What's (Not) Tracking? Factors of Influence in Industrial Augmented Reality Tracking:
A Use Case Study in an Automotive Environment

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Augmented Reality (AR) is a key technology for digitization in enterprises. However, often there is a lack of stable tracking solutions when used inside manufacturing environments. Many different tracking technologies are available, yet, it can be difficult to choose the most appropriate tracking solution for different use cases with their varying conditions. In order to shed light on common tracking requirements and conditions for automotive AR use cases we conducted a use case study spanning 61 use cases within the complete product life-cycle of a large automotive manufacturer. By analyzing the gathered data we were able to note the frequency of different tracking requirements and conditions within automotive AR use cases. Based on these use cases we could also derive common factors of influence for AR tracking in the automotive industry, which show the various challenges automotive AR tracking is currently facing.

CCS Concepts: • **General and reference** → *Surveys and overviews*; • **Human-centered computing** → *Field studies*; *Mixed / augmented reality*; • **Computing methodologies** → *Tracking*.

Additional Key Words and Phrases: Augmented Reality Tracking, Use Case Study, Automotive Industry

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1 INTRODUCTION

Augmented Reality (AR) is often adopted by companies because of its possible benefits. It can help speed up processes, save time in research and development, and increase employee satisfaction by aiding them in their tasks [31, 43]. Research is heavily engaged with adopting AR in industrial use cases [7, 9, 24, 25, 33, 37], as well as in other areas, like military or medicine [17, 25, 34]. Nevertheless, research in these domains often represents a prototypical state [35], as the technology still has shortcomings, such as robustness, stable accuracy, and usability, which prevents its productive use [9]. De Souza Cardoso et al. concluded in their literature survey that tracking is among the hardest challenges industrial AR is facing today [9].

AR applications are based on a form of tracking for virtual content to align correctly with the real-world [30]. Additionally, the position of the virtual content needs to be updated constantly to stay in the correct position with regard to the user's movement [1]. As AR tracking still holds lots of open research questions, it has been a trending research field [43], being one of the most researched topics of AR within the last two decades [19, 43].

Many different tracking technologies have been introduced, each with its own benefits and shortcomings [30]. As tracking is integral to an AR application, choosing the best fitting technology for it can be quite complex [38]. Normally the general conditions of the application's purpose and its environment need to be considered, as these conditions can significantly influence the choice of tracking solution [38]. As this is not a trivial task, AR is not in widespread industrial use yet [21, 35]. Even though in theory the limitations of existing tracking technologies are known [30], it may be hard to map them to real-world scenarios. This can be especially hard for non-expert users with limited knowledge about AR and without honed experience about tracking challenges. Still, in the end, it will be the non-expert users who will have to work with the AR applications, who will have to update and maintain them, it is important to bridge the gap between the theoretical knowledge base and the practical problems.

By conducting a use case study in a large automotive company, we describe the real-world issues the automotive industry is currently facing in using AR tracking. With this, we aim to map and validate the theoretically identified challenges of tracking [30] to real-world use case examples, giving researchers insights into the conditions and requirements the industry has to cope with. Additionally, we identified factors of influence, which should be considered during the development of automotive AR tracking applications. This work aims to bridge the gap between theory and practice, merging theoretical knowledge with practical facts.

2 RELATED WORK

Several scientific works discuss the problem that tracking is a major challenge keeping AR from productive use in the industry [26, 29]. Many surveyed the state of AR in the industrial setting, Boboc et al. concluded in their literature survey regarding AR applications in the automotive industry, that tracking is among the most common challenges currently faced in this domain [4]. They based their findings on the synthetization of 55 studies between 2002 and 2019 about AR systems in the automotive industry.

The current state of the art for AR and Virtual Reality (VR) in the context of industry 4.0 was presented by Eswaran et al. [11] along with challenges and opportunities in the field. In their review study, they also found that tracking is one of the main challenges in industrial AR, as it is a key enabling technology for AR and applications will not work without proper tracking.

In 2020, de Souza Cardoso et al. [9] surveyed the state of industrial AR and found that the automotive industry is the second largest adopter of AR in industrial settings, further they identified five main challenges in industrial AR: *Projection quality, accuracy, and interaction*, *Hardware*, *Tracking methods*, *Users' health and acceptance*, *Development complexity*.

It is clear, that tracking is one of the major step stones keeping industrial AR from productive use. It may even correlate and influence the other known challenges as outlined by de Souza Cardoso et al. [9]. For instance, accuracy usually is directly dependent on the performance of the tracking [2, 3, 8], whereas tracking performance and accuracy is, in turn, dependent on the hardware [10, 22]. Correlations between tracking and other challenges can possibly be made for most of the challenges [27].

The aforementioned works are all survey works, analyzing use cases described in other scientific publications. While they paint a clear picture of the general challenges for AR in the industry, they can not delve deeper into them. As outlined, we strongly believe that tracking has a certain degree of influence on most challenges, which is why we investigate on the tracking challenges more thoroughly. Through acquiring raw use case data, we could analyze the aspects of our use case in detail, ensuring to consider all the details.

The impediments of tracking technologies are known [30, 38], and the topic is trending in research for the last two decades [19, 43]. Using the categorization introduced by Zhou et al. [43], tracking technologies can be classified into *sensor-based*, *vision-based*, and *hybrid*. Each technology has its own general benefits and shortcomings. Generally, within the sensor-based tracking technologies, *Optical Sensor*, *Magnetic Sensor*, *Acoustic Sensor*, and *Inertial Sensor* based tracking technologies exist. Siltanen [36] separated Vision-Based techniques into *A priori*, techniques which need prior knowledge about the environment, either *Model-Based*, *Feature-Based* and *Marker-Based*. Or *Ad hoc*, which describes methods not using any prior knowledge like for example Simultaneous Localization and Mapping (SLAM) or Parallel Tracking and Mapping (PTAM).

Optical tracking is a low-cost solution that yields accurate and robust tracking in controlled environments. However, it is sensitive to optical noise, occlusion, and lighting conditions [18, 30]. *Magnetic tracking* has difficulties keeping accurate over longer distances. Another negative effect is the noise of other magnetic fields in the vicinity [18, 38]. *Acoustic tracking* can be influenced negatively by humidity and temperature, it has to be tweaked accordingly. It is also rather slow, since sound does not travel rapidly in the air [18, 30]. *Inertial tracking* is very lightweight but can suffer from drift when used for longer durations. It can also suffer from mechanical issues, such as friction between the wheel and bearing [18, 38].

Marker-Based tracking utilizes visual markers, like fiducial markers or QR Code like markers. While being a low-cost solution it requires the markers to be placed correctly on the tracked object. In addition, they are prone to occlusion, visual noise, and lighting conditions [5, 6, 13]. *A priori tracking* is a plug-and-play solution, which usually works using a 3D model for reference. By matching the outline of the model with the real object, tracking is very intuitive and easy to use [5, 15, 32]. For this a reference model is needed, it is also sensitive to lighting conditions and too much occlusion can also negatively influence it [14, 32]. *Ad hoc tracking* has the benefit of no prior preparation and knowledge about the environment necessary. However, it usually only tracks itself in relation to a starting point and can drift over time [5, 6].

With the current state of the art outlined, it is clear that tracking can be complex, even more so choosing the best fitting tracking technology for a certain use case. As outlined above AR adoption in the industry struggles, partly due to tracking issues, and tracking is not a trivial topic. Which issues do exactly matter in tracking within the industrial sector is still somewhat vague. Having a ground truth on the conditions in the automotive industry can make the challenges more tangible, some general challenges may not matter in the industry at all, while others can be a deal-breaker. Bridging the gap between theoretical knowledge and practical use cases should not only validate already existing research outlined in this section, but also help intensifying the knowledge base about AR tracking issues in the automotive industry and possibly in industrial settings in general.

3 METHODS

We enlisted 47 domain experts from an automotive company, each with a minimum of five years of experience working with their respective use cases. These experts explained their use cases in detail to us, additionally, we were given live demos of the use cases at the actual locations. During these detailed explanations and live demos, we observed the facts and noted down the requirements and conditions for each use case. Here, we noted hard specifications, like the accuracy requirement for the task and the duration it takes. However, also soft facts like the characteristics of the environment the use case takes place in. As well as the degree of changes the tracked object is going through, but also movement of the tracked object like relocation. In addition, for some of the use cases Proof of Concepts (PoC), done by external companies, were available, which we could also test. In these cases, we could observe challenges 3D object tracking was facing in certain environments, as this was the only technology used. None of the PoCs made it to productive use yet. It

Table 1. List of collected use cases, sorted by their use case cluster

Attaching Items	**(Interactive) Guides**	**Variants**	**Target-Actual**	**Info Visualization**
Crash markings	Process Training	Interior Design	Wiring Harness	Aero Visualization
Measuring Devices Exterior	Global Training	UI Variants	Cooling Circuit	Battery Visualization
Measuring Devices Interior	Rescue Sheets	Roof lining	Joint Locations	Meta Data
Wiring Harness	Repair Guide	Seat stitching	Enginge Components	Factory planning
Cooling Circuit	Repair Guide large scale	Mirrors	Bearer	Plant Navigation
Camouflage	Showcar building	Headlights	Underbody Screws	Factory Infos
Guard Models	Battery training	Paintjobs	Clay Validation	Maintenance guidance
Joint Locations		Interior Sales	Part Validation	Sales Factsheet
Engine Components		Exterior Sales	Construction Feasibility	Guide Interior
Device Plates		Battery variants	Joint Validation	Guide Exterior
Noise Dampening		Version variants	*Baulose* Validation	Robot safety zones
Crash Dummy			CAD Validation	Sales training
Clay Attachment			Testing mule validation	
Measuring Devices Heatmap			Test drive validation	
GOM Cubes			Ergonomic seating	

is worth noting that the experts who presented their use cases to us are specialized in their respective domains, rather than being AR experts specifically. Their proficiency in AR varied, ranging from limited exposure to rare usage . We specifically chose use cases that have future plans to incorporate AR, aiming to leverage the benefits this technology offers. The primary objective was to identify use cases, we did not assess the anticipated benefits. Instead, our focus centered on understanding the tasks that AR is intended to assist with. The use cases we gathered take place throughout the complete vehicle lifecycle, starting in the research and development phase and ending in the after-sales realm. After having detailed descriptions for every use case, we conducted an analysis that drew upon existing research, including the works of Rabbi et al. [30], Ahswini et al. [18], and Syed et al. [38]. We carefully evaluated the use cases in light of the challenges documented in these works, while also incorporating our own findings and observations from the study. Furthermore for approximately a quarter of the reviewed use cases where PoCs already existed, we examined the issues keeping them from productive use. Through this, we derived nine potential factors of influence which should be considered when selecting a tracking technology for automotive AR use cases.

4 USE CASES

Overall, we identified 61 use cases and clustered them into five different groups. Each group representing the general task and goal of the use cases within that cluster on a very abstract level. As describing all 61 use cases would be out of scope, we will instead describe one typical use case for each cluster. An overview of all collected use cases is displayed in Table 1. Short descriptions for each use case can be found in the supplemental material. However, it is important to note that without domain knowledge some use cases may be hard to understand. Not all use cases within the same cluster necessarily face the exact same challenges, instead, they can face diverse problems. The use cases we describe are intended to easily convey many of the common issues AR tracking is facing in the automotive industry.

4.1 Attaching items

The intention of use cases within this cluster is the attachment of additional material to the tracked object. Here, AR superimposes the exact location where to place the extra material on the object. Due to the nature of these use cases, at least marginal changes of the surface of the tracked object are always to be expected. However, also large geometrical changes are possible, due to the placement of additional hardware, sensors or the placement of additional body parts to alienate the chassis of the vehicle in for example prototype camouflaging. Often a requirement for these use cases was the need for a hands-free solution, as this makes to process of placement usually a lot easier compared to having to hold a mobile device in one hand. 15 of our 61 use cases belong to this cluster, it includes laying the electrical wiring for prototype vehicles and attaching camouflage and camouflage parts to testing vehicles.

A typical example in this cluster is crash preparation. During crash preparation, round markings have to be placed on the vehicle's body. Using AR, the location for these markings should be superimposed directly onto the vehicle, for users to easily place them in one run. In early development stages, these vehicles are often incomplete, sometimes they are partly disassembled and occasionally even crashed vehicles are reused. Thus 3D data of the object may not be available at all or be incomplete. Since crash tests are made all along the vehicle lifecycle, they can also have a great variance in surface materials. Sometimes vehicles are taken off the production line, which can have all sorts of paintworks and sometimes they are camouflaged prototypes.

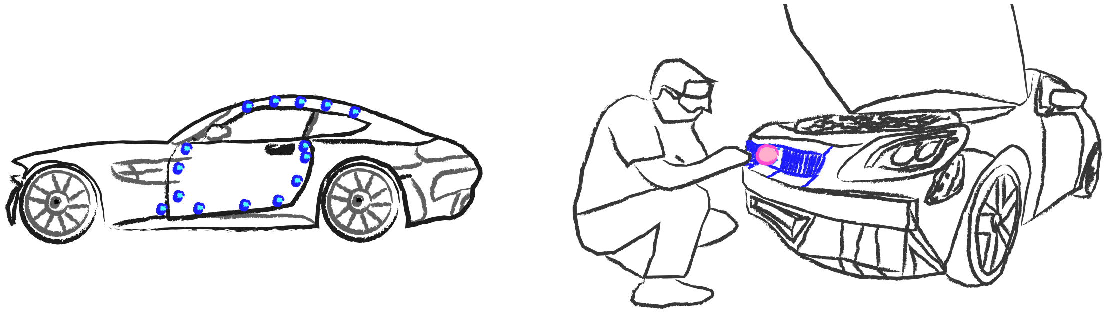
The locations where this process takes place can vary, usually it is done in controlled indoor environments, with sufficient lighting. Sometimes, however, it can also be done in spots that are badly lit. Depending on the location it may also be necessary to relocate the vehicle or lift it up on a hydraulic ramp. The required accuracy for this use case tolerates an offset of up to 1.5 centimeters. The usage of Head-Mounted Displays (HMD) is required and the process takes about two to three hours. A sketch of this use case is illustrated in Figure 1a. In short, factors that can influence the tracking for this use case are:

- Missing or incomplete 3D data (factor *3D Data Match*)
- Accuracy with an offset of less than 1.5 centimeters (factor *Accuracy*)
- Different surface properties, reflective paintworks, matte paintworks and camouflage (factor *Surface Properties*)
- Inconsistent lighting conditions (factor *Environment*)
- Vehicle is sometimes relocated during the process (factor *Target Movement*)
- Target device HMD (factor *AR Device*)
- Application has to run stable and robust for two to three hours (factor *Duration*)

4.2 (Interactive) Guides

The goal of use cases in this cluster is to give instructions or training guides on certain processes. This can be repair instructions to educate trainees, but also more complex tasks. Here, it is often an issue that applications would have to be used in workshops and plants all over the world, which sometimes leads to different requirements regarding devices and technology, but also different work environments. In addition, use cases here can often deal with unknown geometry. Large-scale customers like fire departments and the like can modify the vehicles externally, but still need digital guides for them to get trained on the maintenance of newer vehicle models. Even the company-owned workshops and dealerships would often have to deal with vehicles modified by the customers. As these guides are meant to be as interactive as possible, they mostly require a hands-free solution. Since users will be working on the tracked objects heavy changes in the geometry are typical in this cluster. Seven of our 61 use cases belong to this cluster, it includes digital AR overlaid Rescue sheets for the fire brigade and process training for new carlines on the production lines.

A typical example in this cluster is the interactive repair guide [40]. Here, users will be walked through a repair process, with tasks superimposed onto the object of interest. Repair guides will be used all over the world in workshops, but are also necessary for customers with special vehicles like military, fire brigade, or ambulances.



(a) *Use case: Crash preparation* (b) *Use case: Repair Guide*

Fig. 1. 1a: Sketch of *crash preparation*; The AR view of the user is illustrated. Users have to place markings on the vehicle (highlighted in blue). These highlights will be superimposed onto the vehicle. Here the vehicle is missing parts at the front and is damaged a bit. 1b: Sketch of *repair guide*; Users will be working on the object directly. The part of the current task will be digitally overlaid and highlighted within their view.

In such cases, 3D data might not be properly available, due to the fact that the vehicles were further modified by the customers. They can also be partly deconstructed or damaged. Vehicles can have special paintworks, not issued by the manufacturer, leading to possibly unknown surface properties. Because of its worldwide usage, many different environments are possible, especially with special customers. Here repair guides may be used in the field, or outdoors in bad weather conditions. The accuracy requirement for this use case tolerates an offset of up to two centimeters. However, users need both hands free to work, therefore it requires a HMD solution. Depending on the specific repair tasks the process can take everything from half an hour to a complete working day. The geometry of the object will obviously be changing constantly as parts will get removed or added. And the vehicle will often get relocated, for example lift up on a ramp. In addition, tracking multiple parts of the repair process might help in identifying steps of the work process, or the completeness of certain steps. A sketch of this use case is illustrated in Figure 1b. In short, factors that can influence the tracking for this use case are:

- Incorrect, missing or incomplete 3D data (factor *3D Data Match*)
- Offset of less than two centimeters (factor *Accuracy*)
- Various surface properties possible (factor *Surface Properties*)
- Geometry might be changing significantly (factor *Target Object Changes*)
- May be used outside or in badly lit environments - inconsistent lighting (factor *Environment*)
- Vehicle is sometimes relocated during the process (factor *Target Movement*)
- Target device HMD (factor *AR Device*)
- Application has to run stable for a few hours or complete working day (factor *Duration*)
- Multi tracking targets (factor *Multi Targets*)

4.3 Variants

During vehicle development, many different variants are made. Building all these variants physically is expensive and takes time. Having fewer hardware mock-ups ready and visualizing variants on these mock-ups, can save a great deal of money. This is the goal of the use cases in this cluster, visualizing different variants, not only on mock-ups, but also on complete vehicles. Here, usually the tracked object is not changing at all and stays in the same position during the whole process. It also usually takes place in controlled, inside environments. Usually, a Video-See-Through device is preferred for this as it completely overlays the underlying hardware and is not foreign to users new to the AR technology. Twelve of our 61 use cases belong to this cluster, it includes overlaying variants for the User Interface and superimposing different vehicle part versions onto on another.

A typical use case in this section is the interior design variant use case. In the vehicle development process, many designs both for exterior and interior are proposed constantly. At some point, it has to be decided which designs should go into production and which ones to scrap or revise. Since many vehicles are in development simultaneously, many different variants have to be screened and decided upon. Using AR and superimposing variants on physical hardware or mock-ups to view the variants can be beneficial and speed up the development process. As these serve as a decision base, this use case requires an accuracy offset of at most one centimeter. For comfortable use Video-See-Through Tablet AR is required in this case.

As this use case discusses the interior design variants, the workspace is the interior of a vehicle that is dimly lit and the space to move and track in is sparse. Additionally, many different materials are present, including reflective foil, matte clay, and different kinds of cloth and leather. The application will be running for a few hours. Since this is often used in meetings with higher management the time schedule is usually very tight, and does not allow for any tracking issues or restarting. In Figure 2a a sketch of this use case is illustrated. In short, factors that can influence the tracking for this use case are:

- Offset of less than one centimeter (factor *Accuracy*)
- Different surfaces, shiny, matte, some with many features, some with few features (factor *Surface Properties*)
- Dimly lit environment inside of a vehicle (factor *Environment*)
- Target device Tablet (factor *AR Device*)
- Application has to run stable for a few hours (factor *Duration*)

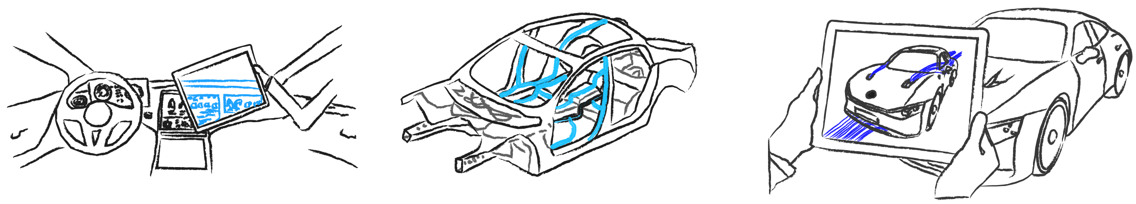
4.4 Target-Actual Comparisons

In quality assurance often the physical hardware has to be cross-checked with the digital data to make sure everything is planned. The tolerated offset between physical and digital can be below one millimeter. Overlaying the digital data onto the physical hardware reduces the effort in these tasks by a huge margin, making it not only easier and more satisfying to do, but also less error-prone and tedious. The tracked object here is not changing as this is a quality assurance process, the device requirement is heavily dependent on the accuracy requirements here. 15 of our 61 use cases belong to this cluster, it includes general validation of vehicles and vehicle parts with their digital data and validation of the location of screws and welding points.

A typical use case in this cluster is the validation of the position of the electrical wiring. In early development stages, wiring is still done manually. In order to ensure that the wiring matches the digital plans, quality assurance has to check the correct placement of the wiring. Doing this by superimposing the correct wiring path onto the body-in-white is much easier than having to compare the data on a screen with the physical object.

The required accuracy for this use case only tolerates an offset of one millimeter. Since this is only a checking task and no interaction with the object is required, the preferred solution would be a tablet device. Depending on the scope it can take a few hours until everything is checked correctly. Here, it would also be helpful to track several cable paths at once. The working environment is usually controlled, indoors with various adjustable lighting settings. In Figure 2b a sketch of this use case is illustrated. In short, factors that can influence the tracking for this use case are:

- Offset of one millimeter tolerated (factor *Accuracy*)
- Target device Tablet (factor *AR Device*)
- Application running for at least a few hours (factor *Duration*)
- Tracking of several objects/cables (factor *Multi Targets*)



(a) *Use case: Interior design variants* (b) *Use case: Wiring harness* (c) *Use case: Aero Visualization*

Fig. 2. 2a: Sketch of *interior design variant*; Displayed is a mock-up of a vehicle's interior. A user is holding a tablet in their view on which an interior variant is superimposed onto the mock-up. 2b: Sketch of *wiring harness*; The user's AR view is pictured. Upon working on the body-in-white the user can view the placement and path of the cables placed. In the sketch these are displayed in blue. 2c: Sketch of *aero visualization*; Users can superimpose the airflow around the vehicle using tablet AR, the airflow is displayed in blue.

4.5 Information Visualization

This use case cluster focuses on use cases with the goal to convey additional information using AR. This can be simple meta-information for parts, like version number, but also information like airflow around a vehicle. In addition, AR navigation systems fall into this category, as well as AR-aided factory planning. Accuracy is usually not much of an issue, still it has to correctly convey the information for which some degree of accuracy is still necessary. Due to the large location variance in this cluster, we have to deal with many different environments here. Twelve of our 61 use cases belong to this cluster, it includes digital data for factory planning, plant navigation but also information about robots and other machines.

A typical use case in this cluster is the aerodynamic data visualization. Using AR to overlay the aerodynamic data of a vehicle makes the aerodynamic workings much more tangible and understandable. It is easy to convey the aerodynamic technology used, and it is also easier to find problems in the airflow and the reasons for these problems. This use case sometimes faces the issue that 3D tracking data, a plain 3D model, of the tracked object is not available in perfect condition. This is due to the fact that it is often done with prototype vehicles, which can be modified on short notice. Accuracy-wise, the application has to be precise enough that the displayed airflow makes sense, in this case, a required tolerated offset of two centimeters. Surface properties of the objects can vary from glossy, metallic paintworks or foils, to camouflaged vehicles. These AR simulation visualizations are often done in different environments. For example in external locations during events or vehicle presentations, especially if the drag coefficient is noteworthy for the particular vehicle it is not uncommon to have it available at press driving events and similar events. At foreign locations like fairs, users usually have to take the environment as is, they won't be able to change the lighting use spotlights et cetera. The device requirements for this use case are mobile devices and Video-See-Through as handing over tablets is more convenient and hygienic than HMDs. Depending on the event this is used at, it often has to run for several hours continously. In Figure 2c a sketch of this use case is illustrated. In short, factors that can influence the tracking for this use case are:

- Sometimes incomplete 3D data (factor *3D Data Match*)
- Offset of less than two centimeters (factor *Accuracy*)
- Various surface properties possible (factor *Surface Properties*)
- Will be used in unknown environments with inconsistent lighting (factor *Environment*)
- Target device Tablet (factor *AR Device*)
- Application has to run stable for many hours (factor *Duration*)

5 FACTORS OF INFLUENCE

In the preceding section, we introduced five use case clusters along with one example use case for each of those clusters. In the use case descriptions, many challenges were highlighted, we describe these in detail here. We outline factors that influence the tracking (technology) or can make it challenging in detail. These are based on our use case study and are therefore grounded in real-world scenarios, to give an informed overview on which things have to be considered in automotive AR tracking. Some factors of influence are use case based requirements, like for example accuracy, while others originate from the surrounding conditions of a use case.

5.1 3D Data Match

3D Model-based tracking techniques like Vuforia[1] or VisionLib[2] are a popular solution [4, 9] for AR tracking. In our survey, we noticed, that all of the use cases which had a PoC used this technique, possibly due to its simple usage. After all most of our use cases will be done by non-AR-expert users, for which a plug-and-play solution would work best. However, *A priori* tracking needs some form of prior knowledge about the tracking object, usually a 3D model is used for this [16]. The quality of this reference model has to match the real-world object as well as possible, otherwise the tracking accuracy will be poor [16]. During our use case study, we observed that a correct 3D model was often unavailable (4.1, 4.2, 4.5). This was primarily due to modifications made by users, damaged vehicles, camouflaged vehicles, or just very early prototypes. Users stated: "*Sometimes we do not know the exact specifics of vehicles beforehand, then they can be partly disassembled and tracking will not work.*" Accordingly, the 3D data matching rate, meaning the percentage of match between the digital model and real-world object is an influencing factor. The worse the matching rate, the bigger the influence on the overall performance, especially accuracy of the superimposition. *Within our 61 reviewed use cases, missing or unsuitable 3D tracking data was an issue for 24.6% of them.*

5.2 Accuracy

The accuracy of the digital superimposition is a use case requirement. Certain processes can only allow for a limited offset of the digital data, due to law regulations as well as internal standards. Many, including ours, AR use cases in the industrial setting are dependent on the augmentation being as precise as possible [9]. Yet, highly accurate augmentations are generally harder to achieve [9, 29]. Some use cases only tolerate an offset of one millimeter (4.4), while others can cope with two centimeters and some even more. Especially Target-Actual comparisons usually need a very high precision to be a promising solution. Depending on the accuracy requirement, some tracking technologies are not able to deliver such high accuracy. As different technologies have different accuracy limitations, developers and researchers have to be aware of this and choose accordingly. We further categorized the accuracy requirements into *High*, which tolerates an offset of up to 0.5 centimeters, *Mid*, with a tolerated offset of up to two centimeters and *Low*, with a tolerated offset of up to five centimeters. We argue that anything above that does not have any accuracy requirement at all. As can be seen in Figure 3a, 34.4% of our surveyed use cases belong to the *High* accuracy requirement, 59% require *Mid* accuracy and 6.6% require the low accuracy requirement. Accuracy is also a key requirement in other areas, such as surgical AR. In a review conducted by Fick et al. [12], various surgical systems were evaluated, revealing a mean offset of about 2.5mm. Submillimeter precision can be a requirement and achievable, however achieving high levels of accuracy often entails extensive setup procedures.

[1]https://https://www.ptc.com/de/products/vuforia
[2]https://visionlib.com/

5.3 Surface Properties

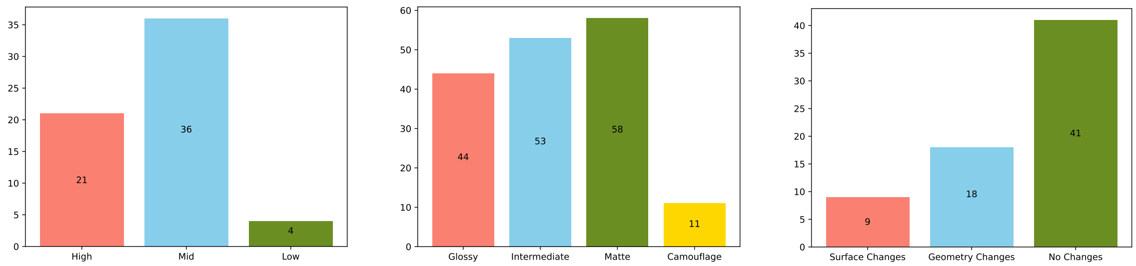
Automotive AR use cases can contain different surfaces and materials with different surface properties. Some are glossy and reflective, some can be matte. Additionally, some surfaces have very few features, some have many features. Some surfaces are camouflaged, which is common for testing vehicles. In some use cases, many different surface materials are present. Therefore, there is a rather large variance in potential surface properties. Dealing with certain surface properties may be easier with some technologies. Some technologies rely on objects having a sufficient amount of features [20]. Smooth surfaces will be hard to track by a natural feature tracking algorithm [20]. Reflective surfaces can also pose a problem for optical and visual tracking techniques [30]. Depending on the surfaces present and the characteristics of the environment (like lighting) some technologies may struggle. Some users confirmed that this can be an issue, stating: "*We often had problems with silver metallic vehicles in well-lit environments.*" We categorized this factor further into *Glossy*, *Intermediate* and *Matte* according to the work of Yoshimizu et al. [41]. Further, we added the category *Camouflage* as this is common in use cases within the research and development cycle. As can be seen in Figure 3b *Matte* surfaces are the most common with 95% occurrence, regardless *Intermediate* and *Glossy* are not uncommon either, with 86.9% and 72.1% occurrence respectively. Some use cases deal with mixed materials, having more than just one of the possible surfaces present. The gap regarding the *Camouflage* property can be explained that this usually only applies to use cases in research and development.

5.4 Target Object Changes

Some use cases need interaction with the tracked object, which can lead to changes in the object during the process, both geometry and surface. This is especially true for use cases in the interactive guide cluster. Changes in the object can inhibit the ability to keep an augmentation on point [15, 42]. This depends on the used tracking technology and the scale of changes. As this is part of the use case it has to be considered and weighed accordingly, to select a tracking technology not affected by this. A user stated: "*In our repair scenarios, simple tasks like removing the wheel completely changes the visible geometry. Tracking usually had issues with that.*" We categorized this factor into *Surface Changes* and *Geometry Changes*, it is though important to note, that some use cases have both. Figure 3c displays the target object changes distribution, showing that *Geometry Changes* occur in 29.5% of our use cases, which is twice as much as *Surface Changes* (14.8%). Having no changes at all is true for 67.2% of our reviewed use cases. Further investigation is needed in the future to establish precise thresholds for object change percentages that can be accommodated by different tracking technologies.

5.5 Environment

The environment, like lighting, a use case takes place in can have a significant influence on the tracking performance [13, 15]. In some cases lighting is completely controlled, in others, especially outdoors it is hard to control. Also often spaces may be dimly lit, like vehicle's interiors or under-bodies. Especially visual tracking techniques depend on sufficient lighting [14, 30]. For one of our use cases a user stated: "*The vehicle is lifted up and we work on the underbody of the vehicle, it is not really dark, but a little dim, however tracking on the underbody never really worked.*" This factor also correlates with the surface properties factor, as reflective materials can increase the challenge sunlight can pose to visual tracking techniques [15, 32]. In our use case study, we identified several outdoor use cases, some interior or underbody use cases with dim lighting and many with controlled, indoor lighting. Some use cases take place in completely unpredictable environments, where the conditions have to be taken as they are (4.5). We further categorized this factor into *Predictable*,



(a) *Accuracy* (b) *Surface Properties* (c) *Target Object Changes*

Fig. 3. 3a: Frequency of different accuracy requirements in absolute values within our survey. 3b: Occurrence of the different possible surface properties in absolute values within our survey, some use cases have to deal with more than just one property. 3c: Frequency of the two different target objects changes in absolute values within our study.

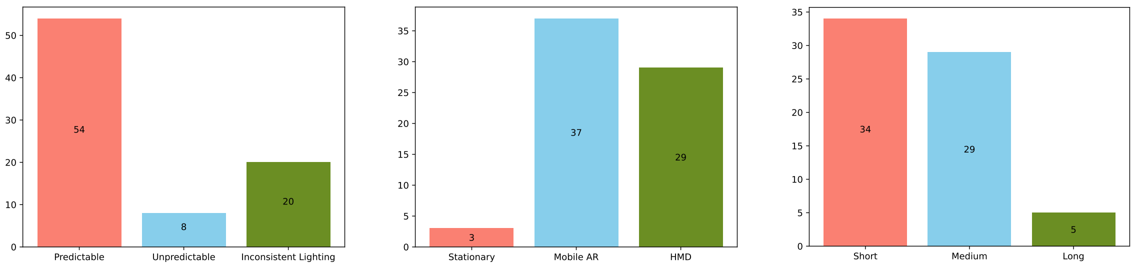
describing environments that are known and can be controlled in terms of for example lighting, this would be indoor design workshops. The second category is *Unpredictable*, describing environments that are unpredictable and usually can not be controlled or only to some degree, like, for example, outdoor environments. Use cases with unpredictable environments need more robust solutions, as the exact circumstances and hence challenges will be unknown. Last is *Inconsistent Lighting*, as for some use cases lighting situation is extra hard, but still predictable. For example being inside a vehicle, or under it, can lead to dim lighting. As displayed in Figure 4a the majority of use cases are in a predictable environment with 88.5% of our use cases. Having inconsistent lighting is not uncommon though, occurring in 32.8% of our use cases. Just 11.5% have to deal with unpredictable environments.

5.6 Target Movement

In some cases, the tracked object has to be moved during the process, for example for relocation to get a better viewing angle on the object or put it on a lifting ramp to get to the underbody. It may even be necessary to track a continuously moving object. This factor might pose problems with some tracking approaches, especially in combination with accuracy requirements. In this factor, we consider continuously moving tracking targets as well as tracking targets that get relocated during the tracking process, like lifted on a ramp. Within our survey, any kind of movement only occurred for 19.7% of all use cases, which is still not rare enough to just neglect this. However, the overwhelming majority of this was just relocation, only two use cases have a continuously moving tracking object at the center of the process.

5.7 AR Device

The choice of AR device depends on the requirements of the use case, which in our study was for almost all use cases the ability to move around, and in addition, for some the requirement to have the hands free. Different devices have different hardware capabilities. Some requirements may not be achievable with some devices [23], because of hardware limitations. Since AR tracking can be computationally expensive [39], the chosen device is an influencing factor as it can limit technologies based on their hardware requirements. In addition, some devices may be equipped with additional sensors which can aid and enable certain tracking technologies like for example Light Detection and Ranging (LiDAR) sensors. Within our study, only three categories for this factor occurred: *Stationary*, *Tablet*, and *HMD*. As displayed in Figure 4b, the requirement for both *Tablet* and *HMD* are common, with 63.9% and 45.9% respectively. *Stationary* is rare with just 4.9% of our use cases. Some use cases may require both a *Tablet* and *HMD* solution.



(a) *Environment* (b) *Device* (c) *Duration*

Fig. 4. 4a: Frequency of different environments within our use case survey in absolute values. 4b: Frequency of different device requirements within our use case survey in absolute values. 4c: Frequency of different duration requirements within our use case survey in absolute values.

5.8 Duration

All of our use cases have different requirements regarding the duration of the tracking. Tracking and augmentation can shift over time, due to noise and other influences. This drift can lead to a substantial offset over time [32]. This effect can be reduced by restarting the tracking. However, this is sometimes not possible, because of time constraints, and a long-term stable tracking would always be preferred. Most of our use cases take somewhere between one and four hours, and tracking should remain stable and accurate during this complete time. Therefore stability over extended periods of time is something to keep in mind, depending on the requirement of the use case. We further categorized this into *Short*, *Medium*, and *Long* durations, with the time frames being less than an hour, less than four hours, but more than one hour, and more than four hours respectively. As displayed in Figure 4c, use cases which need the augmentation for more than four hours are somewhat rare only occurring in 8.2% of our use cases. Most use cases either take less than an hour which is the case for 55.7% or less than four hours but more than one hour as is the case for 47.5% of our use cases. A few use cases can vary in their needed time, leading to some use cases having more than one time frame selected.

5.9 Multi Targets

In some automotive use cases, tracking several objects at once is necessary or preferable. For example, tracking several cables and their path in the wiring process, tracking several screws to make sure all screws were placed correctly. Tracking several independent objects may increase complexity for the tracking technique [28], as well as computational power necessary. In most of our use cases, multi targets were not a necessity or requirement, often it would mostly be a nice-to-have feature expected to increase the overall stability of the application. Still, to reap all of the benefits AR can bring to the industry, it should certainly be considered if the chosen technology can even cope with it. The preference for multi target tracking applied to 31.1% of our reviewed use cases.

6 LIMITATIONS & FUTURE WORK

Our use case study was limited to only one company within the automotive domain. Although processes for other manufacturers might be similar, it is unclear if differences exist and what kind of differences. Further, it is unclear if other industrial branches face the same issues, or possibly other issues. We argue that the factors likely apply to other manufacturers as well as other industrial branches, as the use cases described can easily be abstracted to a point where they match use cases in other branches. The identified factors could be universally relevant, in other areas some factors might not matter as much though. Validating if these factors actually are universally important remains as future work.

While we identified important factors which influence the tracking for automotive AR use cases, we did not rate or weigh them. We did not conduct an in-depth investigation into the relative importance of each factor or explore potential correlations or causal relationships among them. This is just a factual compilation of these influencing factors.

Within our use case study, one additional issue became abundantly clear - the human factor. In the end, the use cases are done by humans, which have to be able to use the technology and who are not AR experts. These users have to be satisfied with AR technology and feel the benefit of it, or else they will not use it. Setting up tracking technologies can often be tedious and complicated, especially for non-AR experts. These tedious setup processes pose a high entry hurdle, which can discourage users, leading to a low acceptance of the technology. This could possibly be one of the most important reasons why many tracking solutions available in the research community are not in widespread use within the industry. They are too complicated, tedious, and impractical and do not have the human user in mind. Even though advances are made, many technologies are not ready for practical use because of this. More research has to be done in that area to make tracking accessible to the users, and not keep it in research laboratories.

7 CONCLUSION

In this work, we surveyed 61 AR use cases within the automotive industry regarding the challenges they face in AR tracking. We clustered the use cases into five clusters, each of them representing a specific goal for use cases within the cluster. For each cluster we described one use case in detail, highlighting the challenges this specific use case has to overcome. Based on all our use cases we then derived factors of influence for the tracking technology.

The factors should highlight the challenges automotive AR faces in a tangible way and shed light on why AR is not yet adopted productively in the automotive domain. By analyzing our retrieved use cases we were able to ground the tracking challenge in nine factors, which can possibly be changed, controlled, and improved on. Tracking methods as a challenge are abstract and broad, knowing why it is challenging, makes them more accessible and easier to work with. In addition, we displayed the frequency of these factors within our study, giving hints on their importance.

We found that inconsistent lighting conditions occur as often as in a third of our reviewed use cases. Missing 3D data is an issue for a quarter of our reviewed use cases, making 3D object tracking difficult in such cases. Having an accuracy of at least 0.5 centimeters is required for more than a third of our surveyed use cases, only 6.6% are fine with an offset of five centimeters. Therefore accuracy is one of the more important aspects. Changes of the object occur in about a third of our surveyed use cases, while geometrical changes happen twice as much as surface changes. Stationary AR does not seem to be very relevant, as less than 5% require this, as opposed to almost 61% requiring Mobile AR and 47.5% requiring HMD AR. The absolute majority of our AR-aided use cases take a time of less than four hours.

It is unclear if our identified factors generally apply to the automotive industry, or would also apply to other industrial sectors or possibly even further. We want to investigate these questions in the future. We also plan to do an in-depth analysis of each factor, find dependencies between them, and categorize existing solutions in regard to our identified influencing factors. By evaluating how much each factor influences certain existing solutions, we aim to clear the path to bring AR research into industrial practice.

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