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Application of Digital Twins in Designing Safety Systems for Robotic Stations

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Abstract: The aim of this paper is to present examples and original solutions related to the application of the digital twin concept in designing safety systems for robotic stations. This paper includes a review of publications on robot safety systems and digital twins. Based on this review, it was concluded that further work in this area is justified. This paper demonstrates the use of a digital model of a robotic casting mold preparation station to design safety components for an industrial cell. A key element of this paper is the presentation of developed algorithms and their applications in building digital twins of existing robotic stations. By characterizing advanced safety systems used in robotic stations, an example of using a digital twin of a robotic station to create safety zones and so-called restricted zones for the robot was developed. As part of the research conducted, a real, comprehensive example of creating safety zones based on the robot's TCP paths was carried out.

Keywords: digital twin; industrial robot; safety systems; robotic station; absolute laser tracker

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1. Introduction

When designing robotic stations, the most important element is ensuring the safety of human life and health. Designing a robotic station must be preceded by a thorough, individual analysis of safety issues and the development of necessary solutions. Examples of solutions for designing safety systems and their role in ensuring the safe work of people are presented in [1]. Using the example of the robotization of the assembly process, the authors discuss various strategies for ensuring safety and their impact on overall system performance. An analysis of the robot as a source of potential threats and harm is the subject of paper [2]. The authors review safety issues in industrial settings where robots manipulate dangerous tools and move with extreme speed and force. The design and operation of safe robots or entire robotic stations is a vast field of knowledge. It is a time-consuming process that requires experience. Therefore, for the analysis of selected safety aspects, it is appropriate to use digital models and the concept of digital twins. The use of a virtual model of the station allows for the design and adjustment of physical safety components at the stage of developing the station's concept. A digital analysis of distances, heights, and the construction of safety elements such as fence systems, optical barriers, or 2D scanners is possible. The importance of digital models in the design of robotic stations and their potential use in teaching and research are the subject of [3]. In [4], the possibilities of using digital models in the specific case of a robotic welding station are presented. In addition to geometric measurements, the digital twin enables the modeling of robot–human interactions and simulations of hazardous situations. A detailed model of the real station allows for quick and easy definition of dangerous zones, and the creation of restrictions for tools, parts, and manipulator arms. Creating a digital model of the station also facilitates training, such as using virtual reality, on the functioning and operation of safety systems. In anticipating the development of safety systems, it is expected that elements of Industry 4.0, such as digital twins, advanced vision systems, and artificial intelligence, will be widely applied. A safe robot in a safe workstation should know its position, dynamically adjust its speed to the surrounding conditions, and recognize the position and speed of people and other elements in its environment. When designing robotic solutions, it is important to remember that an industrial robot is considered an incomplete machine, as it does not have a specific application and is not assigned the CE mark for compliance with the Machinery Directive in force within the European Union. The Machinery Directive is associated with various standards that pertain to machinery in general, as well as to robots and robotic stations. It should be noted that, according to the law, the application of standards is not mandatory; however, the guidelines contained within them are based on technical knowledge and represent expert-developed recommendations. Despite this flexibility, industrial practice shows that the use of standards is widespread, and alternative approaches are rarely chosen. Since the robot and other robotic station devices can pose a potential hazard, it is very important to familiarize yourself with the principles of designing safe solutions. The rapid development of industrial robotics since the early 1970s and the rapidly increasing diversity of its applications led to the development of the ISO 10218 suite of standards, covering requirements for robots as well as robotic systems (cells, lines).

2. Review of the Literature and Standards Related to the Safety of Robotic Stations

Designing safe robotic stations requires the use of many standards but is also the subject of scientific works and numerous articles. Existing safety solutions are examined in terms of effectiveness, advantages, and disadvantages. Various research centers are working on new solutions based on vision systems, the use of artificial intelligence, and new generations of sensors.

An extensive analysis of the literature and trends in research on robot safety is the subject of article [5]. In this publication, the authors examine issues related to collaborative robots (cobots) and autonomous solutions, as well as the directions in which work on safety, especially in terms of advanced human–robot collaboration, is being conducted. The safety of robots working alongside humans, namely cobots, is the focus of paper [6]. The authors present the features of cobots and their applications in production environments, highlighting that the most critical stage in implementing such a robot is the collaboration with the user during the design phase and conducting a thorough risk assessment.

In paper [7], the topic of collaborative robots is also addressed. The paper reviews the literature, primarily focusing on technocentric approaches to robot safety, with a particular emphasis on limiting kinetic energy and ensuring human safety. In the later part of the article, the authors introduce system-thinking methods to analyze the socio-technical perspective of cobot safety, including considerations of shared cognitive systems and distributed cognition. The development prospects of cobots and the topic of their safe use are explored in papers [8–11]. Safety issues in robotic systems that incorporate active vision systems are analyzed in article [12]. This article provides an overview of vision-based technologies used in scenarios of human–robot interaction and/or collaboration and presents a technological analysis of these systems. The primary aim of this article is to provide a comparative analysis of the current readiness of vision-based safety systems to meet industrial requirements, while highlighting important missing components. A safety system utilizing a vision system for robots, based on the combination of LiDAR and RGB cameras, is presented in paper [13]. The safety functionality is evaluated in terms of detecting collisions between an unknown dynamic object and the manipulator's arm. The system provides 29–40% performance compared with a fully fenced system.

In paper [14], the authors introduced a layered control architecture with additional sensors. One of the innovations of the proposed approach is a system that provides feedback from the real environment to the digital model of the environment. This additional component, known as the digital twin (DT), can be used for safely training new employees and visitors.

The topic of safety and human collaboration with traditional (non-collaborative) robots is the focus of paper [15]. In the paper, two workstations are described in detail, which were developed in a laboratory setting as part of the research project titled ToMM2. The goal of the project was to understand safety issues associated with collaborative operations involving large robots. The review of risk assessment methods for human–robot collaboration, along with original solutions in this area, are discussed in articles [16–18]. These works explore various techniques and methodologies for ensuring safety in environments where robots and humans must work in close proximity, with a particular emphasis on risk mitigation strategies and the development of safer systems.

The application of artificial intelligence (AI) and the concept of digital twins in designing safe robotic stations is the subject of article [19]. The authors propose a hybrid solution combining standard safety systems, such as safety light curtains, with AI to monitor large production areas. This system enhances flexibility, particularly in cases where human–robot collaboration requires monitoring over expansive areas. Additionally, the proposed system includes the implementation of a digital twin, which enables a connection between the real and virtual worlds. The authors note that they have used virtual models and simulations of robots to design safe robotic applications. Based on their analysis, they conclude that the effective use of digital twins in safety planning and monitoring remains relatively rare. The analysis of digital twin applications in safety-related issues is also the focus of paper [20]. The authors highlight that the core of the digital twin concept is the ability to gather data from real objects. These data can be used for the dynamic risk assessment and real-time management of various alarm systems. These capabilities allow for improved monitoring and the potential to enhance the safety of robotic systems by continuously updating safety protocols in response to real-time conditions.

The topic of designing robotic stations from a general perspective, without a detailed analysis of safety systems, is addressed in numerous scientific papers. These studies focus on the methods used during the design process and the tools employed. Such an approach is presented in works [21–23], which explore the possibilities of using virtual reality in the design and operation of robotic stations. The issue of designing a flexible robotic production line using a modular construction is the subject of paper [24]. The modular solution proposed in the article allows for the quick and faultless replacement of any robot.

Discussions regarding the robot design process, including the demand for design techniques and methodologies adapted to the multidisciplinary nature of robotics, are covered in article [25]. The work emphasizes the importance of creating design strategies that address the complex, multifaceted challenges involved in modern robotic systems, ensuring that robots can be effectively integrated into various industrial settings.

The concept of digital twins, along with existing definitions and methods of their development, is presented in paper [26]. The authors of the publication highlight the most important features of digital twins and their significance within the context of Industry 4.0. The definitions and potential applications of digital twins are also the subjects of articles [27–30]. In article [31], the authors developed a modular platform based on a digital twin, designed for creating simulations of industrial processes. This platform is system-independent and focused on ensuring user convenience. The solution utilizes visual programming concepts, making it easier for users to create and manage simulations without needing extensive programming knowledge. The modular approach further enhances flexibility and adaptability in industrial environments.

The topic of paper [32] is the construction of a digital twin for production control applications. The study utilizes digital twin (DT) technology and the Industrial Internet of Things (IIoT) to build a multi-agent platform for production control.

Examples of digital twin applications can be found in the areas of product design and manufacturing systems [33] as well as system maintenance [34]. The application of virtual reality and digital twins is the topic of article [35]. The virtual reality system developed within the article is designed to record human movements in a virtual environment, which are then replicated by a real robot. The method is primarily dedicated to situations where it is necessary for the robot to reproduce the movements of a human performing a process that is complex from the perspective of automation.

In the later part of the paper, an absolute laser tracker was used to build digital twins of robotic stations and to design safety systems. The application of laser trackers in robotics is the subject of works [36–38]. The authors of studies [36,37] developed a method for programming industrial robots using an absolute laser tracker and created a dedicated application for this purpose. In work [38], the authors focus on modeling, measuring, and identifying changes in the kinematic chain of articulated industrial robots, based on thermomechanical deformations caused by self-heating from the drives. The estimation of changes in the positioning accuracy of the ABB IRB 1600 robot was carried out using a Leica AT960 laser tracker and a FLIR SC640 thermal imaging camera.

As mentioned in the introduction, the topic of safety in robotic stations is the subject of ongoing research, based on various types of safeguards, sensors, and standards. The occurrence and level of hazards depend on the purpose and size of the robotic station. Therefore, risk assessment and the selection of safety systems should be conducted for each individual project and implementation. Risk analysis for robots and examples of risk metric classes are discussed in [39]. The authors of this paper present ideas aimed at creating a basic framework for quantifying risk (and, consequently, safety) in robotic applications. The assessment of the safety of a robotic cell using the quality function deployment (QFD) method is the focus of [40]. According to the authors, the use of QFD ensures that system requirements are designed to meet the needs of the user. It can be said that an industrial robot is not inherently safe, despite built-in safety features. Thus, a proper approach to designing safety systems is crucial. The concepts and issues related to the safety of robotic stations are extensively covered in standards such as

- ISO 11161:2007 "Safety of machinery—Integrated manufacturing systems—Basic requirements" [41];
- ISO 10218-1:2011E "Robots for industrial environments—Safety requirements—Part 1: Robot" [42];
- ISO 10218-2:2011E "Robots for industrial environments—Safety requirements—Part 2: Robot system and integration" [43].

Figure 1 shows selected references to safety standards using the example of a welding cell model.

The mentioned standards are just a part of the extensive system of documents used in the design of robotic stations and are harmonized with the EU Machinery Directive. A review and analysis of other safety standards exceeds the scope of this publication.

In summary, regarding digital twins in the context of safety systems, the reviewed literature indicates that while this topic is being addressed and analyzed, there is a lack of concrete examples and implemented solutions. Most of the cited publications focus on collaborative robots, with fewer solutions available for standard robots, which dominate the market. Based on the review, it is evident that further research in this area is necessary.

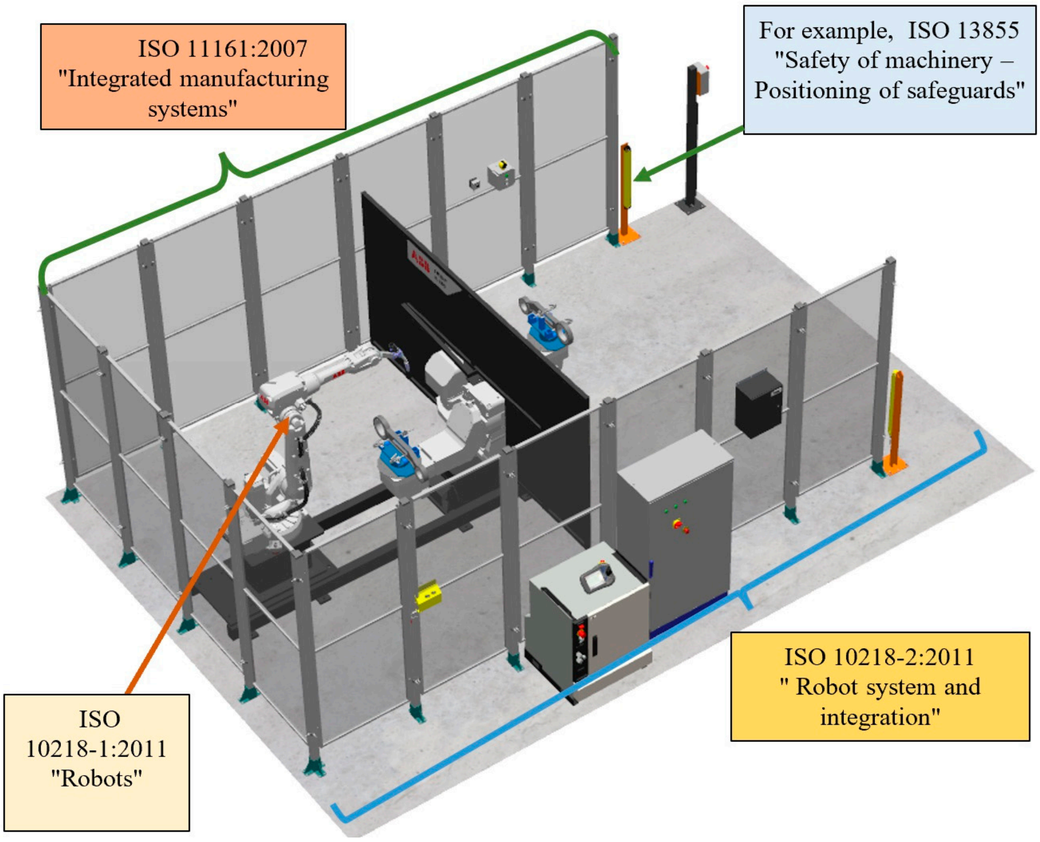


Figure 1. Selected safety standards related to a robotic station using the example of a welding cell model.

3. Building an Accurate Model of a Robotic Station and a Digital Twin in Relation to Safety Systems

A robotic cell is typically designed and constructed with appropriately selected shields and fence systems. Inside the cell, the robot is installed, while outside the cell's area are the robot controller, control panel, and an automation cabinet (see Figure 1). The fence in the robotic cell acts as a physical barrier that prevents operators and other individuals from accessing hazardous areas. An important feature of the fence is its ability to protect the environment from hazardous elements emitted from inside the cell. During the design of safety systems and the equipment of the station, the use of digital models is particularly beneficial (see Figure 2). An accurate model of the robot and cell allows for the following:

- determining the working space of the manipulator along with the attached tool;
- verifying the distances of the fence from the tool at any point in the work cycle;
- designing the size and position of potential inspection windows;
- designing the setup of equipment such as cleaning systems and welding torch calibration;
- designing the placement and determining distances to safety elements such as emergency stop buttons, two-hand safety control panels, mode switching panels, etc.

An example of applying the concept of a safety system design based on digital models is illustrated by an original solution for a robotic station (see Figure 3), the operational concept of which is detailed in paper [35]. In this case, the 3D model was used to design the fence system, doors with electromechanical locks, and to plan the layout of safety elements such as emergency stop buttons and station equipment.

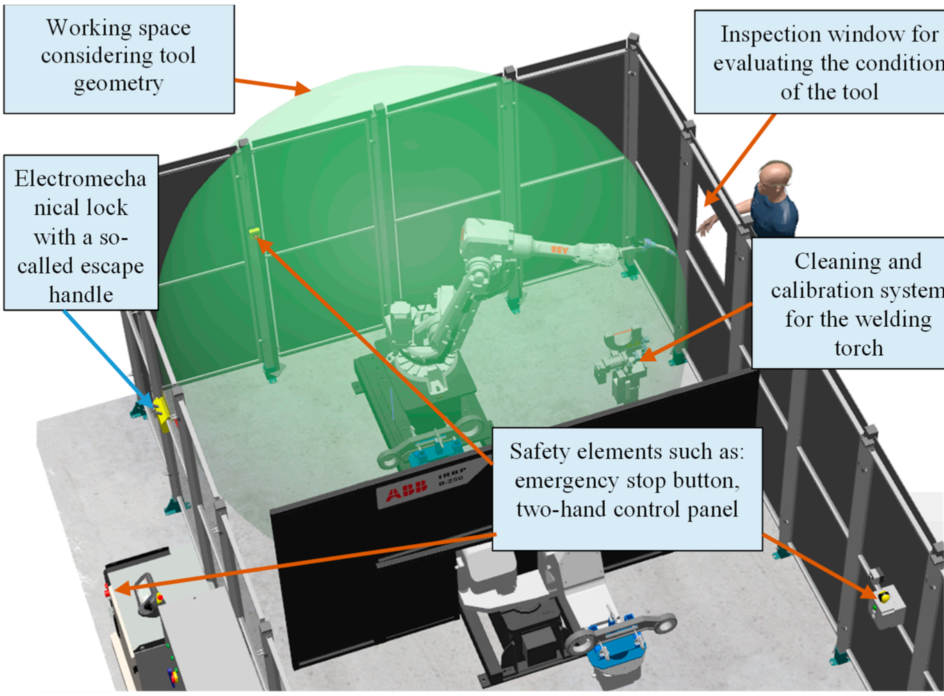
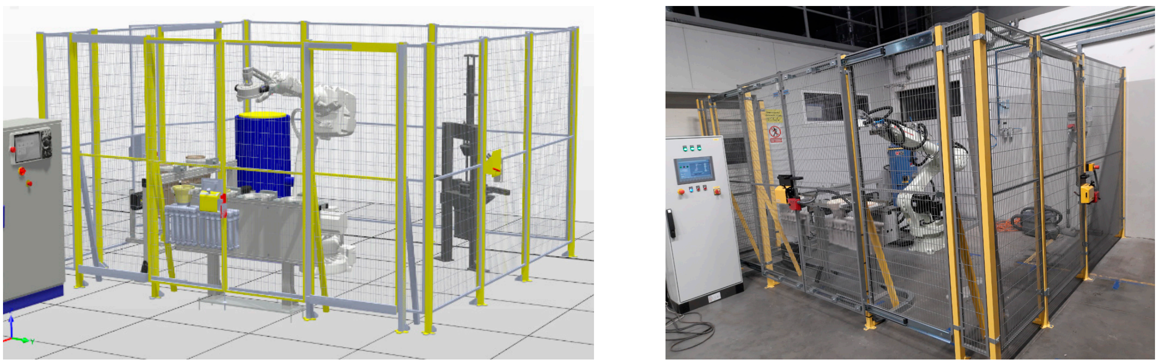


Figure 2. Digital model of the station with highlighted selected safety elements.



(**a**) (**b**)

Figure 3. Robotic station for preparing casting molds: (**a**) digital model; (**b**) real station during assembly.

Based on the developed digital model of the station (see Figure 3a), a company specializing in the design of fence systems prepared a specification for the panels used in the construction of the fence using dedicated software (see Figure 3b). The resulting 3D model of the fence was added to the station model, completing its detailed digital twin, which was used in other work, including programming, as shown in study [35]. In addition to the design of the cell fencing, equipment elements, and safety features, the digital model of the station can also be used to select and position devices that detect human presence. Such elements are essential when it is not possible to enclose the entire area of the cell, for example, when conveyors are used to handle parts or tool magazines are present. During the design of safety solutions for the robotic station, the digital model can help determine the number of safety curtains, their distance from the hazardous area, and the resolution and options used. The digital model can also be valuable when designing solutions that use safety scanners and vision systems (see Figure 4).

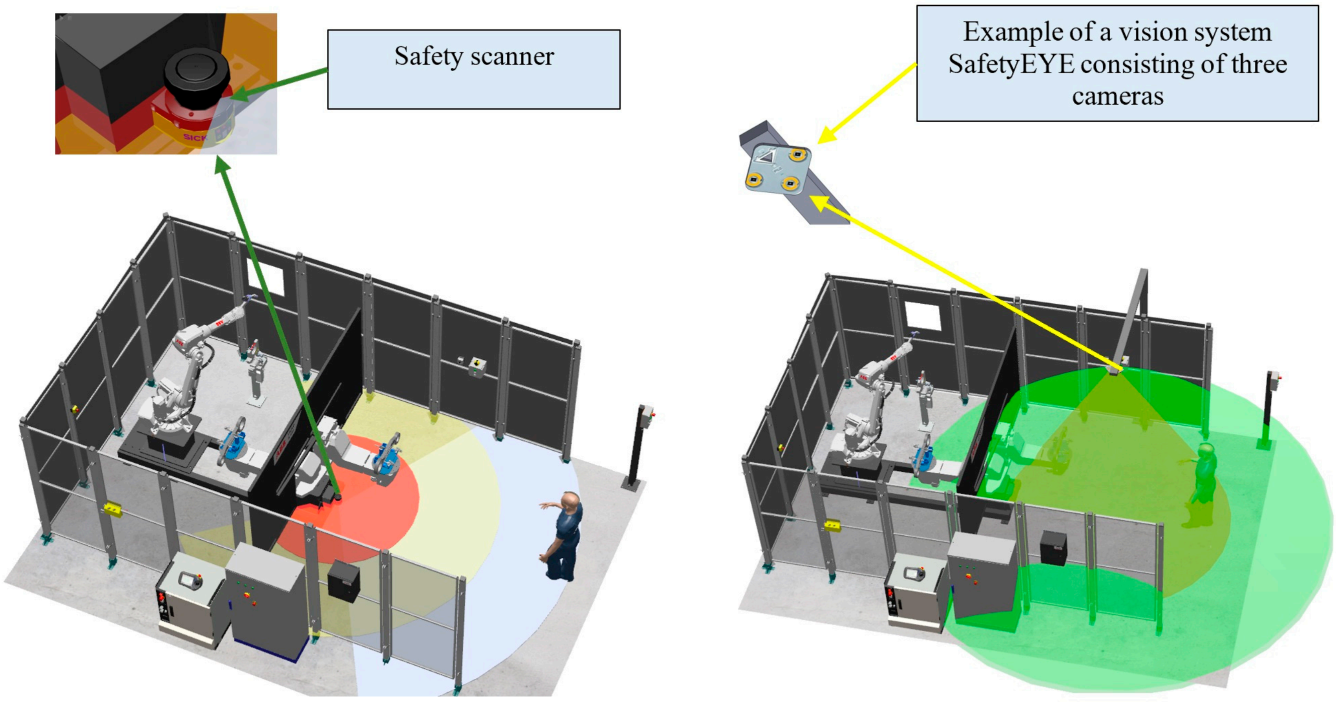


Figure 4. Digital model of the station: (**a**) with a safety scanner; (**b**) with a vision safety system.

Thanks to the software for safety scanners, advanced modifications of the size and shape of the scanner's detection zones are possible. Additionally, the scanner's configuration software allows for testing and documenting settings and provides protection against unauthorized actions (unauthorized tampering with the settings). When designing solutions with safety scanners, it is important to remember that these devices only analyze the presence of objects in a single plane, and the outline of the safety zone is not visible. When determining the range of safety zones, it is useful to define warning zones that are indicated by auditory or visual signals when breached. This approach helps minimize the frequency of station downtimes caused by unintentional breaches of the safety zone. For safety scanners, as with safety curtains, the use of a digital model facilitates design and shortens the implementation time of safety systems. The digital model helps plan the placement of safety scanners, anticipate the placement of warning and safety zones during the design phase, and also allows for operator training on the use of these systems.

Another group of devices for detecting human presence is vision-based security systems. These are among the newest and fastest-growing types of security devices used in robotic stations [1]. In these systems, when a dangerous situation is detected by the security system, immediate actions are taken to minimize the risk of an accident. Such systems are used to monitor areas in 2D or 3D modes. A key advantage of these systems, compared with previously analyzed solutions, is the ability to monitor three-dimensional space and the capability to record and analyze data. An example of a vision-based security system is the SafetyEYE solution from PILZ. Details of the SafetyEYE system are provided in paper [1]. The most important component of this system is a monitoring device consisting of a set of three cameras. These cameras are positioned above the monitored area as shown in Figure 4b. The control system for this setup includes an analysis module and a programmable safety system. Data acquisition and analysis are performed in real-time. Depending on the degree of intrusion into the defined zone, the system can, based on the input settings, either slow down the movements of the industrial robot or perform an emergency stop of the station. A characteristic feature of vision-based security systems is their short implementation time and flexible deployment, allowing for maximum adaptation to user needs. Issues with their use include sensitivity to changes in lighting, significant costs, and a lack of trust in image-based analysis solutions. Despite these challenges, it is anticipated that such solutions will become increasingly widespread.

In the design of robotic stations and their safety elements, such as those previously mentioned (Figures 3 and 4), the digital model is crucial. Various types of models are also the foundation of the digital twin concept. Creating a virtual twin using attributes of a physical entity requires modeling geometric, physical, and behavioral characteristics. The accuracy of modeling these characteristics depends on the available information about the object and the intended applications of the twin. There is always a risk of adopting an overly simplified model that might omit significant features of the station that affect its operation. Conversely, an excessively complex model can lead to, for example, complicated mathematical calculations and significant economic costs. It is also important to define the position and orientation of individual elements of the station relative to the adopted coordinate system for applications related to designing safety systems, tooling, and programming the robot's TCP paths.

To build an accurate model of a robotic station, an absolute laser tracker and solutions and software (LeicaConnector 1.0) developed as part of the work presented in papers [32,33] can be used. The precise position measurements obtained through the tracker and the dedicated software allow for the rapid and accurate modeling and construction of robotic stations. Figure 5 presents the developed algorithms showing methods for building both an accurate model of the robotic station and a real solution. Two algorithms are proposed due to the variability of the solution. Often, there is a need to construct a digital model of an existing station (Figure 5a). At other times, a real station is built based on its digital model (Figure 5b).

To build a digital twin using a digital model, it is crucial to ensure data flow between the physical object and the digital model, with bidirectional data exchange (Figure 6).

To define a solution as a digital twin, it is necessary to have a two-way exchange of information between the digital model and the physical object. In the case of implementing the algorithms from Figure 5, the digital model will be expanded into a digital twin using a solution for designing and programming robotic stations. Due to the most advanced features and existing experience, the ABB Robot Studio 2020 software was used to create the digital twin (Figure 6). In this software, as well as in most other offline robot programming tools, the most important method of data exchange with the real station is synchronization. This involves transferring programs and data from the real robot controller to the virtual system and vice versa. The arguments presented and the diagram in Figure 6 suggest that the algorithms from Figure 5 enable the creation of accurate station models and their expansion into the concept of digital twins. The research primarily focuses on the geometric mapping of safety systems and potential geometric errors that occur during modeling. The authors emphasize this topic because, based on their experience in programming and designing robotic stations, they consider it the most significant problem and challenge in building such twins. According to established definitions, a digital twin should be characterized by a faithful reproduction of the real object and two-way data exchange. Creating a twin in virtual space using the attributes of a physical entity requires modeling geometric, physical, and behavioral features. The degree of accuracy in modeling individual features depends on the available information about the object and the intended applications of the twin. When designing robotic stations, it is assumed that the physical features of the robot (its geometric and kinematic properties) should be modeled, along with the geometric features of other critical elements, particularly the station's safety systems. An accurate model of the robot's kinematics, dynamics, cycle time, etc., is obtained using the virtual controller provided by the robot manufacturer (guaranteed 99% accuracy) and offline simulation software. Thus, the research mainly focuses on the geometric mapping of safety systems.

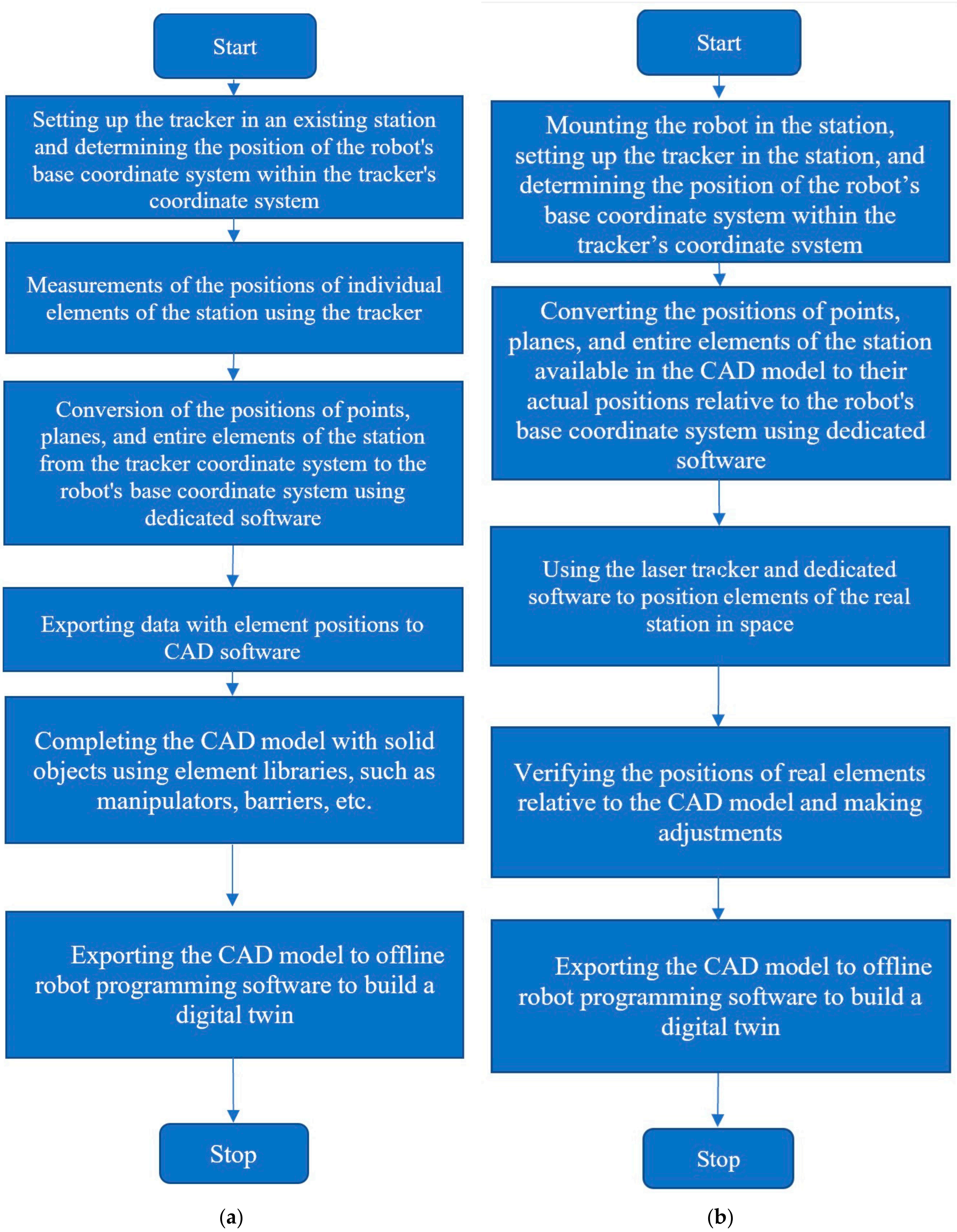


Figure 5. Algorithm for building a digital twin of a robotic station: (**a**) for an existing station; (**b**) based on a digital model.

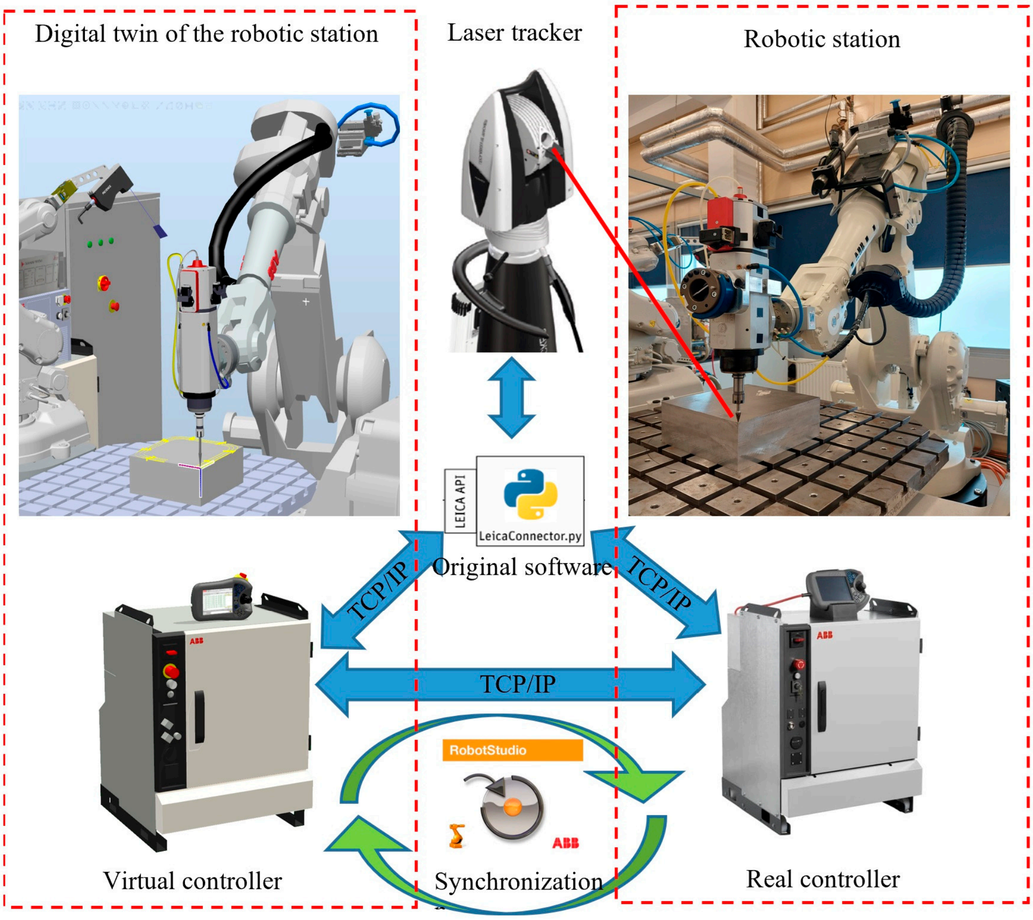


Figure 6. The concept of a digital twin in relation to a robotic station.

Detailed descriptions of measurements, procedural steps, and proprietary algorithms related to the use of laser trackers in robotic stations can be found in the authors' works [36,37]. These works explain how to set up the tracker, determine the robot's position, and measure points in the robotic station using custom software. This study focuses on the use of digital twins in safety systems. At the current stage, no other methods for building accurate digital models are available to us other than using the tracker. We believe it would be beneficial to develop an accurate model using, for example, photogrammetry or structured light methods. Comparing the quality of models obtained through different measurement methods could be an interesting topic for future research. A real-life example of building a digital twin of an entire robotic station will be the subject of another publication. In the subsequent sections, the developed algorithms and solutions will be used to design advanced safety systems for robotic stations.

4. Advanced Safety Systems Used in Industrial Robots—An Example of How a Digital Twin Can Be Employed in Building Such Systems

The development of robotic technologies, the need to shorten work cycles, and the increasing collaboration between humans and robots have created the need to integrate safety systems with robot control systems. As safety systems evolve, there is a focus on reducing the use of safety fence systems around robotic cells by expanding functions such as zone control, tool position monitoring, axis range control, and robot's TCP speed control. Advanced safety systems offered by most industrial robot manufacturers include, among others

- SafeMove 2—ABB;
- Functional Safety Unit—Yaskawa;
- Dual Check Safety (DCS)—Fanuc;

- Cubic-S—Kawasaki;
- Safe Motion—Comau;
- Safe Operation—KUKA.

A detailed review of advanced safety systems exceeds the scope of this paper, and key information can be found in papers [14,44]. The listed advanced safety systems offer functions related to, among others

- defining and controlling "safe zones" and permissible robot axis ranges;
- defining and controlling "restricted zones" for the robot;
- controlling the robot's TCP speed and the rotational speed of individual axes;
- monitoring the position and orientation of the tool;
- controlling the stopping of the robot's axes.

Most of the solutions offered by robot manufacturers are based on the use of digital models and offline programming tools to define specific safety functions. In the following section, the method for building an advanced safety system, SafeMove 2 (an ABB solution), using the concept of a digital twin will be demonstrated. SafeMove 2 is based on software and an expansion card added to the IRC5 robot controller. The safety functions of SafeMove 2 are defined using the Robot Studio offline programming tools. This system is offered in three variants:

- SafeMove Basic—allows the use of the most basic functions, such as one safety zone and 8 angular ranges, axis rotation angle limits, angle supervision, and Tool Supervision (up to 8 tools);
- SafeMove Pro—enables professional use of safety functions, such as up to 16 safety zones and 8 angular ranges, support for tool changes (up to 16 tools), axis rotation angle limits, and axis speed limits;
- SafeMove Collaborative—provides access to all safety functions while allowing human–robot interaction.

To build an advanced safety system around the IRB 2400 robot station (Figure 7), an accurate model, the concept of digital twins, and the SafeMove 2 Pro solution were used. A detailed model of the station and the digital twin were constructed following the algorithm shown in Figure 5a. The digital twin of the station, along with a laser tracker (Figure 6), was used to define the main safety zone and the so-called restricted zones for the robot. The main safety zone is the area in which the robot is allowed to move. The TCP (Tool Center Point) paths of the real robot were utilized to create a zone that the robot's TCP cannot leave. While exploring the potential of using digital models in safety systems, the SafeMove function called Tool Supervision was employed, which oversees the tool within a designated zone. Based on the precise CAD model of the spindle, the tool zone was automatically defined, which was used to supervise its position, speed, and orientation (Figure 7). Defining the zone around the tool allows for the creation of restricted zones around station elements such as workpiece holding fixtures or other robots. In Figure 7, the role of the digital twin is to designate the so-called tool zone in the option called Tool Supervision, which monitors the tool within the designated zone. It is possible to automatically generate safety zones for any CAD model of the tool, workpiece, and the entire robot body, including equipment (e.g., a welding wire feeder). We believe that such an application is very important, as it allows for the precise definition of safety zones and is frequently used in our production practice. The concept of using a digital twin to define individual zones in a robotic station is illustrated in Figure 8.

According to the concept illustrated in Figure 8, the laser tracker was used to precisely define restricted zones for the ABB IRB 2400 robot in the digital twin. The coordinates defining each zone were measured using the tracker and retroreflector at the real station, and then converted to coordinates in the robot's base coordinate system according to the algorithm presented in [36]. After verifying the accuracy of the defined parameters in the station model, the data, along with other settings for each zone, were uploaded to the memory of the real robot controller (communication and synchronization solution,

Figure 6). Defining restricted zones in the robot controller ensures that the robot cannot reach these zones both during manual control and while executing programs.

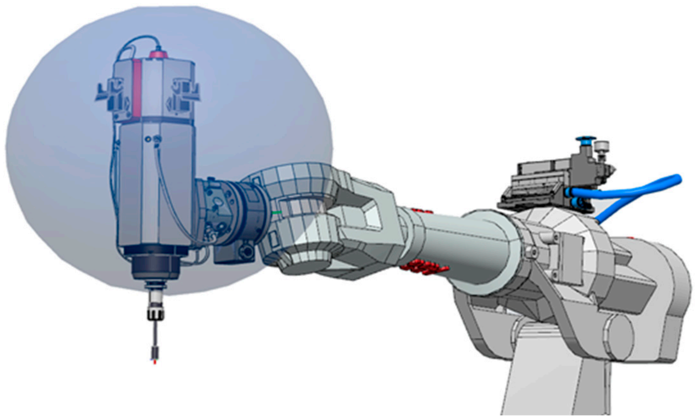


Figure 7. The defined zone around the tool based on the CAD model.

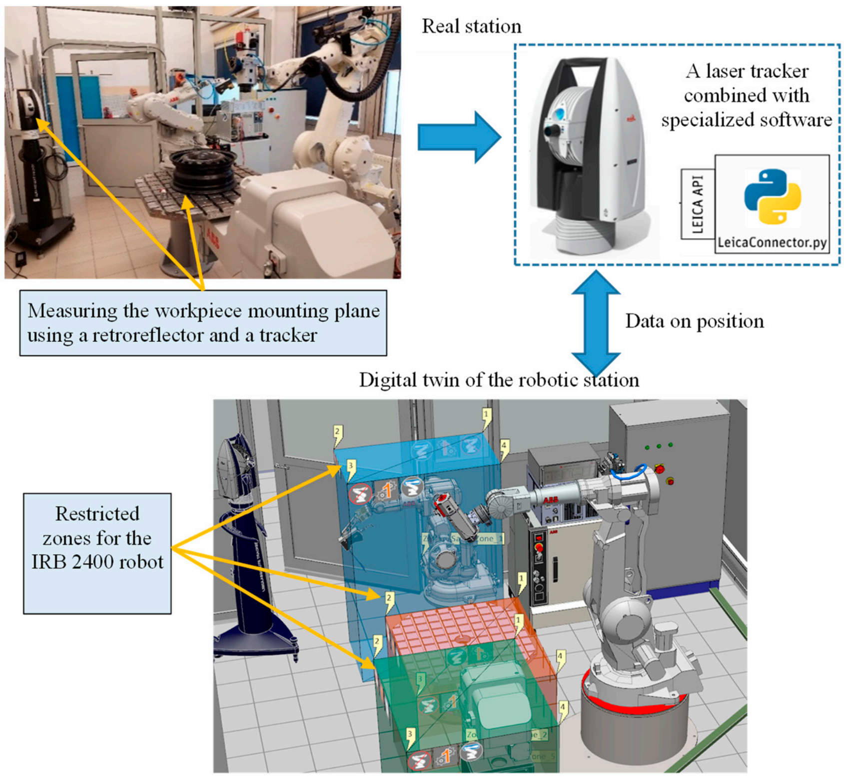


Figure 8. The concept of using a digital twin to define specific zones in a robotic station.

A particularly interesting solution demonstrating the capabilities of digital twins in designing safety systems is the Record Simulation tool. This tool allows for the generation of safety zones based on any TCP path of the robot (Figure 9). The TCP path of the robot shown in Figure 9 was generated using the original robot programming method presented in paper [37].

The concept of creating safety zones based on a robot's TCP paths is illustrated in Figure 10.

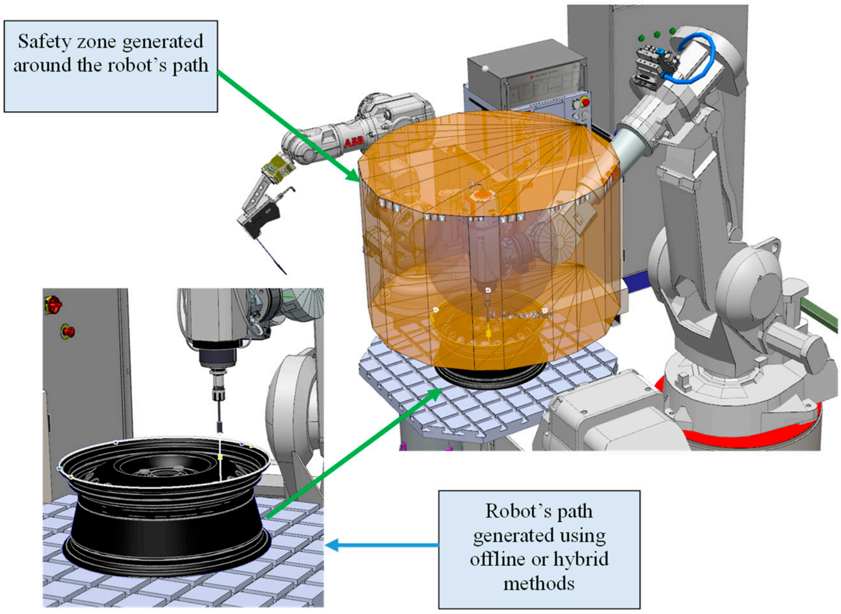


Figure 9. Safety zone generated around the robot's TCP path.

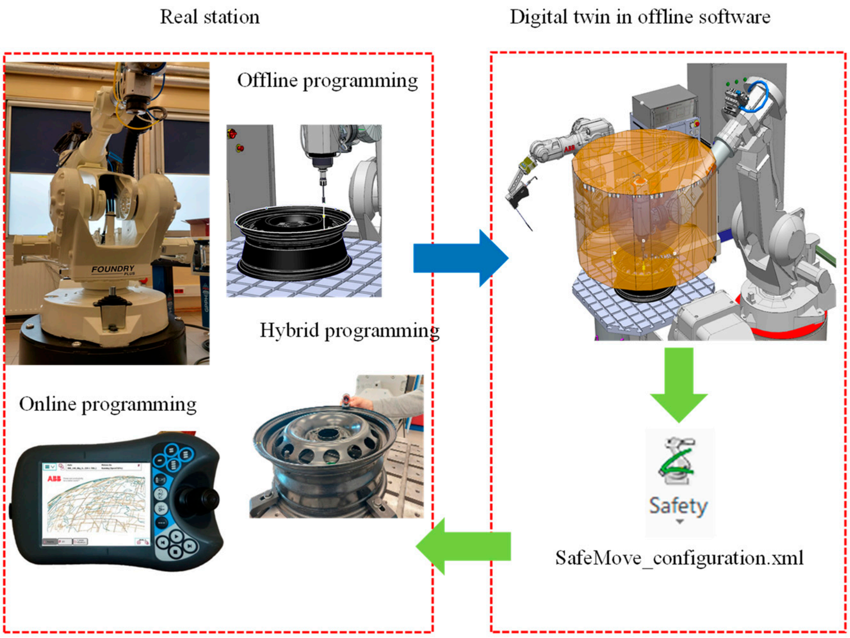


Figure 10. The concept of creating safety zones based on robot's TCP paths.

Since the presented solution involves a digital twin, the robot's TCP paths can be created using online programming methods on the real workstation, offline methods in a digital model, or hybrid methods as described in [36]. After implementing the concept from Figure 10, the program containing the paths is transferred to the digital twin during synchronization. There, a safety zone for the given process is generated as a result of the simulation recorded by the SafeMove solution. The final stage involves generating a file containing the safety settings and loading it into the real robot controller. In the case of the machining shown in Figure 6, the workpiece changes during production. However, the use of robots for milling-type machining is rare (although we occasionally build such stations ourselves) due to their lower rigidity compared with CNC machines. Figure 6 is included only to illustrate the concept. The real example shown in Figure 9 presents a grinding process, where changes to the workpiece are minimal and do not affect the safety zones. Based on our experience, we can state that, in machining processes, the safety margins of the zones can be adjusted (appropriately increased) to account for changes in the workpiece during machining. It should be noted that the safety zones created according to the adopted methodology also apply to devices and fences, which do not change. In the adopted solution using the ABB SafeMove 2 system, it is also possible to configure the system to allow zone switching during the robot's operation, e.g., in response to a signal or program command. When building a safety system using the SafeMove solution, you can automatically generate a safety settings report containing defined safety signals, created safety zones, and prohibited zones for the robot. This file, available in PDF format, can be used to prepare documents related to CE marking of the station and instructions for operators and programmers.

5. Conclusions on the Use of Digital Twins in Designing Safety Systems for Robotic Stations

In the process of designing robotic stations, analyzing safety issues and selecting appropriate solutions are crucial tasks. As part of the literature review, selected publications on robot safety systems, digital twins, and methods for the precise modeling of robotic stations were analyzed. The analysis of requirements and the design of safety systems is a time-consuming process; therefore, it is beneficial to use the concept of digital twins, as illustrated by examples. Digital models of stations can be used to design elements such as safety fences, door positions, or the placement of safety buttons. The ways of using models in the design process of safety solutions are presented with consideration of the possibilities provided by CAD tools. This paper demonstrates the use of a digital model of a robotic station for preparing casting molds to design cell fencing. During the analysis of available solutions, the use of digital twins for selecting and placing human presence detection devices, such as safety scanners, was described. An important aspect of this paper is the presentation of developed algorithms and their applications in constructing digital twins of robotic stations. By characterizing the advanced safety systems used in robotic stations, an example of using a digital twin of a robotic station to create safety zones and so-called restricted zones for the robot was developed. As part of the research, a real, detailed example of creating safety zones based on the TCP paths of a robot generated by methods characterized in another original paper was realized.

We believe that the use of a digital twin enables the quick and highly precise design of safety systems. The creation of the digital twin described in Section 4 took approximately 5 h. The most time-consuming task was setting up the laser tracker and measuring the characteristic points of the station, such as the position of the robots and the planes of the device walls, which took around 2 h. Thanks to the software used, the elements could be measured together within a common coordinate system. Another 2 h were spent modeling in the CAD system and positioning the created models relative to the points measured in reality. About 1 h was spent transferring the CAD model to the offline programming tool and building a virtual controller based on the backup of the actual station.

We consider the time spent relatively short, given the complexity of the station (which includes two robots, a positioner, fences, a part, and various equipment components). One of the major disadvantages of the method of building digital twins using a laser tracker is the cost. The purchase of a tracker with accessories is around EUR 280,000. This cost is significant, but it should be considered in the context of the ability to use the tracker for designing multiple robotic stations (spreading the cost across many stations) and its use for other tasks, such as programming robots or verifying their accuracy. Another potential drawback of using digital twins is the need for frequent updates due to changes in the industrial environment, such as when the range of parts processed or assembled by the robot changes. This problem can be mitigated by using the offline programming tools shown in Figure 6, which allow for the quick and easy import and modification of CAD models. The presented technology for building digital twins, in addition to the above-mentioned limitations related to the cost of purchasing a tracker and the need for updates due to changes in the industrial environment, also has other limitations. These include the need to use solutions from specific robot manufacturers. In our solution, to build a digital twin of a robotic station, we use a virtual controller that is part of the RobotStudio 2020 software. To build a digital twin of a station with a Fanuc robot, a virtual controller from the RoboGuide 2020 software is necessary, while for Kuka robots, a controller from KukaSimPro is required. Therefore, our solution can be tailored only to a specific robot manufacturer and requires modification for other manufacturers. Another limitation is the need for CAD models of the robotic station elements, such as devices or fence elements. These models are not always easily accessible and may need to be created. As potential future directions for the development of digital twins in the solution presented in this article, we envision integration—combining offline programming software with communication software for the laser tracker (LeicaConnector shown in Figure 6). Work on this is already underway. More generally, we believe that the concept of digital twins in safety applications will evolve toward modeling and simulating human behavior in robotic stations. An interesting avenue for future research would be the application of artificial intelligence methods to analyze potential human behavior in robotic stations.

In the methodology presented in this article, we use tools provided by the robot manufacturer, specifically RobotStudio software and SafeMove 2 safety functions. We believe that this is the best option due to the use of real industrial solutions and the need to obtain CE certification for the station. Our solution is based on integrating a laser tracker and proprietary LeicaConnector software with the manufacturer's solutions to build an advanced system for creating digital twins of safety systems. This approach allows for the quick and relatively easy construction of accurate digital models, which can be used in various ways, including those related to safety systems. In our methodology, it is also possible to incorporate solutions from other robot manufacturers, such as Fanuc's RoboGuide software and their advanced Dual Check Safety (DCS) safety functions.

The benefits of using digital twins in designing safety systems include accelerating the design process and enabling the quick analysis of various placements and configurations of elements. The reduction in the design phase is achieved by preparing and being able to order a complete safety system specification at the virtual design stage. The use of digital twins allows for conducting staff training and creating safety zones in ways that are not possible with other tools. In summary, this article presents the opportunities provided by the use of digital twins in designing safety systems for robotic stations.

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