9.5. The TM require less information about the WCR to be able to have enough SA to perform their tasks, because they only need to act if they see that something is wrong. Since the TC also have a tablet on hand during the operation, they will be able to see more information about the WCR. This adds up to the following division of SA requirements per type of ground personnel:

TM:

SA 1:

- What is the pose of the WCR?
- What is the WCR currently doing?

SA 2:

- Is something wrong with the WCR?

TC

SA 1:

- What is the WCR currently doing?
- What is the speed and desired speed of the WCR?
- What is the pose and desired pose of the WCR?
- What is the amount and desired amount of chocks being carried by the WCR?
- What is the pose and desired pose of the chocks after they have been placed?
- What is the amount of TM that are free to help the WCR?

SA 2:

- Does the current pose of the WCR correspond to the desired pose of the WCR?
- Does the current speed of the WCR correspond to the desired speed of the WCR?
- Does the current amount of chocks correspond to the desired amount of chocks being carried by the WCR?
- Are the wheel chocks placed at the correct LG?
- Are the wheel chocks placed correctly at the MLG?
- Are there any discrepancies with the wheel chock placement?
- What is the reason for the incorrect removal of the wheel chocks?
- What is the amount of TM that are needed to help the WCR?

SA 3:

- What is the future state of the WCR?
- Does the future state of the WCR bring any problems?
- Does the incorrect removal of the wheel chocks bring any problems or safety issues?
- How can the wheel chocks still be removed?

9.7. SA design

According to step 4 from the workflow, the SA requirements outlined in the previous section were applied to create and/or modify the design of the WCR interfaces to convey all the information required to gain proper SA for the ground personnel. The 50 SAOD design principles from [50] were used for this as well.

Phase colors

To convey the information to the TM, not many options are available, since they do not all have a tablet on their person during the turnaround operations. The information should be delivered to them when they encounter or see the WCR because that will also be their only interaction with it. The domain requirements state that only visual communication is possible, but because the WCR can move quite far away, the amount of details can be limited. This reasoning led to the idea of using ‘phase colours’ to indicate what phase or action the WCR is doing at a specific moment. If the WCR would be going to the interaction point, the colour would be ‘blue’ and if something is wrong, the colour would be ‘red’ for example. The colours ‘red’, ‘yellow’, ‘green’ and ‘blue’ are often used in industry to indicate ‘danger’, ‘fault’, ‘normal operation’, and ‘auxiliary functions’ respectively. These standards could inform the choice of phase colours, to provide better consistency between the machines that are already in use by KLM and the WCR. To understand what each colour means, the ground personnel should be trained beforehand.

Verification picture

To verify the correct placement and removal of the wheel chocks, it would be inconvenient for the TC to have to walk towards the wheel chocks and back to check this. Since the TC already has access to a tablet, a picture will be sent from the WCR to the tablet, such that the TC can look at the picture to verify the placement and removal of the wheel chocks. This picture should provide a clear view of the wheel chocks and where they are placed with regard to the landing gear wheels.

TC tablet

Aside from only receiving an image each time the placement or removal of the wheel chocks has to be verified, the TC should have access to more information regarding the WCR. The SA level 2 information should be displayed directly here, for example, the possible deviation of the WCR position to its desired position. Information regarding the possible causes of discrepancies should also be given. The probabilities of success of each action should also be given here, to improve level 3 SA. Other information that is not listed in the SA requirements should be available here as well, to cater to information requirements in unforeseen circumstances.

WCR interface

Although the TM does not need that much information from the WCR in normal situations, the other information should always be available to them, in case of unexpected situations. An example of this could be in case the wheel chocks are stuck or the WCR is behaving unexpectedly. A solution would be to ask the TC for this information since he/she has the information on their tablet, but this could take an unnecessary amount of extra time. This is why a simple interface should be added to the WCR which displays the information the TM would need at these moments, with the possibility for the TM to also search for the other available information. According to the IATA [59], an interface should also be present on the agent, to allow for the control of the agent.

9.8. Functional requirements

Aside from the functions related to SA, the WCR needs to be able to perform other functions. According to step 5 of the workflow, the global functions from Section 9.4. act as a starting point to determine what subfunctions the WCR should be able to do for it to perform its task. These subfunctions will subsequently inform the design of the WCR in the following sections.

Get task-specific information

- How many chocks
- Where should the chocks be placed
- Location of the aircraft
- Type of the aircraft
- Path towards the MLG
- Start

Go towards the MLG

- Carry the wheel chocks
- Drive over the aircraft stand (concrete or asphalt, slightly slanted)

Position correctly in front of the MLG

- Localize the MLG
- Determine how to position correctly in front of the MLG
- Manoeuvre correctly in front of the MLG

Place/remove the wheel chocks

- Move forward to in between the MLG, such that the wheel chocks are at the correct position
    - While checking the sensors to determine when this is
- Place/remove the wheel chocks
- Sense when it is not possible to pick up the wheel chocks

Verify if the wheel chocks are placed/removed correctly

- Send a picture to the TC
- Wait for verification

Signal to the cockpit that the wheel chocks are placed correctly

- Connection to the central system

Leave the MLG

- Move back from the MLG
- Drive away from the MLG towards the next interaction point

Avoid obstacles

- Exteroceptive sensors

Determine own location

- Proprioceptive sensors, exteroceptive sensors
- Map-based localization

Provide transparency

- Interactive interface
- Lights for phase colours
- Connection to the central system

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9.9. Design

This section will explain how for step 6 of the workflow, the design of the autonomous agent, each of the functions from the last section are met in the design of the WCR, which is shown in Figure 20. This will be done by clustering the aforementioned functions into subcategories for a more convenient explanation. The following subcategories were chosen: ‘carrying, placement and removal of the wheel chocks’, ‘movement on the aircraft stand’, ‘localization and object recognition’, ‘human interaction’ and ‘autonomous behaviour’.

Figure 20: Render of the final design of the WCR

9.9.1. Carrying, placement and removal of the wheel chocks

The wheel chocks that will be used to test the WCR are around 12kg each, have a triangular shape and are made out of synthetic rubber. To keep the amount of moving parts to a minimum for simplicity, electromagnets were chosen for the method of carrying, placement and removal of the wheel chocks. Because wheel chocks are not made of magnetic materials, a metal plate is attached to them to enable the electromagnets to hold onto the wheel chocks. Figure 21 shows how the wheel chock is adapted for this purpose. This metal plate should be added to every wheel chock in use by KLM to be used by the WCR.

Because the wheel chocks will be placed in between the MLG wheels of a Boeing 787, the two wheel chocks are carried, placed and removed simultaneously, by an extending grabber that works using linear actuators, as shown in Figure 22. This grabber is driven in between the MLG wheels, then extended and lowered, after which the electromagnets are disengaged, placing the wheel chocks.

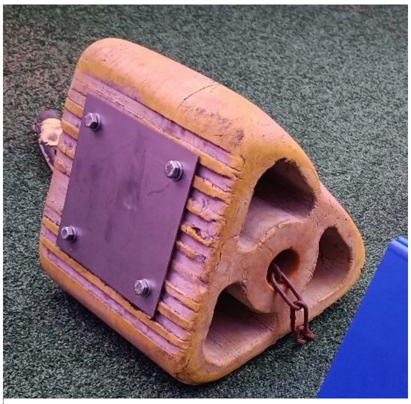

Figure 21: Picture of an adapted wheel chock, with a metal plate attached using bolts

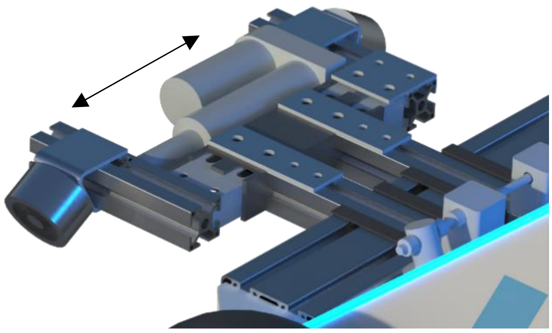

Figure 22: Render of the grabber assembly, the arrows indicate the direction of extension and retraction of the grabber

9.9.2. Movement on the aircraft stand

For the WCR to move around on the aircraft stand at the interaction points, different steering types could be chosen, three of which were considered for the WCR: Skid, differential and Ackermann steering. Which accounted for the following wheel setups to be considered, shown in Figure 23:

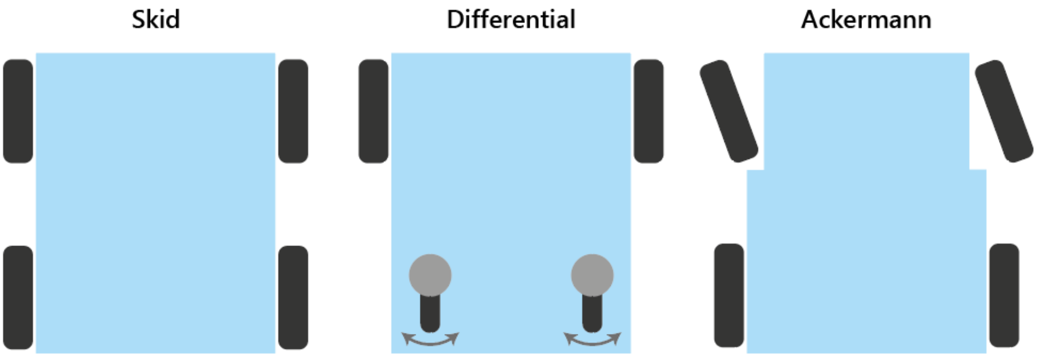

Figure 23: Illustration of the three different steering setups that were considered, the front-facing direction is up

Skid steering uses 2 driven wheels per side to enable steering, by either driving one side faster than the other to steer around a radius, or by alternating the direction of the wheels, allowing for on-the-spot rotation. Skid steering does induce wheel slippage. Differential steering works similarly to the skid steering setup, but in this case, it uses 2 freely swivelling caster wheels to remove the need for the wheels to slip, making the setup kinematically locked, which would allow for more accurate odometry measurement. Ackermann steering works by turning the front wheels simultaneously, allowing the robot to drive around a radius.

The size of the WCR and the intended driving surface, asphalt, does not permit the use of ball casters for differential steering. Instead, swivelling caster wheels should be used, which results in less stable steering and driving. An Ackermann steering setup requires a more difficult mechanical design and increased control complexity, because of the added steering actuation. Therefore, a skid steering setup was chosen to make the robot more stable and robust, while keeping the steering setup simple. Figure 24 shows a top-down view of the WCR, where the skid steering wheel setup can be seen.

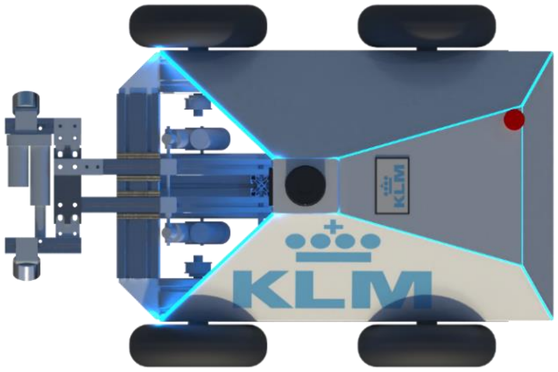

Figure 2421: Top down view of the WCR

The WCR does not include a suspension system to keep the mechanical design simple. Inflatable rubber tyres ensure that the WCR can handle irregularities in the driving surface. This means that the WCR's tyre pressure should be checked periodically and that there is a chance of obtaining a flat tyre.

Using on-the-spot rotation, the WCR could drive to a position perpendicular to the MLG, rotate to align itself to it, and then drive straight towards it. Figure 25 shows an example of this approach. The approximately 10 meters in between the wheels of wide-body aircraft leave enough space to perform this approach.

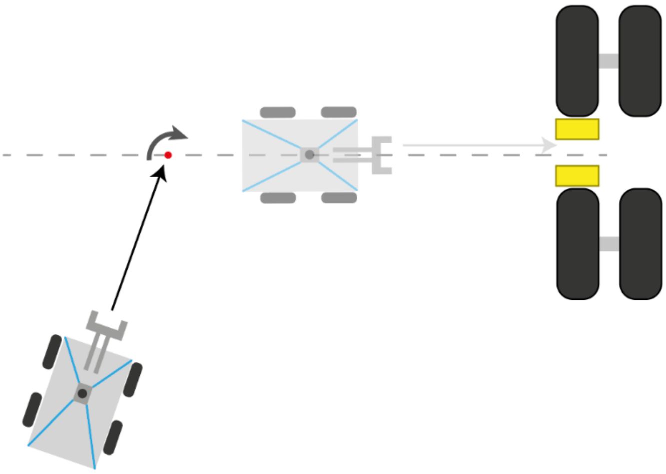

Figure 25: Illustration of a possible approach towards the MLG of the WCR, using on the spot rotation

9.9.3. Localization and object recognition

For the WCR to place the wheel chocks at the MLG, it needs to be able to localize itself on the aircraft stand, as well as to be able to detect where the MLG is, to position itself correctly in front of it. As discussed in Section 5.6, it is unclear which localization technologies to use for localization yet. This means that for the WCR, multiple different sensor types will be mounted onto it for testing and comparison. The sensors that will be mounted onto the WCR, are a 3D camera, a 2D lidar sensor, wheel encoders, and an IMU. A 3D camera was chosen instead of a normal camera, to be able to also detect distances in front of the WCR, if the lidar were not to be used. Figure 26 shows how the sensors are mounted to the WCR. The camera should also be used to perform marker-based object recognition and pose estimation for the detection and localization of the wheel chocks relative to the WCR. This would require the addition of visual markers to the wheel chocks that will be placed or removed by the WCR.

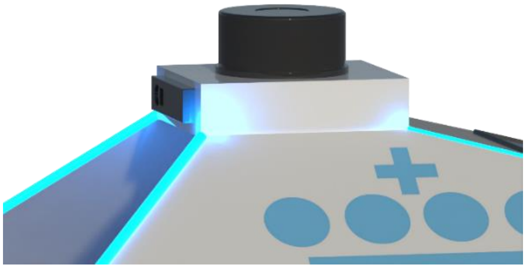

Figure 26: A render of the positions of the sensors on the WCR, a 3D camera is pointed to the front of the WCR, left, while a lidar sensor is mounted on top.

The 3D camera will take the verification picture for the correct placement/removal of the wheel chocks. The same goes for being able to sense the incorrect removal of the wheel chocks, which will be picked up by the camera when the detected location of markers on the wheel chocks does not correspond to their normal position once picked up.

9.9.4. Human interaction

As mentioned in Section 9.7, certain aspects need to be integrated into the design of the WCR to account for the human interaction part of it, according to the SAOD part of the workflow that was performed. These aspects are the phase colours, verification picture and the WCR interface. The TC tablet is not part of the design of the WCR, but a separate device.

Phase colours

The phase colours are integrated as shown in Figure 27, and denote the specific phase the WCR is currently in, during the task it is performing. Table 1 shows what phases correspond to what colour. The colour coding is based on the ISA-101.01 standard for ‘Human Machine Interfaces for Process Automation Systems [60]. Blue is used to indicate specific machine states, which for the WCR translates to driving towards the MLG and positioning itself. Green indicates its main function, placing wheel chocks, and yellow for the removal, because of the increased danger that is associated with removing the wheel chocks. The verification of the WCR is denoted by the additional colour purple.

Figure 27: Renders of the WCR displaying different phase light colours. Blue, red and green from left to right

Table 1: Phase colour distribution per phase

Phase	Colour:	Note:
Drive towards MLG	Blue	
Position correctly in front of MLG	Blue	Blinking
Approach MLG	Blue	Blinking
Place wheel chocks	Green	
Remove wheel chocks	Yellow	
Waiting for verification	Purple	
In need of assistance	Orange	
Error	Red	

Verification picture

The verification picture can be captured using the RGB part of the 3D camera that is mounted on the WCR and transmitted through the information broker to the tablet of the TC. The tablet of the TC should push a notification to the TC, for him/her to verify whether the wheel chocks are placed or removed correctly.

WCR interface

On the back of the WCR, the WCR interface will be placed, where the TM and TC can interact with it to gain more information about the WCR, either by looking at it for the most important information, or via a touchscreen to search for more in-depth information. Figure 28 shows an impression of how this can look like. To account for the IATA recommendation which was explained in Section 9.7, the ground personnel should also be able to control the WCR using this display. A red emergency button is also present on the back, to shut down the WCR in emergency situations.

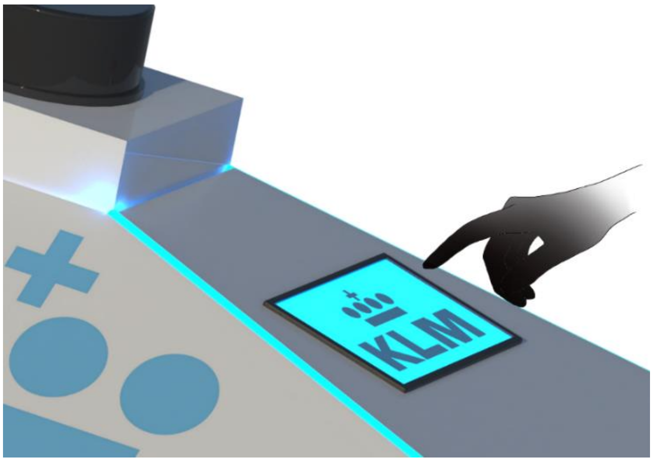

Figure 28: A render of the WCR interface on the back of the WCR, illustrating a possible interaction

9.9.5. Autonomous behaviour

As explained in Section 6.6, behaviour trees are expected to increase the explainability of the autonomous agents, which is one of the key aspects of HAT. For the WCR, behaviour trees will be used to increase the explainability of the agent by linking the specific phases of the WCR to the nodes of the tree. And to simplify the development of autonomous behaviour, by creating modular components for the development. The functions from Section 9.4 determined the design of the behaviour tree for the WCR, which is shown in Figure 29.

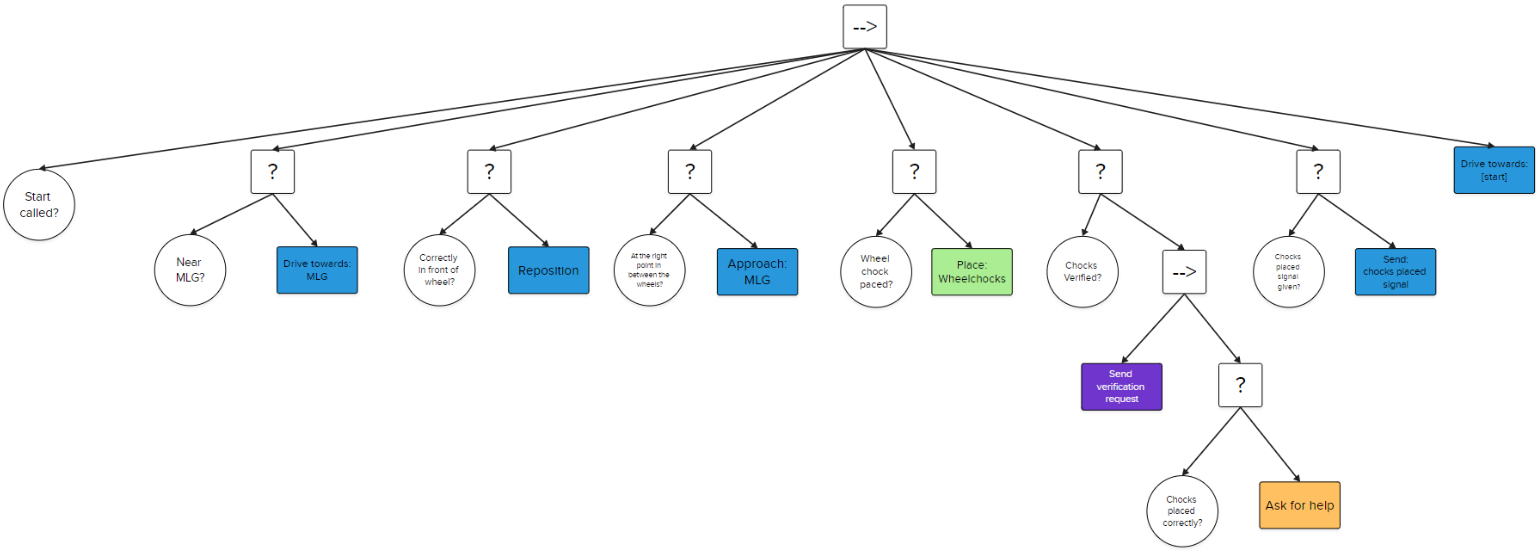

Figure 29: Behaviour tree for the wheel chock placement of the WCR

Each of the action nodes, coloured in Figure 29, corresponds to a ‘phase’ in the behaviour of the WCR, for example ‘drive towards MLG’. Every phase is connected to a specific phase colour, as mentioned in the previous section. In the case of the phase ‘drive towards MLG’, the phase colour would be blue.

For error catching, each node can have a timer built in, which will trigger an error if the subtask is taking too long and thus deviates from normal operation too much.

Note that this behaviour tree could be specified further, by for example adding more error-catching capabilities to each specific function, as shown in Figure 30. However, this is not always beneficial for the overview and explainability, since the tree could become convoluted [57].

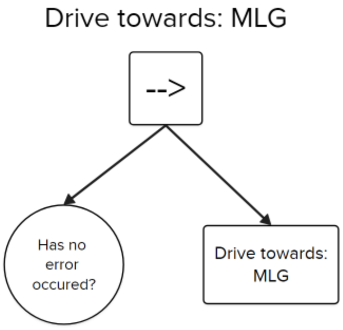

Figure 30: Illustration of how the action node 'Drive towards: MLG' could be split up for increased error catching capabilities

For the WCR to be able to localize and navigate itself on the aircraft stand autonomously, autonomous navigation packages will be used. These will be elaborated on in Section 9.11.3.

9.10. Prototype

The functionality of the aforementioned design aspects was evaluated through the design, manufacturing, development and testing of a prototype of the WCR. A side-by-side comparison between the envisioned design of the WCR and the prototype can be seen in Figures 31 and 32. The following sections will explain the software used for the development of the WCR and the differences between the envisioned design and the prototype are laid out.

Figure 31: Render showing the WCR

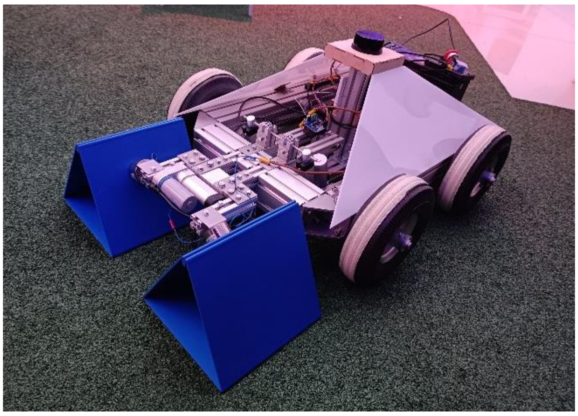

Figure 32: Picture showing the prototype of the WCR

9.10.1. Requirements for the prototype

The following requirements are set for the prototype of the WCR. These requirements are based on the main functions that the WCR has to be able to perform, and which were also perceived to be feasible for this project.

- The prototype should be able to autonomously drive towards the MLG of the incoming aircraft while avoiding obstacles.
- The prototype should be able to correctly place and remove the wheel chocks in between the wheels of the MLG.
- The prototype should be able to inform the operators about its current phase of operation.
- The prototype should be able to show the colleagues at KLM what is possible in terms of autonomous turnaround operations.

9.10.2. Software development

A Jetson Orin Nano running Ubuntu 22.04 with ROS2 Humble [61] (Robot Operation System 2) and subsequent packages enabled the development of the software that runs the WCR prototype. ROS2 allows a developer to use a variety of different software libraries, in combination with the possibility of including their own packages, to create a modular robotic system, where each package contributes to one or more functionalities of the robot. This modular approach allows for the development of the prototype to be split up into different pieces and makes testing each individual functionality more convenient.

The packages Slam toolbox [62] and navigation2 [63] provide localization and autonomous navigation capabilities for the WCR prototype. For an overview of all the packages and programs that are used for the prototype and how they work together, please refer to Appendix B.

9.10.3. Functionalities and limitations

This section explains the functionalities of the prototype, which are also compared to the envisioned functionalities of the WCR that were explained in Section 9.9. This showcases the limitations of the prototype, which will later inform the recommendations for the possible implementation of the WCR into the turnaround operations.

Carrying, placement and removal of the wheel chocks

The grabber on the prototype is manufactured as designed, however, the EMs are not capable of picking up the 12kg wheel chock in the current configuration. Lighter, mock-up, wheel chocks replace the actual wheel chocks for testing and demonstration of the other functionalities. The adapted wheel chocks and their blue mock-up counterparts can be seen in Figure 33. The extending grabber can be seen on the right, in Figure 34.

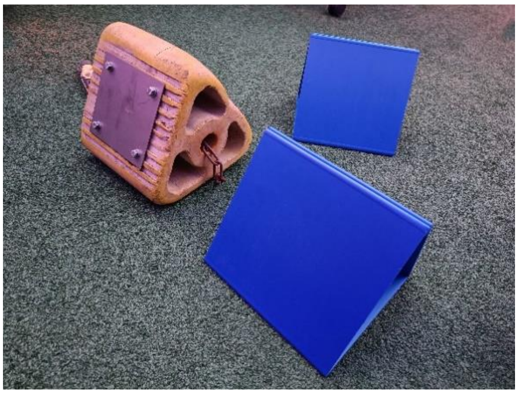

Figure 33: Picture of the wheel chocks, left, and the mock-up wheel chocks, right

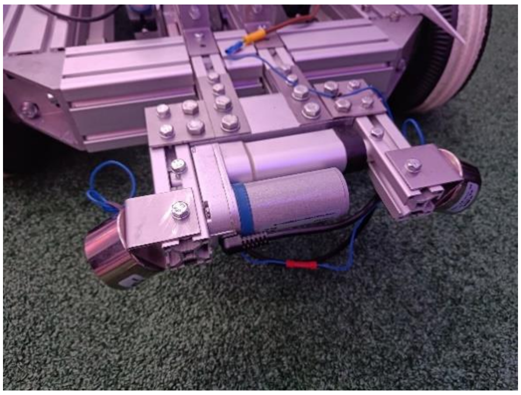

Figure 34: Picture of the grabber assembly of the prototype

Movement on the aircraft stand

The wheel setup is the same as in the original design, 4 fixed wheels, using skid steering for the ability to rotate, Figure 35 shows this wheel setup. Each side, left and right, is driven by a DC motor, connected to the wheels via drive belts, including a reduction to increase the torque, shown in Figure 36. The motors are connected to a hub which can slide alongside the chassis to allow for the tightening of the driving belts. However, due to inaccuracies during the manufacturing process, the belts are not tightened equally and some asymmetries in the wheel setup are present, which cause problems for the movement of the WCR, as will be explained in Section 9.11.1.

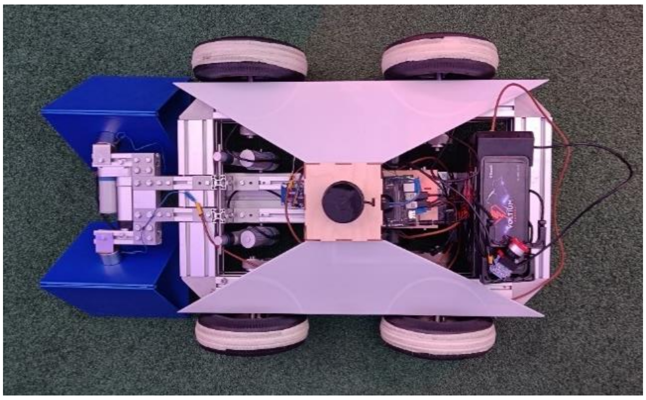

Figure 35: Top down view of the prototype

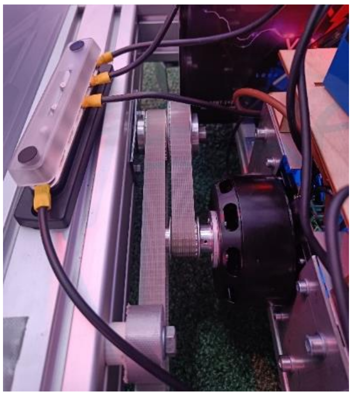

Figure 36: Picture of the drive belts attached to the motor hub on the right

1.
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3.
4.
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7.
8.

Localization and object recognition

The sensors that will enable the localization of the WCR are a 50 meter range 2D lidar, an Intel Realsense 3D camera, integrated motor encoders and an IMU sensor. The lidar sensor and IMU are integrated at the top of the prototype, as shown in Figure 37. These sensors will allow the use of the Navigation2 package on ROS2, which in turn makes it possible to test the localization and autonomous navigation capabilities. The use of a 2D lidar instead of a 3D lidar, means that synthetic map based localization using 3D models of the aircraft is not possible. The integration of the 3D camera within ROS2 was unsuccessful, preventing the testing of both marker-based object localization and 3D camera-based localization at this stage.

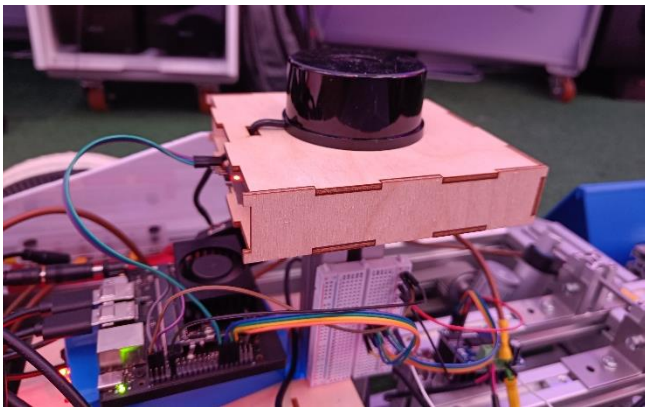

Figure 37: The sensor box on top of the prototype, with the IMU attached to the back (left) and the lidar scanner op top

Human interaction

This part is the least integrated part of the prototype because both the WCR interface and phase colours are not present on the prototype and the TC interface and its functionalities have not been developed yet. This means that the SAGAT analysis can not be performed using the current prototype.

Autonomous behaviour

Due to difficulties in the development of the prototype, the autonomous capabilities are not yet integrated sufficiently. The Navigation 2 package for autonomous point-to-point navigation works inconsistently and the behaviour tree is not integrated as of yet. Section 9.11.4 explains the tests that were conducted regarding the Navigation 2 package for autonomous navigation.

9.11. Testing the prototype

In this section, in line with step 7 of the workflow, the tests regarding the different functionalities of the WCR are explained, detailing how the WCR performs in those aspects and what this means for its possible deployment for aircraft turnaround operations.

9.11.1. Movement on the aircraft stand

By driving the WCR prototype around using remote control, its capability to do different kinds of manoeuvres was evaluated. This included the following types of driving: forwards/backwards, on-the-spot rotation and differential turning.

Forwards and backwards driving is effortless for the prototype, however, due to the increased size and mass of the robot, small and more precise movements are difficult to control. On-the-spot rotation requires a high initial torque to overcome the friction of the wheels that need to slide over the surface. This was not a problem in the first rounds of testing, but after this, turning to the right visibly became more 'strenuous' for the prototype. The reason for this is most likely the inaccurate manufacturing of the prototype, causing asymmetry within the wheel and motor drive setup. Differential turning is easier for the prototype, however, due to the aforementioned asymmetry, left and right turns are not equal. These problems with turning and small movements subsequently created difficulties with the control of the prototype.

9.11.2. Carrying, placement and removal of the wheel chocks

As can be seen in Figure 38, the prototype is able to carry the demo chocks using electromagnets and linear actuators. However, due to the difficulties with controlling the prototype, it is not possible to accurately align the prototype with a specific point, as is needed according to Section 9.9.2. This means that it is currently unwieldy to drive the prototype towards the wheel chocks to pick them up.

Figure 38: Picture of the prototype that is carrying the mock-up wheel chocks

9.11.3. Localization

By driving the prototype around and comparing its real location with the location that is displayed by the prototype, the localization capabilities of the prototype were evaluated. This turned out to be quite accurate, according to the similarities between the position of the prototype relative to its virtual and real surroundings. However, because the 'go to point X' capabilities from the Navigation 2 package are currently not working on the prototype, the exact accuracies could not be tested. The aforementioned results were gained through the fusion of the IMU readings and the wheel odometry from the motor encoders with the use of the robot_localization package [64]. Using only the wheel encoders caused significant drift due to wheel slippage, making it impossible for the localization package to determine a consistent location of the prototype, and align it to the lidar scanner readings on the map.

9.11.4. Autonomous behaviour

According to Section 9.9.5, the behaviour tree that would dictate the autonomous behaviour of the prototype is not yet developed and integrated into the prototype. However, the Navigation 2 package does allow for autonomous navigation. This was enabled by connecting the motor controllers to ROS2, allowing them to be controlled manually, or by control algorithms that in this case the Navigation 2 package provides. By providing a goal pose to the prototype to move towards and evaluating the behaviour of the prototype while it is moving towards that point, the autonomous navigation capabilities were tested. The start of the movement towards the goal point seemed positive, however, after some time, the prototype stopped and started turning towards a different, wrong, direction. This was caused by latency issues according to the error log, which caused the prototype to follow a point on the path in the past. A solution for this is not found yet.

9.11.5. Obstacle detection and avoidance

Obstacle recognition could not be tested, as explained in Section 9.10.3. However, the lidar scanner that is installed on the prototype is still able to detect objects. As mentioned in the former section, the Navigation 2 package did work on some occasions, for simple paths. This allowed for a test to determine whether the prototype could detect a sudden object while driving and stop in time without making contact with the object. The prototype was able to detect and stop the obstacle in time, but it could not recover and move around the obstacle, because of the reasons mentioned in Section 9.11.4. It should be noted that this object was visible for the 2D lidar since it extended through the scanning plane of the sensor. Objects that are below this scanning plane are not visible to the lidar sensor, but if the 3D camera is installed, these objects could be detected when positioned in front of the prototype, as shown in Figure 39, with the point of view of the 3D camera.

Figure 39: Screenshot of the point of view of the 3D camera, when mounted on the prototype

9.11.6. Latency issues

The 3D camera and lidar scanner produce a significant amount of data, which caused latency issues when this data was needed by ROS2 nodes on another system, which required the data to be transmitted via a WiFi connection. This issue was resolved by adding these ROS2 nodes to the Jetson system, removing the need for this type of data to be transmitted via WiFi. This reinforces the decision to distribute the localization of the autonomous agents among themselves, instead of requiring each agent to transmit its sensor readings to a central system for localization.

9.12. Case study conclusion and recommendations

Most of the steps of the workflow from Section 8 were followed during this case study which subsequently helped the inclusion of SA aspects into the design of the wheel chock robot. The workflow facilitated the inclusion of SA aspects by systematically following the SAOD steps, while also offering a fresh perspective on turnaround operations and enabling new insights into the design of the WCR. Because the workflow was finalized after the development of the WCR had begun, the case study subsequently informed certain steps of the workflow. The creation of a functional requirement mind-map to outline the possible technical functions of the WCR inspired the inclusion of the functional requirement aspect of the workflow.

Using SAGAT, the impact of the SA design should be measured, as explained in Section 8.8. The result of this test will determine whether the workflow is beneficial for the development of autonomous agents that will be implemented into the aircraft turnaround operations.

In Section 6.8, the possible link between interdependence level and transparency level was hypothesized. Following this case study, the SA requirements step specifically showed that different types of ground personnel have different levels of interdependence between them and the autonomous agent. This resulted in different SA requirements per type of ground personnel and implies that the increase in interdependence also increases the required level of transparency. However, results of the SAGAT test could indicate that the currently proposed interfaces do not sufficiently cater for the SA of the ground personnel with less interdependence. This implies that from these results, no link between the level of interdependence and the required level of transparency can be confirmed.

One of the requirements for the prototype is *"the prototype should be able to show the colleagues at KLM what is possible in terms of autonomous turnaround operations*". This is currently not possible, because the prototype is not able to perform the task of placing wheel chocks at the MLG during the turnaround operations. The following steps should be taken to enable these demonstrations:

Manufacturing components

The components that account for the asymmetry in the prototype, should be remade in order to improve the handling of the WCR.

Packaging

The cabling for the electrical system of the prototype is not neat and could easily be misunderstood, which increases the chance of short circuits. The packaging should therefore be improved by grouping the wiring and tucking them away neatly, to improve the overview of the electrical system.

Grabber system

To enable the prototype to grab the currently used wheel chocks, the grabber system needs to be redesigned. The new, lighter wheel chocks that KLM plans to use in the future may already be compatible with the grabber system, except for the addition of the metal plate for the electromagnets.

Autonomous behaviour

The autonomous navigation capabilities should be implemented correctly by solving the current latency problems, which should then be integrated into a behaviour tree to lay the foundation of the autonomous behaviour of the WCR.

Before it is allowed to use the WCR to demonstrate its capabilities during a turnaround operation, it needs to go through several checks with the safety and procedures department at KLM. The WCR should be tested and redesigned when necessary to convince them that it is safe for demonstration.

The electrical system of the prototype was designed while it was being manufactured. This approach enabled quick feedback on its functionality, and subsequently allowed for changes to be made, without the need to redesign the whole system. A downside of this approach was that when new components were required, they had to be ordered, leading to delays in the manufacturing process.

The WCR that is used for the demonstration, should enable further testing to allow for the open knowledge gaps to be covered. This includes the testing of different sensor setups in terms of synthetic map-based localization performance, the implementation of transparency on the aircraft stand using other communication modalities than text, and the use of behaviour trees to increase the explainability of the WCR. These results should then inform future iterations of the WCR and other autonomous agents.

10. Possible impact

In this section, the possible impact of this thesis and the wheel chocking robot will be explored, both in the short term and in the long term. The possible impact is explored based on the directions that were laid out in the problem definition. The results of this section will then be used to evaluate the outcomes of this thesis project. It is assumed that the workflow and framework will cater to the design of autonomous agents on the aircraft stand, and over time increase the amount of autonomous agents that are deployed on the aircraft stand, with the implementation of autonomous docking as a starting point. This assumption will be the basis for the possible impacts that are explored in the following section.

10.1. Required ground personnel

One of the main goals of the AO project is to alleviate some of the workload of the ground personnel. Implementing a wheel chocking robot for placing the chocks at the MLG, does not immediately achieve this, since this is a task that is currently done by a TM, who will later on in the turnaround operation also perform other tasks, like the connection of the ground power or baggage handling, as shown in Section 3.8. In this same section, it is also shown that every TM that is needed to perform the arrival service also helps with the baggage handling after this. This suggests that the implementation of a single autonomous agent will not directly impact the required amount of ground personnel for turnaround operations. Instead, each step will be a piece of a puzzle that would contribute to, over time, a reduction in the required labour hours for turnaround operations. The framework could also speed up this process, by combining the different autonomous agents into one coherent process.

Completely removing the need for human operators from the turnaround operations will not be possible, since there should still be at least one human operator present who verifies and maybe corrects the autonomous agents where needed.

10.2. Performance

The use of autonomous agents during turnaround operations will be quite novel in the beginning. This means that it will take some time for the ground personnel to get used to this new way of working, which could influence the performance and subsequent turnaround times. Because of this, it is important to have a robust training plan for the ground personnel, to prepare them for this as best as possible, reducing the decrease in performance once the agents are implemented. In the longer term, when autonomous docking is being performed, performance could be increased, since the ground personnel will have fewer tasks that they are responsible for, which they can perfect and perform more efficiently. The implementation of the framework could reduce the amount of congestions that could happen during turnaround operations, improving the performance.

10.3. Physical health implications

In terms of improvement of physical health implications, if autonomous docking would be implemented in the future, the ground personnel would only need to approach the aircraft after the engines have been turned off and the arrival service is done. This could mean that the engine emissions and particulate matter have settled more than they would normally have when approaching the aircraft directly after arrival. Which in turn would reduce the exposure to these harmful particles towards the ground personnel.

The physical strain of the operation would immediately be reduced after the implementation of autonomous agents since the ground personnel would have to perform fewer activities that require repetitive movements and/or physical strain.

10.4. Aircraft stand

The inclusion of the ‘invisible’ keep-out zones in the synthetic maps used for localization on the aircraft stand, would make it possible for autonomous agents to keep clear of keep-out zones and other dangerous areas, without them being indicated on the aircraft stand. This would mean that the ‘no parking areas’ or ‘passenger bridge moving areas’ do not have to be indicated anymore on the aircraft stand if the aircraft turnaround is done autonomously.

The autonomous agent proposed in the case study from Section 9, uses a battery as its power source, and it is expected that future autonomous agents will also use batteries for this as well. This means that a significant amount of autonomous agents need to be charged, requiring additional infrastructure for this on the aircraft stand.

10.5. Operations

Building on the notion that autonomous agents can steer clear of ‘invisible’ keep-out zones, the placement of the cones during the turnaround operations could also become obsolete. The view on safety during the operations and how to implement it could shift as well, but this should be done carefully since there will always be a possibility that human operators will have to take over if something does not go as planned during an autonomous turnaround. This shifting view could also flow to other parts of the company besides only the turnaround operations from Ground Services, by showing colleagues what is possible with autonomous agents. This could open up new possibilities regarding current operations, which have been done using approximately the same methods for quite some time now.

11. Concluding remarks

11.1. Conclusion

This thesis is about exploring the challenges regarding the implementation of autonomous agents into aircraft turnaround operations at KLM and how to subsequently tackle these challenges during the development of said agents. The goal of using autonomous agents during turnaround operations is to alleviate the workload for airline ground personnel to counteract the possible problem of staff shortages and the increasing awareness about physical health risks that come with working around aircraft and repetitive physical tasks.

The implementation of autonomous agents into turnaround operations is expected to be gradual, and that means that there will be a period where ground personnel have to work together with these agents. This will have a negative influence on performance when done improperly, as explained in Section 2.3. The workflow from Section 8, should be used to guide the development of autonomous agents for use during aircraft turnaround operations, by taking into account both the situation awareness aspect and the functional aspect of the implementation into the operations. This will ensure that the situation awareness of the ground personnel that will still be present during the operation does not decrease, thus minimally influencing the performance. The use of behaviour trees for the development of autonomous agents is expected to increase the explainability of these systems.

The practical application of the workflow during the case study showed its use for the development of autonomous agents, through guiding the development of an autonomous wheel chocking robot. By following each step, the design of the robot successfully integrates both situation awareness aspects for human interaction as well as the technical aspects for the task of placing the wheel chocks.

As it is expected that multiple autonomous agents will be deployed during the turnaround operations in the future, the framework from Section 7 should be used as a backbone for these agents. This will allow for communication between agents themselves and ground personnel, also allowing the ground personnel to verify and remotely take control of the autonomous agents. The framework also enables the autonomous agents to localize themselves on the aircraft stand, since the visual docking guidance system will send the location of the arrived aircraft to the central system, allowing it to create a synthetic map for localization.

For the localization on the aircraft stand, the focus should be on visual sensors, since these should already be installed on each type of autonomous agent, as explained in Section 5.6. This in combination with synthetic map-based localization will allow the autonomous agents to localize themselves on the aircraft stand, based on the position of the arrived aircraft, without having to map the aircraft stand each turnaround.

In section 10, the impact of the implementation of autonomous agents through the workflow and framework was explored. The results point to that the biggest impact on KLM is not in the required ground personnel or performance, but in a shift in view towards the operations. This could influence how the operations are performed in the future since these operations are now built on the fact that they are done only by human ground personnel. The novelty of the use of autonomous agents is also one of the reasons why training alongside them is critical in preparation for the implementation, to ensure seamless integration.

The implementation of autonomous agents into the aircraft turnaround operations at KLM should not be done with the notion that performance will just increase and that it will immediately alleviate a significant part of the workload from the ground personnel. If done correctly, the changes will be gradual and the impact on performance and workload will be limited, but it should start somewhere. Using the workflow and the framework from this thesis, should provide a good starting point for autonomous aircraft turnaround operations.

11.2. Recommendations

The knowledge gaps that were presented in Sections 5.6 and 6.8 are not completely covered by this thesis, as well as other knowledge gaps that arose during this project. This section will elaborate on these knowledge gaps and explain how to cover them in the future.

11.2.1. Required sensor types

Tests regarding the required sensor types for localization on the aircraft stand should be executed. If the WCR can perform its tasks using a 3D camera for localization, without the addition of a lidar sensor, the 3D camera would suffice for the exteroceptive sensor part of the localization on the aircraft stand. However, since safety is an important factor during the turnaround operations, the robustness of the system could require redundancy in the form of multiple types of sensors. This could indicate that the use of both a 3D camera and 3D lidar should always be recommended for use by autonomous agents during turnaround operations.

11.2.2. Localization at the interaction points

Synthetic map-based localization enables the autonomous agents to be localized without the need for repeated mapping of the aircraft stand after the arrival of the aircraft. However, it is unclear whether this type of localization could also be used for the localization near or at the interaction points around the aircraft. As explained in section 5.6, the required accuracy of this localization could be higher than in between the interaction points. Tests regarding synthetic map-based localization near these interaction points should be conducted to indicate whether it is sufficient for these positions as well. If this were not the case, the next step would be to implement a localization method 'switch' for the autonomous agents when entering the interaction points. Going from absolute localization on the aircraft stand to relative localization based on the markers that are already placed for object recognition and pose estimation. In this same line of reasoning, it could be argued whether or not the repeated creation of a synthetic map is necessary to account for the difference in the pose of the aircraft. Because the localization in between the interaction points is expected to require less accuracy, it could be possible to use an inaccurate synthetic map, without the need for the aircraft location to be incorporated from the VDGS readings. This should also be tested by comparing the capabilities of the WCR with and without the use of a more accurate synthetic map. These results could point to a simplification of the framework, by removing the need for the VDGS to localize the aircraft for use in the creation of synthetic maps.

11.2.3. Task division

In Section 9.5, the assumption was made that the TC will have the monitoring role over the autonomous agents since they currently have this role during the turnaround operations. However, as explained in Section 6.4, information overload could be a problem when a person is confronted with too much information. It could be argued that the TC may also experience information overload, caused by the additional monitoring task. Tests regarding the number of autonomous agents that the TC can effectively monitor at the same time should be conducted to determine at what point extra ground personnel is required for monitoring. Since each turnaround task is different and could thus bring different SA requirements for different autonomous agents, this test should be repeated after additional autonomous agents are implemented, to verify whether the TC is able to monitor this altered version of turnaround operations.

11.2.4. Planning of multiple autonomous agents

The framework from Section 7 takes path planning into account, but not 'task planning'. This is something that needs to be implemented in the future, especially when autonomous agents are deployed that could take on multiple tasks, such as an autonomous agent that can place the wheel chocks, as well as connect the ground power.

The use of autonomous agents is not expected to be limited to a single aircraft stand, this will also increase the efficiency, by using these agents on other aircraft stands while they are not required at their current aircraft stand. The task planning of these agents will become more complex in that case, since there will be more 'open tasks' available to fill, increasing the number of combinations for task divisions. Because this problem already occurs with the task division of ground personnel, KLM uses a system that solves these problems and subsequently indicates which ground personnel is needed at the specific aircraft stands at the right times. Exploring possibilities for adding autonomous agents into this system would be a first step in solving this task division problem.

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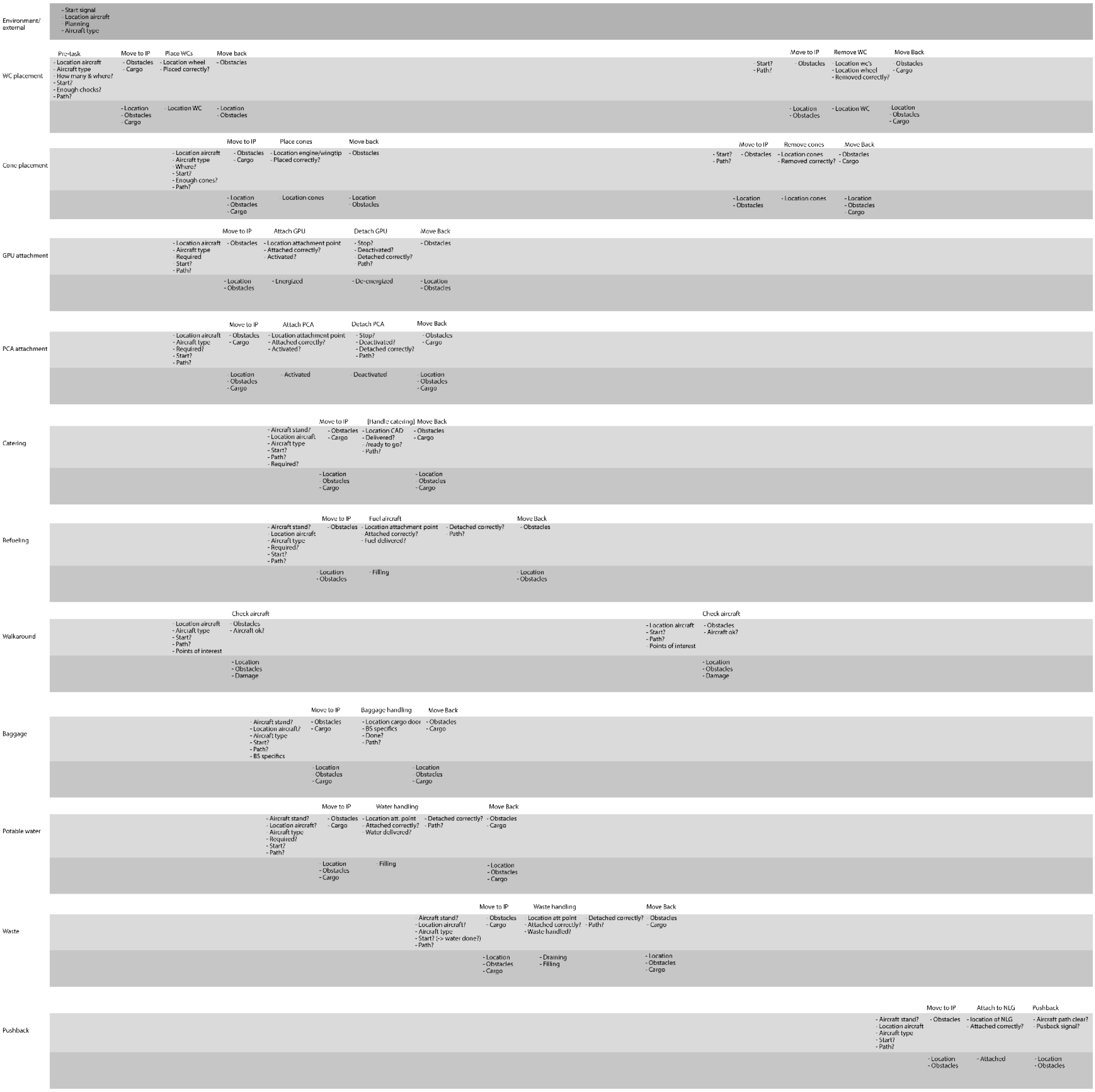
Disclaimer regarding the use of AI:

AI was used during this thesis project in terms of spelling and grammar checking, guidance during software development, guidance in academic writing and guidance in searching for specific terms or research directions.

Appendix A: Information map

The following figure depicts the information map, showcasing the required and produced information per step of the turnaround operations. The light grey bars indicate the required information and the darker grey parts the produced information. The steps are ordered in consecutive order from left to right.



Appendix B: ROS2 architecture WCR prototype

The overview presented below illustrates the ROS2 architecture of the WCR. The arrows indicate the ROS2 topics that are used for the communication between the nodes. The grey arrows indicate connections outside the ROS2 architecture, from for example sensors or motor controllers.

Please note that the overview is simplified around the Slam Toolbox and Navigation 2 nodes, to only show the connections and nodes relevant to this project. The /(location) and /(goal_location) topics do not exist for example, but for a better understanding of the general workings of this architecture, they were placed there.

The following architecture allows for both manual control through the ‘WCR_remote’ interface and also shows how the control would look like when handled by a behaviour tree.