DIGITAL ASSISTED COLLISION AVOIDANCE FOR MOBILE MACHINERY

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ABSTRACT

Despite high safety standards and numerous preventive measures, both employees and objects on the construction site are exposed to a high risk of accidents. These scenarios are often caused in the handling of construction machinery, such as excavators or wheel loaders. Today there are different technologies and technological solutions for avoiding such scenarios including mobile machinery, provided by OEMs or third-party developers. This paper presents on the one hand an overview of existing technologies and technological solutions, classifying them into perception sensor, transponder-based and digital twin approaches. Furthermore, various available sensor modalities with their pros and cons for obstacle detection and classification as well as complete solutions are discussed more deeply. On the other hand, this paper introduces a dynamic collision avoidance system for mobile excavators using the cross-platform game engine unity, which combines advantages of digital twin and transponder based approaches. The system collects machine data based on so-called 3D-systems on a construction site and connects them with planning data as well as regulations and guidelines concerning protection zones. By using multiple colliders for static and dynamic objects, a reliable collision prediction on the construction site is realized. The system interacts with the excavator respectively the machine control by limiting actuator speeds, wherefore a certain minimum distance between mobile machinery and objects can always be ensured. For demonstrating the applicability of the solution, different tests on a real construction site environment are presented. The investigated scenarios are oriented towards typical track construction activities.

Keywords: Digitalization, Safety, Mobile Machinery, Conncetivity, Construction Site

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1. INTRODUCTION

The rules for occupational health and safety on construction sites, RAB for short, are defined and adapted to current developments by the Committee for Safety and Health Protection on Construction Sites (ASGB), which is affiliated to the German Social Accident Insurance Institution for the construction industry. These rules are regarded as the state of the art for safety on construction sites and are binding for the client during construction. It is therefore the client's responsibility to ensure that all measures to maintain the rules are organised and enforced [1].

The "risk of construction sites" is generally known. Due to the uneven terrain, the many machines and tools moving around there, construction sites conceal a particularly large number of risks. Safety represents an elementary basic human need, whether this concerns the working environment, the private household or the public space. According to the definition of the Federal Ministry for the Environment, Nature Conservation, Building and Risk Safety, objective safety can be considered to be given if real danger scenarios are prevented in the best possible way. Safety is guaranteed when damage occurs and the extent is reduced as far as possible. Technical safety requirements are part of product development and are demanded by customers in order to avoid accidents [2].

Despite legal requirements and preventive measures, employees in the construction industry are exposed to a particularly high risk of accidents and health hazards. The frequency of accidents on construction sites in Germany is on average more than twice as high than in the commercial sector. This is also confirmed by statistics from the German Social Accident Insurance (DGUV). In 2021, 49.84 notifiable occupational accidents per 1000 full-time workers were recorded in the construction industry. In the commercial economy as a whole, however, the rate was only 22.83 per 1000 fulltime workers. In 2021, 103,970 reportable accidents occurred on German construction sites, 85 of which were fatal [3].

One general issue of mobile earth-moving machinery is the often repeating, monotonous cycle-type workflows. In many cases, wheel loaders and excavators cyclically pick up material at one location and dump it at another. Dump trucks drive between loading and unloading points over-and-over again in short distances. Cycle times vary between around 20 seconds up to multiple minutes, but repeat often over a full work shift. Depending on the machine type, vehicles can travel up to 50% of their time in the backwards direction (e.g. a wheel loader in a short Y-cycle).

Multiple risk factors can come into play:

- very monotonous work cycles can lead to a gradual reduction of attention of the operator after long periods of time, especially in uneventful scenarios
- in stressful scenarios (e.g. a recycling yard) with multiple other vehicles and pedestrians around the machine, high productivity targets and the requirement to monitoring the environment 360° around the machine over a full shift can be very exhausting
- night-time operation can lead to accelerated fatigue and inattention

Today there are different technologies and technological solutions for avoiding accidents including mobile machinery on construction sites, provided by OEMs or third-party developers. This paper presents in section 2 an overview of existing technologies and technological solutions. In order to reduce the number of accidents and ensure safety on the digitalised construction sites of the future, different solutions are presented in this paper. Section 3 discusses solutions for mobile machines based on on-board perception sensors. In section 4, a dynamic collision avoidance system for mobile excavators using the cross-platform game engine unity is introduced.

2. STATE OF THE ART

As mentioned before, there are various technologies and technological solutions, which are already being used today for increasing safety on construction sites. Regarding the safety of mobile machinery, these solutions can be clustered into two general approaches:

- Perception Sensor Approach (Camera, lidar, radar, ultrasonic, …)
- Transponder-Based Approach (UWB, Bluetooth,…)
- Digital Twin Approach (position sensors, e.g. IMU, GNSS tracker, angle sensor)

The perception sensor approach aims to increase site safety by using local sensors and corresponding electronics on the mobile machine. For example using cameras or radar sensors for detecting potential obstacles or humans. Within this approach, the priority is always to improve site safety based on sensor data, independent of external information sources. Transponder-based approaches collect tracker information of mobile machinery and construction workers for avoiding accidents. The digital twin approach aims to improve the safety by combining different information sources, which means sensor data and a digital environment as well as machine model. In the following, the state of art for these approaches is explained. Each solution has their pros and cons, which will be discussed further in the next chapters.

One general requirement for any solution is a high tolerance towards harsh environmental conditions. Mobile machines experience high levels of shock and vibration, dust, fog, snow, high heat and extreme cold weather conditions, uneven terrain and are also typically cleaned with high-pressure washers. Typical requirements for any electronic device exposed to the outside are therefore a temperature range of -40 … +85°C, an IP69K protection class and a multitude of environmental certifications such as salt-spray tests, chemical resistance, radiation resistance etc.

2.1. Perception Sensor Approaches

The main benefit of equipping a mobile machine with on-board perception sensors for obstacle/pedestrian detection and avoidance is the fact that this machine can be operated anywhere without the need for special organizational measures, special infrastructure or equipment on other vehicles or pedestrians.

Suitable sensors can be classified into passive or active sensors. Passive sensors only passively receive information from the environment (e.g. camera, stereo-camera), while active sensors send out signals and react based on the return of those signals (e.g. ultrasonic, radar, lidar or various time-of-flight solutions). In general, both types are suitable for the task, but with active sensors additional regulations need to be considered such as limitations in transmittable signal power, regulatory approval for certain emitted frequencies etc.

One important aspect to consider is that many mobile machines operate in tight environments and need to travel close to stationary obstacles regularly – often even in every consecutive work cycle. This brings us to the topic of obstacle classification.

Depending on the sensor modality there are various possibilities to tune the reaction of the vehicle (i.e. if a warning is given, how the warning is given, if the machine is stopping automatically) depending on the type of obstacle that is present. We describe two extreme scenarios on different ends of the spectrum on what is possible today.

a) Simple System (Obstacle recognition)

A simple system could be realized by using an affordable sensor modality like an ultrasonic sensor that only provides range data to an obstacle. Depending on the travel direction of the vehicle, an alarm can be sounded in the operator’s cabin when an obstacle comes closer than a predefined threshold value. This system is easy to obtain and tune and might work well in rather open environments, but fails to gain the operators acceptance in confined spaces due to the constant sounding of unnecessary warnings. The subsequent "alarm fatigue", i.e. the operator becoming accustomed to constant warnings, leads to warnings being ignored, even if they could be relevant in exceptional cases.

b) Smart System (Obstacle classification)

In an intelligent system scenario, the type of obstacle approaching the machine is classified (e.g. into classes such as pedestrians, cyclists, wheeled machines, vegetation, etc.). This can typically be done using AI-based approaches in combination with different sensor types such as cameras, radar and lidar. In addition to knowing the type of obstacle, the relative movement of the obstacle is also tracked. Together with the known ego-movement of the vehicle, the basis for decision-making for warnings and movement reduction is very broad.

With such a system, the challenge of driving in a confined construction environment and the goal of not overwhelming the human driver with unnecessary warnings can be achieved. A machine equipped with this technology warns the driver or intervenes in the vehicle's movements only when it is really necessary - for example, when pedestrians are present and there is a risk of them being involved in collisions. Avoiding 'alarm fatigue' and ensuring that the operator does not become accustomed to constantly appearing unnecessary warnings in a confined working environment offers clear practical benefits.

2.2. Transponder-Based Approaches

Another approach is to equip both the machines as well as the pedestrians around the machine with tracking devices or transponders. With technologies such as UWB (ultra-wideband), these devices can be tracked relative to one another using vehicle-fixed antenna arrays. A control system of a machine will therefore always know where the specially equipped pedestrians are in relation to the vehicle. A clear benefit against on-board perception sensor approaches is that this technology is independent of pedestrian poses (standing, kneeling, lying on the ground), can localize pedestrians around corners or even through certain obstacles and is very tolerant against environmental impact such as dust or fog.

On the other hand, this approach relies heavily on organizational measures to provide site safety. Every pedestrian that can potentially get close to a machine always needs to be equipped with a tracking unit, the battery always needs to be charged and access to the work area without passing through a dedicated checkpoint must be prohibited. There are many approaches such as integrating the tracking devices into high-vis wests or helmets to try to make sure people do not forget to carry them. This is the main reason that these types of solutions are limited to very few scenarios such as underground mining and certain industrial plants today. For typical construction sites, the applicability is very limited with often multiple companies working on one site and no complete separation against external pedestrians. Scaling of costs is another challenge, since every additional potential person at the site needs another tracking device. Another issue is that this technology can potentially create unnecessary warnings or machines braking even if pedestrians are not actually in the danger zone. A typical example is a trench construction scenario in which the machine works on one side of the trench and the person works on the other.

One such system to mention is the PLINX [4] of Mesafox. This system is based on tags/ transponders, which are attached to machines, objects and people. These tags are equipped with a variety of sensors, including GNSS, proximity sensors, accelerometers, which send their data to local networks via various interfaces such as Bluetooth or UWB. If two tags draw near to each other, an event is triggered, and therefore acoustic, haptic and visual signals are activated to warn the people affected. Furthermore, individual events, which trigger corresponding warning signals, can be defined with the help of the associated software. Such individual events can be SOS signals, dead man’s switches and the definition of danger zones.

2.3. Digital Twin Approaches

The implementation of 3D machine control systems in mobile machinery is becoming increasingly common. This technological development is revolutionising the precise control of excavators and other heavy machinery through the integration of tilt/ rotation sensors, RTK-GNSS system and digital, geo-referenced construction site models. Regarding achieving higher accuracy, efficiency and cost-effectiveness, more and more companies are using these control systems. There are few advanced collision avoidance systems based on such existing 3D control systems. These systems [5] [6] offer generating virtual barriers in the digital construction site environment. These virtual barriers prevent the excavator from crossing certain areas. If the mobile machine draws near such a virtual fence, the speed is automatically slowed down or the movement is completely stopped. These measures ensure a precise and immediate response to potentially dangerous situations.

3. SOLUTIONS BASED ON ON-BOARD PERCEPTION SENSORS

Solutions that are established on the market and commercially available for the use on mobile machines today can be classified based on the protection goal (all obstacles or specifically pedestrians) and the sensor modality used.

Basic systems use ultrasonic sensors that measure a distance from the sensor to a possible obstacle in a short, cone-shaped field-of view. These types of sensors are active sensors that typically use a diaphragm actuated by piezo crystals. The returning wave is measured back using the same diaphragm and converted back into an electric signal by the piezo. The distance is calculated based on the time-of-flight principle. Typical measuring ranges are between ~0.1 m up to ~6 m, the lower limit given by the fact that the diaphragm needs some time to come to a standstill after transmitting before it can receive an incoming wave. The measuring ranges are very practical for many scenarios, however smaller obstacles such as cables or very thin posts might not be detectable. Typically multiple ultrasonic sensors are combined to cover for example the rear of a machine. If enough overlap is provided between neighbouring sensors, the position of the obstacle can be calculated based on multiple range measurements from neighbouring sensors using trilateration. This can be used for more advanced visualizations and warnings for the operator.

Radar-based systems in comparison typically allow for much greater measuring ranges (up to several hundred meters) and higher field-of-views, meaning a single sensor can easily cover one face of a vehicle. Most types of radar also not only report a range measurement but provide a relative speed output based on the Doppler principle, which can be used for filtering and smarter alarm strategies (e.g. ignore dynamic obstacles, that are close but moving away fast). Radar signals often include multiple returns that can be used to classify the object that is being measured (e.g. by AI methods), allowing for even more advanced vehicle integration strategies and solutions avoiding alarm fatigue (e.g. ignoring all obstacles that are not classified as pedestrians).

Camera-based solutions can be classified into the used spectrum (visible spectrum vs. infrared spectrum for pedestrian detection) and the amount of cameras. While most types of digital cameras allow for AI-based obstacle classification especially stereo-cameras have the added benefit of being able to calculate the distance of objects based on the stereo-vision principle (at the cost of heavy computing power needs on the vehicle).

To mitigate this cost and scalability issue many approaches have been developed also for the mono-camera to provide distance information, the structure-from-motion algorithm or AI mono-depth-models being named as examples.

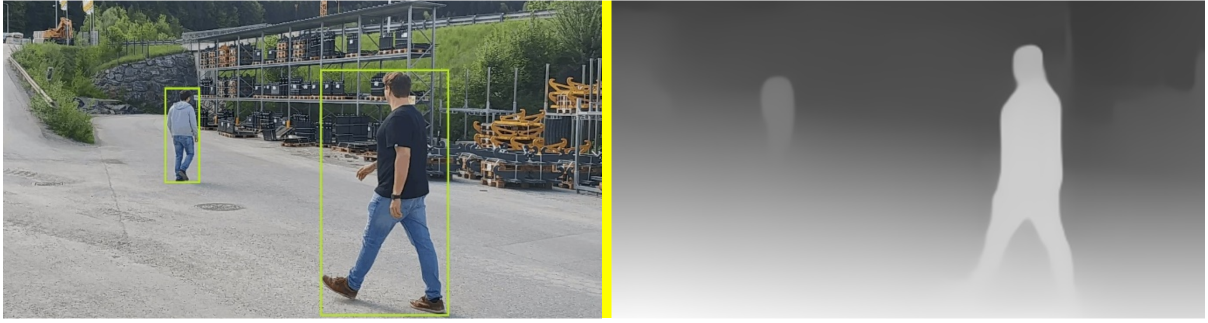

Figure 1: Example of 2D RGB camera with AI-based object classification and AI mono-depth estimation

Lidar sensors are positioned on the upper end of the spectrum of on-board perception sensors when it comes to capabilities (and costs). Depending on the model up to multiple hundreds of thousands of points are measured in a 3D space per second, allowing for a very detailed point-cloud of the environment with sub-cm range measurement precision. This data can be used in a variety of applications from simple 3D obstacle avoidance (using live-data) to 3D site mapping (aggregated data), GNSS-independent vehicle localization and object classification to name a few.

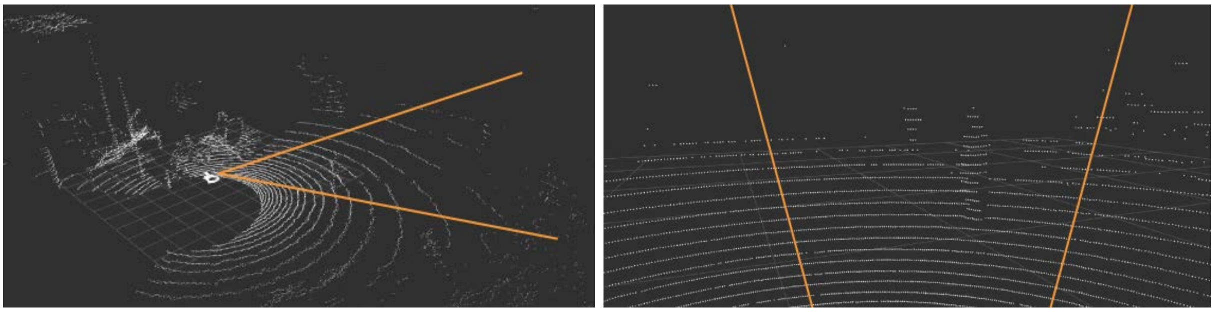

Figure 2: 3D lidar point cloud of the same scene as above with the approximate camera field-of-view highlighted.

Various other types of sensors exist that can be used for the task, such as 3D PMD cameras.

One of the most advanced commercially available solution today is [7]. Using a stereo-vision camera at the rear of the machine the system is able to both classify the detected obstacles into “pedestrians” and “other obstacles” and measure the relative position between the obstacle and the machine. Subsequently warnings for the operators are tailored by a) two different warning zone sizes (pedestrians up to ~7m, obstacles only ~2.5m) and b) different display visualizations and audible warnings depending on obstacle type. With that approach a high level of operator acceptance is achieved, since the vehicle can be driven close to obstacles in tight confines without unnecessary warnings while early warnings are given when pedestrians are present.

Since this particular system is not a retrofit option but a fully integrated OEM solution automatic speed reduction can be realized instead of just providing warnings to the operator. The clear benefit lies in even shorter stopping distances and more practical collision scenarios avoided since the reaction time of the operator is skipped and the machine brought to a stop earlier. At a typical reverse speed of 10 km/h and an estimated reaction time of the operator of 1 s the machine comes to a standstill 2.78 m sooner than with a pure active warning system.

Aside from the machine operator and the pedestrian in the danger zone immediately benefitting from this system in a potential collision scenario it is assumed that organizational deficiencies at the work site have to occur in order for the pedestrian to appear in the danger zone in the first place. This is also addressed by the system in that a data package with time stamp, vehicle speed, GNSS-position and other related data is sent by the machine into the OEMs IoT system. The end-customer can then use this information to bring transparency into the workforce (e.g. inform safety-responsible personnel about practical risk areas) and subsequently improve work processes by organizational measures in order to avoid pedestrian to vehicle convergence in the first place. Both individual incident markers as well as a site heat map representing pedestrian detection occurrence rates can be accessed via web interface.

Aktive Personenerkennung heckseitig: Gefahrenkarte

L580:53538 von: 11.07.2021 15:18 bis: 22.07.2021 15:18

Person erkannt
L580:53538
14.07.2021
09:56:56

Figure 3: Left: Wheel loader with smart pedestrian detection (approximate warning zones for obstacles and pedestrians highlighted). Right: Online incident map

4. COLLISION AVOIDANCE SYSTEM FOR EXCAVATORS BASED ON DIGITAL TWINS

The developed dynamic collision avoidance system for mobile excavators combines advantages of digital twin and transponder based approaches. In general, the system is able to collect data of the presented 3D-systems from different machines on a vendor independent platform in a local network on the construction site and connects them with planning data as well as site specific guidelines and regulations concerning protection zones. In contrast to the solutions mentioned in section 2.3, also accidents between different mobile machines can be prevented in this way.

4.1. System Architecture

The system architecture of the collision avoidance system can be seen in **Figure 4**. The core of this architecture is the so-called safety control station, which is a variation and simplification of the Site Execution System (SES) developed in the joint research project “Bauen4.0” [8] and is mainly based on the Site Information System introduced in ISO 15143-1 [9]. The safety control station is a micro-service-based software environment, which runs on a local Edge Cloud Server. Basic micro-services are located in a virtual machine environment with defined access rights.

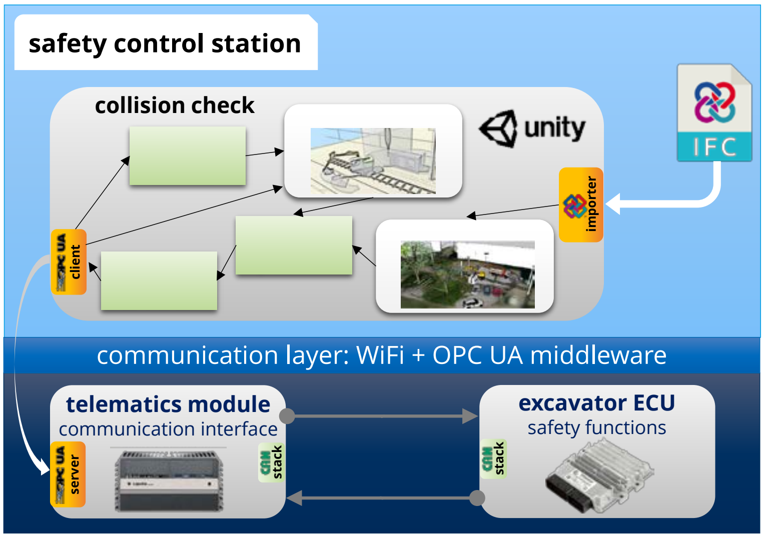

Figure 4: System Architecture of the proposed collision avoidance system

The core micro service is the so-called collision check, which represents the digital twin of a construction site. This digital twin, running on the cross-platform game engine unity, includes all static and dynamic information for predicting potential accidents, respectively collisions between mobile machines and their working environment. The construction site facilities including static collision bodies (based on German safety regulations and guidelines, e.g. DIN 18920) for facilities worthy of protection, e.g. trees, can be imported to unity via a plugin for BIM-files. The creation of the construction site layout and the static collision bodies in form of a BIM-file can be done in typical 3D design review packages like Navisworks. The investigated mobile machine, a hydraulic excavator, was directly built in unity in the aforementioned research project “Bauen 4.0” (see [10]) and extended by dynamic collision bodies. The function of the collision bodies and the collision prediction itself is explained more detailed in section 4.3. For displaying the mobile machine in real-time as well as calculating the collision bodies, unity includes an OPC UA Client, which collects the data of the real-world excavator respectively its 3D machine control systems. So the excavator can be displayed in the digital environment based on the GNSS position and the IMU sensor values. The OPC UA Client is also used for sending speed limits or emergency stops to the excavator in case of predicted collisions. The communication concept using the middleware OPC UA in combination with WIFI is explained more detailed in following section 4.2. The planned but not implemented workflow actually envisages the mobile machinery to login to the control station and transmit an *.xml file in the urdf schema via OPC UA, which contains the complete kinematic description of the machine including the collision bodies.

4.2. Communication Concept

A middleware approach using OPC Unified Architecture (OPC UA) has been chosen for the communication on the construction site. This decision is based on the promising results of the aforementioned research project “Bauen 4.0”. Using the middleware OPC UA enables interoperable communication on the construction site between different participants, i.e. all kinds of mobile machinery, as well as various applications, e.g. the micro services of the safety control station. As stated by the OPC Foundation, OPC UA is “a platform independent service-oriented architecture that integrates all the functionality of the individual OPC Classic specifications into one extensible framework [11].” OPC UA typically includes protocol specifications from the third to the seventh OSI layer and can be combined with Ethernet (IEEE 802.3) or WIFI (IEEE 802.11).

The concept of “Bauen4.0” provides for each mobile machine to offer its information and services via an OPC UA server, which is hosted on a machine's own telematics module. The central control station on the construction site uses a so-called aggregating server, which aggregates the data from all mobile machines via OPC UA clients and acts as an interface to the individual applications. A 5G campus network was used in the research project to enable an IP-based network on the construction site. The offered information of the mobile machinery include mainly telematics data defined in ISO 15143-3 [12], as well as the description of the kinematic tree for monitoring mobile machinery during operation and hydraulic condition monitoring data. These data sets had been formalized into information models based on existing Companion Specifications. For further information regarding the concept as well as developed information models, have a look at [13], [14].

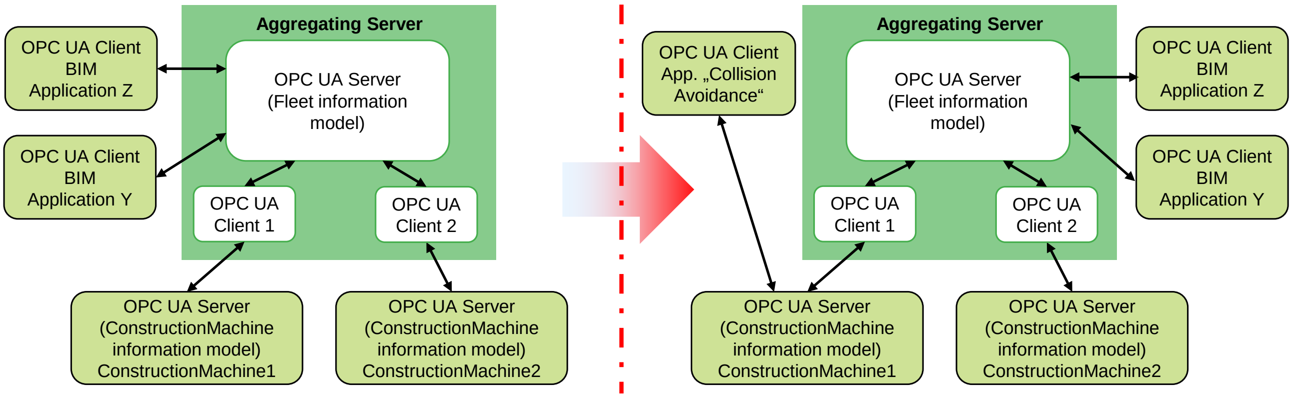

Figure 5: Adaption of the Bauen 4.0 communication concept; left: Bauen 4.0 concept; right: communication concept for the safety control station

For reasons of efficiency and decreasing communication delays, the concept was simplified. The adapted version is shown in **Figure 5**. The aggregating-server is bypassed by connecting the OPC UA client of the application, hence the collision check, directly to the OPC UA server of the mobile machine. In addition, the campus network was dispensed and WIFI 6 (IEEE 802.11ax) was used instead. The application requires the angles of the attachment and the global position of the excavator by reading corresponding OPC UA variables. On the other side, the application has to set the speed limits as well as the status regarding the actuators by writing corresponding OPC UA variables. These speed limits are sent afterwards via CAN by the machines telematics module to the Excavator ECU, which controls the excavator and takes them accordingly into account (compare **Figure 4**).

While the desired information is already covered by existing information models and therefore available by the OPC UA server on the used excavator, speed limits and status information had to been integrated into the information models. Therefore a new *ObjectType*, called *TaskControlTypeExtension*, had been developed, which compromises this information, compare **Figure 6**. The Type is based on the *TaskControlType* of the OPC UA Companion Specification for Robotics [15] and adapted to the use-case.

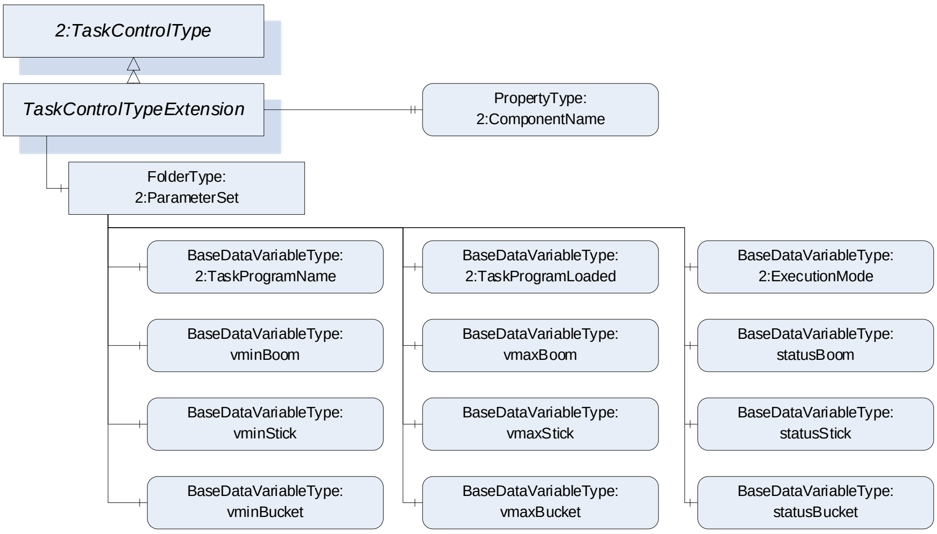

Figure 6: Visualisation of the ObjectType TaskControlExtensionType

Reading and writing OPC UA variables by the client has been realised by using standard OPC UA read and write requests of the implementation open62541. In general, each read or write request of every variable causes two TCP Acknowledgements (TCP ACK). For reducing network traffic and therefore potential time delay, all read requests have been integrated into one request (Batch Request) and all write request vice versa. The communication loop of the OPC UA client is shown in the sequence chart in **Figure 7**. Read and write requests are executed one after the other as described, whereas acknowledgements follow each request and response.

Furthermore, concerning the client/server pattern, it would have been possible to switch to *Subscriptions* by specifying desired nodes in form of so-called *MonitoredItems*. However, an additional wait cycle, the publish interval, is integrated into the communication cycle within this method. Therefore, this variant is not suitable for low-delay communication and has not been considered in this investigation. Another option would have been to switch to publish/subscribe patterns. This would eliminate the TCP ACK, which would presumably lead to performance advantages. However, this approach was not pursued further because of the good results regarding batch requests in section 5.1.

In this investigation, as mentioned, WIFI 6 (IEEE 802.11ax) was used to provide an IP-based network without the need of physical wiring. For evaluating the communication concept and the network, different tests with various test setups have been carried out, see section 5.1.

In general, it has to be stated, that in case of using the collision avoidance system completely independent from the operator as an automation function, the communication concept does not meet required safety standards. Such a use would require safety functions implemented on the excavator ECU, which set the machine into a safe-state in an event of disconnection or other errors. There are two prerequisites for this, which cannot be met currently. On the one hand, the whole communication has to be in accordance with the requirements of DIN EN IEC 61784-3 [16] and DIN EN IEC 61508 [17]. In fact, the OPC UA Core Specification “OPC 10000-15: UA Part 15: Safety” [18] defines mechanisms for the transmission of safety-relevant messages among participants within a network using OPC UA technology fulfilling these stated standards. Yet, there are no OPC UA implementations available, which fulfil this core specification. Reliable information concerning the publication of such stacks are not accessible, compare [19]. On the other hand, the OPC UA server of the mobile machine, which is an integral part of the excavator control loop, has to be implemented on a device, which is able to fulfil the applications specific required Safety Integrity Level (SIL, see IEC 61508). Simply using a safe communication is not sufficient to qualify a safety device, compare [20]. Commercially available telematics modules for mobile machinery are not able to fulfil any SIL. Commercially available ECUs, which are able to fulfil SIL-2, cannot be combined with typical OPC UA stacks. In this investigation, the OPC UA server was therefore implemented on an industrial PC, spectra powerbox 410-I5, using Ubuntu 22.04 LTS as operating system.

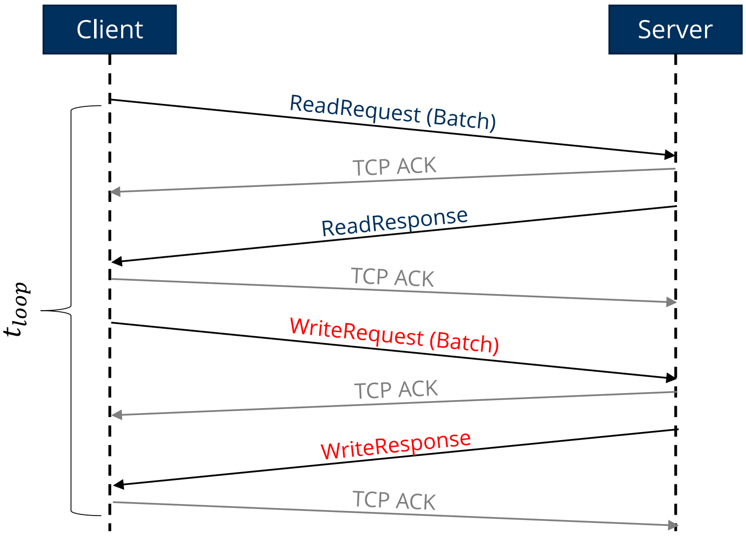

Figure 7: Communication loop OPC UA client

4.3. Collision Detection

As mentioned in section 4.1, the collision check is realized in unity, which offers mechanisms for recognising collisions between bodies using so-called ‘colliders’. In order to utilise these functionalities and prevent collisions in the real world, static and dynamic bodies, so-called collision bodies, have to be generated. The intention is to use these elements for predicting potential collisions between mobile machinery and the construction site facilities and deriving permissible machine control signals in order to ensure collision avoidance. In general, the collision check is able to consider the rotating movement of the upper carriage and all possible movements of the working attachment of a hydraulic excavator. Driving is currently not taken into account and has to be implemented in future for extending the functionality of the collision avoidance system.

As already mentioned, a distinction is made between static and dynamic collision bodies. This differentiation is necessary for depicting static and moving objects. Static bodies, as shown on the left side in **Figure 8**, represent protection zones and include all fixed objects of the construction site as well as existing infrastructure and vegetation. The critical areas are defined in accordance with the latest standards and guidelines. An overview of the existing regulations is given in **Table 1.** The zones ensure the protection and integrity of existing structures, mobile machines are not allowed to harm.

The static collision bodies are created manually and placed in the georeferenced digital construction site environment. Simple geometric bodies such as cuboids, cylinders and spheres in accordance with the applicable specifications represent the shape of these bodies. Therefore, an automatic workflow for generating these bodies based on a database including the standards, should be easy to implement in future.

In contrast to static, non-adaptive collision bodies, dynamic bodies are variable in time and represent the permitted motion space of dynamic objects. Their main purpose is to monitor the motion space of mobile machinery and detect potential collisions, so that measures can be taken to prevent accidents. For creating dynamic collision bodies, the first step is to approximate the machine geometry using simple surfaces. In case of the chosen demonstrator, a hydraulic excavator, the geometry is approximated by rectangular surfaces. It is important that these surfaces include all components of the machine, even small attachments, such as working lights. In simple terms, dynamic collision bodies represent the breaking distance of mobile machines respectively their components. They adapt to the actual movement of the machine in order to achieve a good balance between safety, operability and productivity. This ensures that the machine is only slowed down when necessary, minimising 'false positive' errors. By analysing the dynamical behaviour of the real machine, parameters were derived for calculating the breaking distance and stored in the digital twin.

Table 1: Regulations for the definition of protection zones on static bodies concerning infrastructure sites

Regulations	Description
Eisenbahn-Bau-Betriebsordnung (EBO)	EBO defines construction and operation railways in Germany.
DIN 18920	DIN 18920 describe the protection of trees and vegetation areas.
ASR A5.2	ASR A5.2 describes requirements for work-places and traffic routes on construction sites.

The dynamical behaviour of the machine was comprehensively analysed experimentally, focusing on the individual actuators, which means the hydraulic cylinders. Several measurements were carried out in which the actuators were subjected to square-wave signals, so that the cylinders were retracted and extended in various load situations. By evaluating these measurements, it could be shown, that the dynamical behaviour of all the actuators can be approximated by simple linear decelerating respectively accelerating equations based on the actual cylinder velocity $\dot{x}_{cyl,i}$, compare following equations:

$$\Delta x_{break,i} = \frac{a_{break,i}}{2} \cdot {t_{break,i}}^2 + \dot{x}_{cyl,i} \cdot t_{break,i} \tag{1}$$

$$\Delta x_{break,i} = \frac{3}{2} \cdot \frac{{\dot{x}_{cyl,i}}^2}{a_{break,i}} \tag{2}$$

The breaking distance $\Delta x_{break,i}$ of an actuator of the digital twin, is calculated with the help of the experimental determined breaking acceleration factors $a_{break,i}$. As each actuator is attached to the working attachments, these translatoric cylinder movements are transferred to rotational movements of the members of the working attachment, such as boom, adjust boom or stick. The relationship between the translatoric cylinder position $x_{cyl,i}$ and the rotatory angle of the transmission element φ_i can be derived as follows for each cylinder, respectively transmission element:

$$G_i = \frac{\dot{\varphi}_i}{\dot{x}_{cyl,i}} \approx \frac{\Delta \varphi_i}{\Delta x_{cyl,i}} \tag{3}$$

In consequence, the necessary breaking angle $\Delta\varphi_{break,i}$ can be calculated for each component of working attachments according to equation 4:

$$\Delta \varphi_{break,i} = \frac{3}{2} \cdot \frac{{\dot{x}_{cyl,i}}^2}{a_{break,i}} \cdot G_i \tag{4}$$

This breaking angle is ultimately used for discharging the dynamic collision bodies in the direction of the movement. **Figure 8** shows an example of the dynamic collision bodies of the excavator model on the right side, which are calculated using the described method.

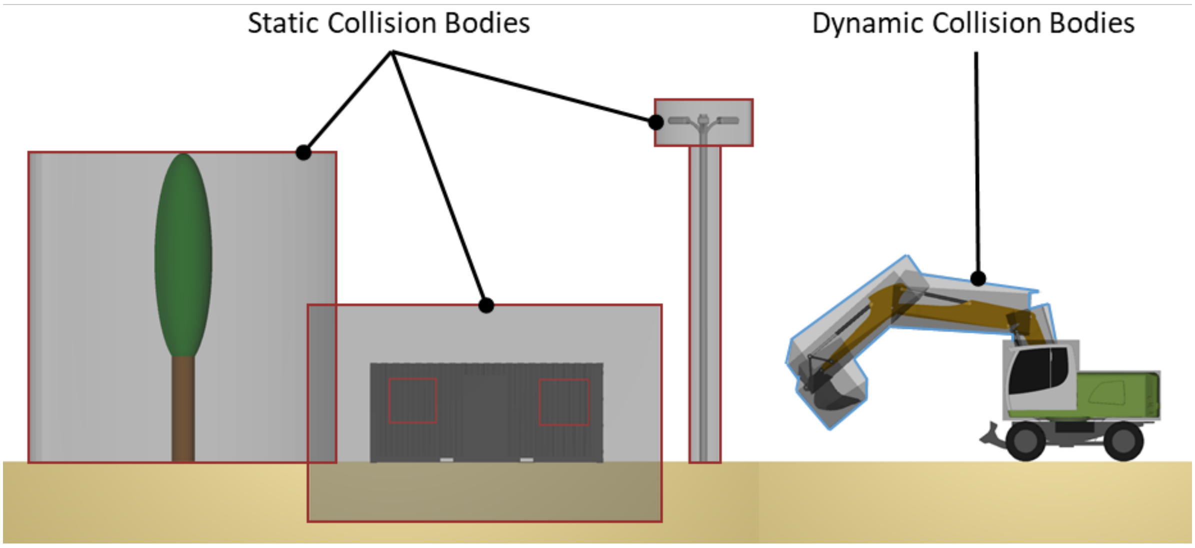

Figure 8: Static Collision Bodies (Left) and Dynamic Collision Bodies (Right)

As already mentioned, the development environment uses so-called collider components for collision detection between physical bodies. These components define the geometric shape and size of a specific body so that the integrated physics engine can recognise collisions based on the collider geometries. Collision detection is performed by cyclic checks of the collider positions and shapes in each unity frame cycle. The tests in chapter 5 were due to the use of storage and computing intensive BIM-files for the virtual construction environment performed with fixed frame cycle times t=20 ms. From a safety point of view, fixed cycle times < 10 milliseconds should be strived for. As soon as an overlap or contact between two collider geometries is detected, a collision is recognised by the engine, which leads to recording and storage of data such as the collision status and the collision points. By using so-called collision masks, it is possible to individually define collision pairs, which means two colliders, where contacts shall be detected. By default, all other collisions are ignored. In this specific context, only collisions between static and dynamic collision bodies are handled. All other possible collision pairs, such as collisions between static colliders, are deliberately excluded in order to utilise the computing power of the engine in a targeted and efficient manner by avoiding unnecessary calculations.

4.4. Intervention in the machine control

The described collision results in the previous section are the basis for determining permissible interventions of the machine control system. The primary aim is reducing the speed of the excavator actuators respectively stopping them in case of critical movements. In addition, in the event of a collision, the system must always allow the operator to move the attachment out of the static collision zones if a collision occurs again. The permissible control signals of the mobile machine are generally determined according to a predefined sequence diagram, which is shown in **Figure 9**.

In the first step, various pieces of information, such as collision status of each dynamic collision body and current control signals are aggregated. Afterwards these information are checked, whether collisions have occurred. In case of no recognised collision, no further measures are taken. If a collision is detected, the system limits the permissible speed of each actuator, which can lead to the collision. If, for example, a possible collision of the excavator bucket with an overhead line is detected by the upward movement of the excavator arm, all actuators that could lead to a collision, i.e. boom, stick and bucket cylinders, are limited.

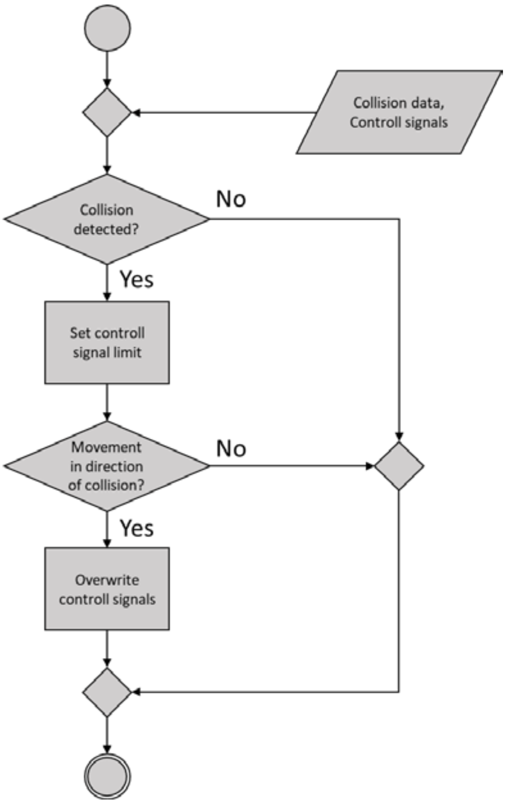

Figure 9: Sequence diagram of machine control intervention

Thereby the system takes the direction of the actuator movements in account. The actuators are not completely blocked for operation, yet only the retraction or extension speeds of the cylinders. At the end of the sequence diagram, the permissible control signals are stored in a data struct, which the OPC UA client thread can access and send them to the mobile machinery, compare section 4.2.

Furthermore, in case of an actual collision, so that all actuator movements (retraction and extension of a cylinder) lead to further collision, a so-called emergency motion state is triggered after half a minute. As mentioned above, this shall allow the operator to move the attachment back out of the static collision zones again.

In contrast to the collision avoidance in section 2.3, the selected procedure does not deactivate the entire machine control system when the machine approaches a safety zone, but the operator is still able to effectively counteract the dangerous movement of the machine, thus increasing operating comfort, safety, acceptance by the driver and productivity.

5. SENSITIVITY AND ROBUSTNESS ANALYSIS

For evaluating the sensitivity and the robustness of the developed collision avoidance system, two kinds of tests were performed. On the one hand, the communication concept is evaluated by measuring the minimum achievable cycle times of the OPC UA Client. On the other hand, the accuracy of the whole system is evaluated by measuring the distances between excavator bucket and protected facilities in two different scenarios. All tests were done with the OPC UA Server running on an industrial PC, spectra powerbox 410-I5 (i3-8100T, 8 GB RAM, Intel I210, Intel Wi-Fi AX200, Ubuntu 22.04.3 LTS) inside the mobile excavator, and the OPC UA Client running on a PC (i7-1355U CPU, 16 GB RAM; Realtek USB GbE Family Controller, Windows 11), which represents the control station for these tests. The OPC UA Client is integrated in unity and performed in a separate thread as fast as possible. For wireless connection an Ubiquiti Dream Router was used with WIFI 6

(IEEE 802.11ax).

5.1. Communication Tests

The general test layout is shown in **Figure 10**. The excavator is located approx. 9.5 m apart from the control centre and approx. 3.6 m to the WIFI router, which is standing on a platform (3 m). The following setups were selected:

- **Ethernet:** Mobile machine and control station are connected directly via Ethernet (IEEE 802.3).
- **WIFI:** Industrial PC of excavator is connected via WIFI (IEEE 802.11ax) to control station.

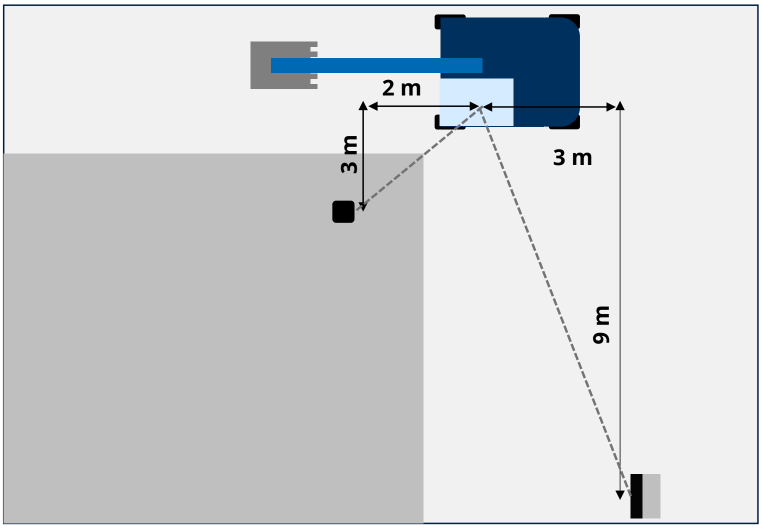

Figure 10: General test layout.

The following tests were performed:

- **Standard:** Reading and writing (sample size: 1000) the in total 31 variables by the OPC UA client with standard read and write methods of open62541.
- **Batch:** Reading and writing (sample size: 1000) the in total 31 variables by the OPC UA client with batch read and write methods of open62541.

The results of the performed tests can be seen in **Table 2** and **Figure 11**. In general the experiments show, that the cycle time can be significantly reduced by using the single batch request instead of standard write and read request, independent from the physical layer. Furthermore it is clear, that reliable communication (reliable cycle times<<<10ms) is only possible with the use of Ethernet at the moment, compare especially the standard deviation of Ethernet and WIFI. These experiments also show that the variating communication time with WIFI is likely to be a major influencing factor on the measured distances in the following section 5.2. In future, it would be very interesting to carry out these tests again with secure OPC UA communication according to OPC UA Core Specification “OPC 10000-15: UA Part 15: Safety” [18], compare section 4.2.

Table 2: Results of the communication tests

nr	setup	com. pattern	mean [ms]	max [ms]	min [ms]	std [ms]
1	Ethernet	Standard	19.6	55.8	9.50	4.1
2	Ethernet	Batch	1.1	3.6	<0.1	0.5
3	WIFI	Standard	87.9	874.6	53.2	61.9
4	WIFI	Batch	5.9	256.4	2.5	11.4

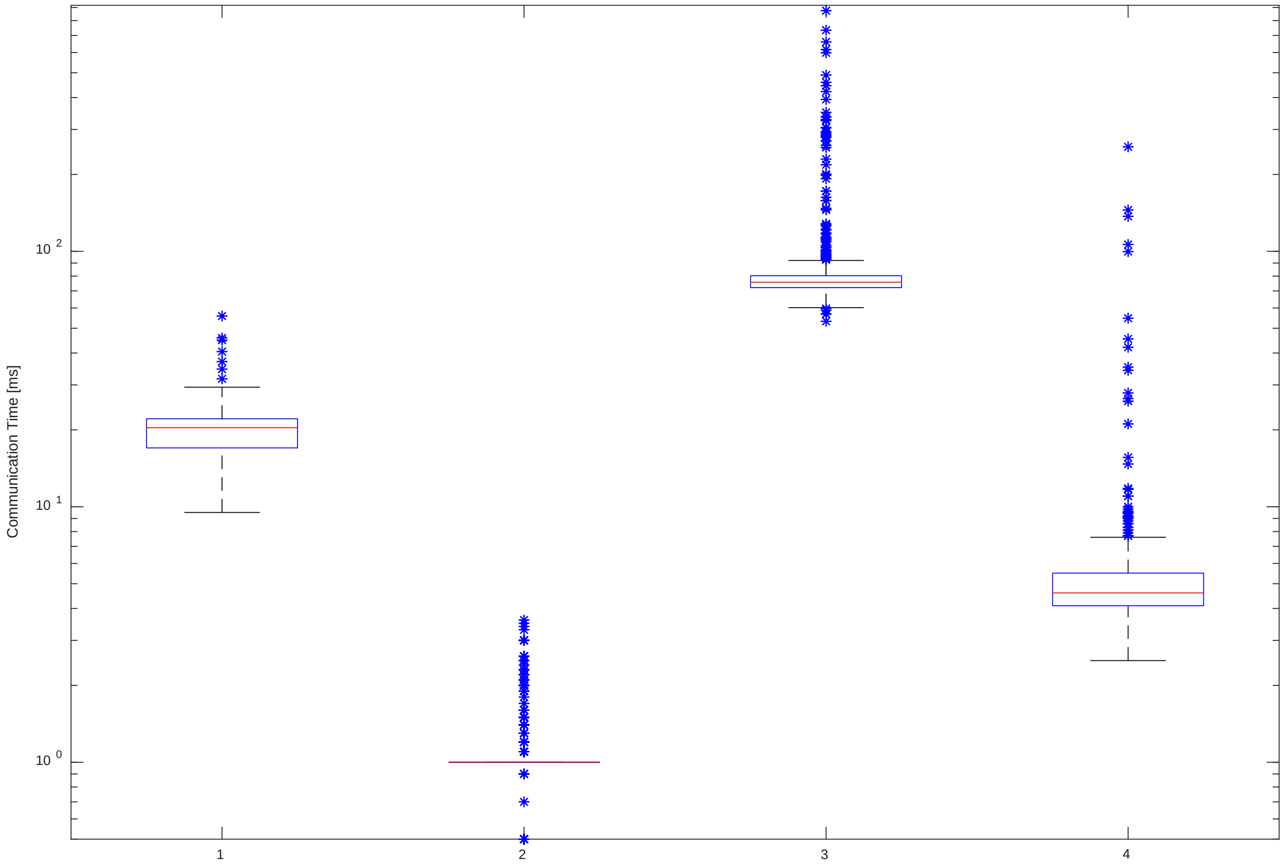

Figure 11: Box plot of the measured communication times for the configuration 1-4 displayed in **Table 2**.

For additional classification of the results standard ping test (sample size: 100) for measuring the round-trip time (RTT) for messages between host (control station) and destination computer (excavator) were performed, compare **Table 3**. The results show also, that using WIFI, there is a high risk that single communication cycles exceed the desired cycle time vastly and may lead to large deviations with regard to the predicted machine stopping points.

Table 3: Results of the ping tests

setup	test	mean [ms]	max [ms]	min [ms]	std [ms]
Ethernet	Ping	0.2	4	<0.1	0.5
WIFI	Ping	233.5	484	4	134.4

5.2. Collision Tests

In order to evaluate the accuracy of the overall system, collision tests are carried out focussing on a practical track construction scenario with the use of two-way excavators. These machines are mainly used on track construction sites or in track construction, where overhead lines are usually also present. Despite the presence of protective equipment, collisions between the machines and the overhead lines occur repeatedly, often with health and financial consequences. In the selected scenario, the boom cylinder of the excavator is extended so far that the excavator bucket or its dynamic collision element collides with the static collision element of the overhead line of a railway line (in Germany at a height of 5.5 m), as shown in **Figure 12**. A platform was set up next to the real machine, from which the minimum distance between the excavator bucket and the overhead line was measured at a height of 5 m using a laser rangefinder (Bosch DLE 50). According to legal regulations, the safety distance between the machine and the overhead line must be 0.6 m, which is defined as the target value. The measured values are compared with this target value in order to assess the effectiveness of the system in preventing collisions. The general communication structure corresponds to the previous section 5.1

(compare **Figure 7**), whereby WIFI and the batch method are used for communication. The test is repeated 25 times (n = 25) in order to be able to reliably record the various mostly stochastic influencing factors on the collision test statistically. In general, the following disturbance variables must be taken into account:

- positioning error of the GNSS system
- sensor errors of the working attachment
- varying dynamics of the mobile machine
- varying cycle times of the communication loop

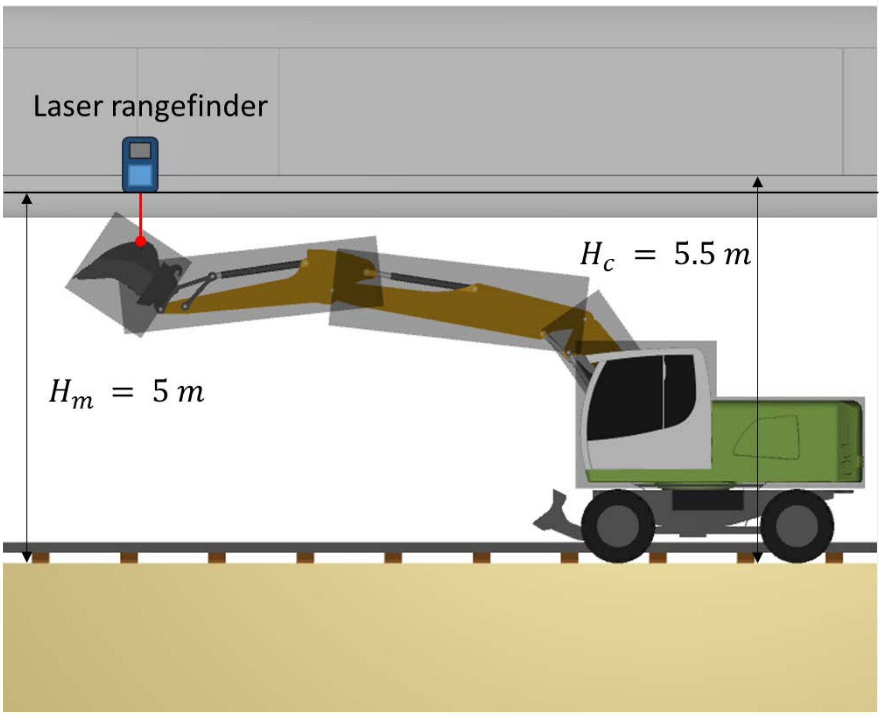

Figure 12: Test setup collision tests

Regarding the specific scenario, the positioning error of the GNSS system can be neglected due to the fact that the excavator is always positioned on the surface in unity and therefore the height deviation of the GNSS system does not disturb the calculation. In the context of a thesis at the TU Dresden [21] the accuracy of the used position sensors (IMUs) has been analysed. Over various poses of the excavator max. deviations regarding the TCP of the bucket in one spatial direction of 88 mm could be detected. Regarding the varying dynamics of the machine, no reliable conclusions can be drawn in respect to its influence on the breaking distance of the machine. For estimating the influence of varying cycle times, the communication loop and the frame times were measured during the tests. **Table 4** shows the results.

Table 4: Results of the collision tests

	mean [m]	max [m]	min [m]	std [m]
distance	0.9094	1.0680	0.5930	0.1243

The measurement results of the tests carried out show that the achieved average distance to the overhead line is 0.9094 m, which is approx. 0.3 m above the legal requirements. In terms of occupational safety, the required minimum safety distance can always be maintained. However, the system restricts the productivity of the machine by reducing the usable working space by approx. 20 %. This means, that the used parameters for the calculation of the collision bodies are at the moment way to conservative. Especially concerning the improved communication loop, safety factors concerning the calculating of braking distances can therefore be reduced.

6. SUMMARY AND OUTLOOK

This paper presented solutions for collision avoidance between objects, respectively pedestrians on the construction site and construction machinery to increase site safety. Solutions with on-board perception sensors are already being used for detecting people. Also tracker-based solutions are used today to prevent collisions between mobile machinery and workers. The use of digital twins and reliable radio technology opens up new possibilities for collision detection and avoidance. While conventional collision avoidance systems based on 3D machine control systems only focus on collisions between mobile machinery and static objects of a digital construction site, the presented solution allows in general the integration of other machines or construction workers. Using a track construction scenario, it was shown that a safety control station, where the digital twin of a two-way excavator moves almost in real time in a georeferenced environment imported from BIM tools, allows safety distances to be maintained depending on the situation and in accordance with standards. This offers a real alternative to solutions with environmental sensors. As all mentioned technologies have their advantages and disadvantages, these are summarized and compared in the following table.

Table 5: Pros and cons of the different approaches

	on-board perception sensor solutions	**tracker-based solutions**	**conventional digital twin solutions**	**new digital twin approach**
pedestrian detection	✓ independent of infrastructure or organizational measures / setup ✓ affordable and proven technology ✓ no reliance on GNSS (fully functional in and near buildings, etc.) ✓ high operator acceptance (few unnecessary warnings) - affected by harsh environmental conditions (dirt, fog, dust, etc.)	✓ affordable and proven technology ✓ no absolute reliance on GNSS (functional in and near buildings, etc.) ✓ barely affected by harsh environmental conditions (dirt, fog, dust, etc.) - organizational measures (pedestrians have to be hardware-equipped) necessary	- not supported at the moment	✓ barely affected by harsh environmental conditions (dirt, fog, dust, etc.) ✓ reliable object classification - organizational measures (pedestrians have to be hardware-equipped) and infrastructure (site network, etc.) necessary - reliance on RTK-GNSS
collision avoidance (static & dynamic obstacles)	✓ independent of infrastructure or organizational measures / setup	✓ barely affected by harsh environmental conditions (dirt, fog, dust, etc.)	✓ barely affected by harsh environmental conditions (dirt, fog, dust, etc.)	✓ barely affected by harsh environmental conditions (dirt, fog, dust, etc.)

	✓ affordable and proven technology ✓ no reliance on GNSS (fully functional in and near buildings, etc.) - expensive on-board sensor setup necessary (e.g. lidar for wire detection) - affected by harsh environmental conditions (dirt, fog, dust, etc.)	✓ no absolute reliance on GNSS (functional in and near buildings, tunnels, etc.) - organizational measures (all objects have to be hardware-equipped) necessary	✓ reliable object classification - organizational measures (digital 3D-map) necessary - reliance on RTK-GNSS - collision with unknown obstacles	✓ reliable object classification - organizational measures (digital 3D-map) and infrastructure (site network, etc.) necessary - reliance on RTK-GNSS - collision with unknown obstacles

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