TECHNISCHE UNIVERSITÄT MÜNCHEN

Professorship of hybrid control systems

Professorship of Hybrid Control Systems

in cooperation with BMW GROUP

Implementation of a sensor-based Worker-Assistance-System for the automotive prototype production

Master Thesis

of

Selim Ben Zekri (03651983)

Supervisors: Prof. Dr. Majid Zamani

Stephan Rupp, M.Sc. (BMW Group)

Mahmoud Mahmoud Khaled, M.Sc. (TUM)

Start: 01.12.2018

End: 14.06.2019

Confidentiality clause

This master thesis contains confidential data of BMW Group. This work may only be made available to the first and second reviewers and authorized members of the board of examiners. Any publication and duplication of this master thesis - even in part - is prohibited until 15.06.2024. An inspection of this work by third parties requires the expressed permission of the author and BMW Group.

A. Declaration of Authorship

I hereby declare that the thesis submitted is my own unaided work. All direct or indirect sources used are acknowledged as references. I am aware that the thesis in digital form can be examined for the use of unauthorized aid and in order to determine whether the thesis as a whole or parts incorporated in it may be deemed as plagiarism. For the comparison of my work with existing sources I agree that it shall be entered in a database where it shall also remain after examination, to enable comparison with future theses submitted. Further rights of reproduction and usage, however, are not granted here. This paper was not previously presented to another examination board and has not been published.

first and last name | city, date and signature

B. Table of Content

Deleted

C. List of figures

1. Introduction

Digitalization is the integration of digital technology with everyday life [1]. Digitalizing information has profoundly transformed, in a short lapse of time, the way we live and work. Nowadays, the world is witnessing a new era of technology that simplifys outdated processes and gives rise to innovative business sectors. Under the scope of the global digital transformation brought by the 4th industrial revolution, companies started to quickly integrate digitalization as part of their strategy.

1.1. Motivation

The internet of things (IoT) bridges the gap between the physical world and its representation in information systems. Indeed, another definition of digitalization is the interconnection of physical products, people and processes through the IoT and related information technology [1, 2]. Actually, IoT could be defined as a worldwide infrastructure of interoperable communication and self-configuration. The interconnected smart devices generally sense and collect relevant data that would be analyzed, processed and exchanged in order to achieve a certain purpose. IoT is the core component of the digital transformation of manufacturing, and mostly in the automotive industry. The automotive sector is the backbone manufacturing industry in Germany.

In recent years, the product palette of automobile manufacturers have risen steadily, due to the desire for customer-specific products and the development of new customer segments. Due to the high complexity in globally networked production systems under different site conditions, there are often problems and delays in the start of production. Harald Krueger, BMW's chief executive, emphasized the importance of digitalization and that the digital strategy should concern every part of the company [3]. That should fully translate the will of the German manufacturer to embark on a holistic digitalization strategy and drive towards a digital future.

The use of digital assistance systems creates new potentials for humanizing the world of work, which uses technological progress to relieve or support employees in monotonous but also in new, challenging and cognitively complex tasks in order to increase the quality of their work and also to support learning and innovation-conducive work processes [4]. In this thesis, we focus on assembly assistance systems which are designed to support assemblers with contextual instructions and thus, reduce stress, while also reducing the amount of mishandling [5]. Due to the high proportion of manual activities in assembly which results from the high number of variants, special attention must be paid to this area.

Ramp up of the series production of new car models is not running as smooth as desired. Many problems are detected very late in the development process, which leads to a loss of money and delays in the production schedule. Hence, it is desirable to test and secure the manual assembly processes as early as possible in order to confirm the suitability for series production and to avoid problems during production ramp-up. The production of prototypes following the series production conditions is therefore particularly important in order to track the series process via the interconnected smart devices and evaluate it regarding its maturity.

1.2. Context

This master thesis, presented at the chair of hybrid control systems (HCS) at the Technical University of Munich (TUM), realizes a cooperation with the BMW Group, as part of a research project aiming at increasing the maturity of assembly processes for the series production during the assembly of prototypes.

The department "Produktion Werk 0", in which the project was launched, manufactures hardware prototypes to enable the product development departments to validate new concepts and the planning department to test and optimize processes. For this purpose, partial structures as well as fully functional prototypes and test vehicles are assembled at the Research and Innovation Center in Munich (FIZ) during the series development phase of the product development process. The evaluation and optimization of assembly processes is an interdisciplinary task that is, currently, carried out in time-consuming expert workshops. In those workshops, representatives of various departments analyze the assembly processes regarding the capability for series production under high time pressure, resulting product quality, risks and physical load on the worker. This binds plenty of workforce and the resulting evaluation is subjective.

This thesis explores the use of digital Worker-Assistance-Systems to help the assembly worker in the prototype assembly follow the processes planned for series production, in order to test and validate such processes on the hardware. The focus of the present work is to select and integrate sensor-modules into the Worker-Assistance-System to form a cyber-physical System able to control and track the assembly process on the one hand and evaluate the process regarding its maturity on the other hand.

In opposition to other conventional assistance systems, the main purpose of the developed worker-assistance-system is not just to attain a zero-defect production but also to test and optimize the new production processes in small and fast cycles before the series production is started. The worker-assistance-system was deployed in the cockpit pre-assembly at the Plant 0. The prototypical implementation allowed for an agile development approach. Thus, different features could be integrated and tested in close cooperation with the users.

1.3. Structure

At the beginning of the thesis, the main thematic components will be presented and delineated: Beginning from a general overview of assembly assistance systems, followed by the state-of-art industrial and research applications, a summary of manual assembly tasks and frame conditions for the case of the prototype production is presented. Subsequently, an analysis of the requirements is carried out, using the cockpit assembly sequence of a BMW M440ix as a reference. Based on the defined requirements, needed system components are selected. Then, the concept for the integration of sensor modules into the worker-assistance-system (W-A-S) is developed. Starting from the analysis of conceptual requirements, existing approaches and frameworks for the design and integration of cyber-physical Systems are discussed. Based thereon, a concept for the presented use case is derived and illustrated in an application example. The steps for the implementation of the prototypical W-A-S will be laid out in chapter 5. An evaluation of the work will lead to a discussion about what has been achieved. An outlook regarding the potential ofother

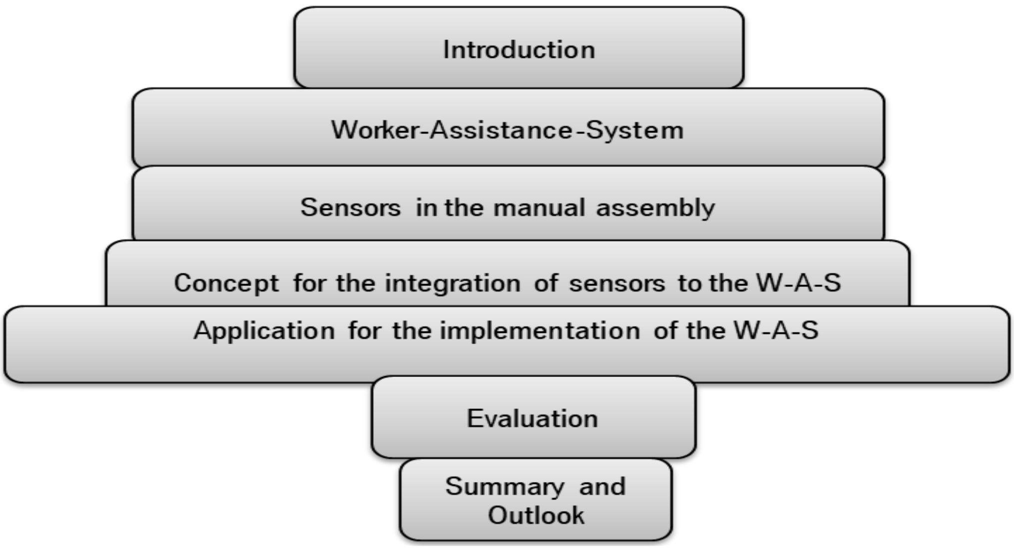


Figure 1: Structure of the work

sensor-modules will conclude the work. The structure of the work is illustrated in Figure 1.

2. Worker-Assistance-Systems

The competitiveness of a manufacturing company can be strengthened by increasing its flexibility and ability to face the dynamics and fluctuations of global market. Due to the steadily increasing variant diversity and the constantly augmenting market demand, the assembly usually takes place manually or semi-automated, despite high labor costs [6]. It is, therefore, important to reduce waste in manual assembly processes. The trend in major manufacturing industries goes towards sensor-based assisting systems that control the assembly process and point out the errors.

2.1. Description of assembly assistance systems

A basic version of assembly assistance systems could be characterized as a software-based solution composed of a screen that displays the required assembly instructions to the user and connected tools such as a barcode scanners and a pick-by-light systems. Such a system would allow the acknowledgment of the assembly process in real-time thanks to the scanning of the different components and, at the same time, to the detection of handling errors using the pick-by-light system. Through the displayed instructions, the workers are able to complete the tasks in the planned order. Human errors can largely be mitigated, the stress level of the staff is therefore reduced and a better productivity is achieved [7]. Moreover, many other cyber-physical systems can be integrated into such an assistance system in order to track the physical environment and the assembly situation and communicate information to the worker [8]. For example, Zamfiresu et al. [9] integrated augmented reality to assist workers during assembly processes. A hand tracking module with an overhead 2D static camera was used to capture the environmental changes and detect tools and object picked and virtual instructions were available to the worker by means of a Microsoft Kinect Different kinds of reactive and proactive assembly assistance systems are being implemented and used, besides, several application scenarios of such systems are available. [10]

One use case of the assembly assistance is the training of apprentices. In addition to the detailed description of the steps, pictures and/or CAD images are available to give more details and thus avoid confusion. This could be a more efficient way to learn than being given the instruction from an instructor. The mishandling would be detected thanks to the interconnected sensor-modules and the learner would be informed through acoustic or haptic warning signals. The possibility of personally fixing the error is available and this leads to greater motivation and involvement of the employee.

The correctness of the learned moves is also guaranteed by the system and the learning time is reduced as the learning process no longer depends on any other external factors such as the degree of agreement between the apprentice and the instructor. However, to achieve an unobtrusive recognition and tracking of all the assembly steps, wearable systems could be of a great importance. Stiefmeier et al. [11] conducted a case study in cooperation with the European car manufacturer Skoda. RFID tags were attached to the tools, an RFID reader was placed between the worker´s thumb and index finger to detect which tool was being used. Moreover an array of force sensitive resistors integrated into a strap worn around the arm could detect grasping or clipping actions thanks to the muscle contraction of the worker. Thanks to an inertial measurement unit mounted on the palm, the hand vibration could also be detected when the screwing ends, notifying the system that the current step has been completed. The learning apprentice was guided through all the assembly process and all the steps could automatically be detected and analyzed. However, such wearable sensors could be a source of hindrance to the worker, if not used in a training situation.

Another use case is the assistance of experimented workers in real production environments. The provided information here does not need to be that detailed. The worker relies on the system in case of a lack of concentration or in case of forgetting the previously accomplished step or even for inspection issues in order to further support quality. Instruction can be displayed or told to the worker in real-time in order to spare reworking-time and an error-report functionality can be provided to acknowledge the failure that would be directly sent to the corresponding stakeholder through the system. The system should not disturb the employee while doing his jobs, it should on the contrary support him in a direct or an indirect way.

2.2. State-of-the-art

To give an overview about the state of the art, four commercially available assistance systems from the industry and three research projects are selected among the variety of existing cyber-physical assistance systems.

2.2.1. Examples in the research field

Motion EAP Project [12] is a project of the University of Stuttgart in collaboration with hciLab. The assisting system is composed of a depth camera to detect the assembly process, to detect grasping actions and also for tools detection. In addition to that, the system comprises a beamer that highlights the storage boxes and projects instructions and videos onto the work table.

The Plant@hand assistance system [13] is implemented by the Frauenhofer Institute for Computer Graphics Research and it consists of a display attached to a mobile workshop trolley containing assembly tools and various proximity sensors. The removal of materials and the usage of tools is directly detected by the system. In addition to that, thanks to a smart watch, gesture control allows for a hands-free interaction with the system.

Operator Support System [14]is the solution proposed by the research organization TNO for a fast, flexible and faultless assembly with projected instructions. The projector enables a pick-to-beamer support so that the worker quickly sees which part has to be picked from the corresponding box. In addition, a MS Kinect motion controller is available to track the removal of parts.

An overview of the main system-components and most important functions are presented in the Table 1.

Formatte

Deleted:

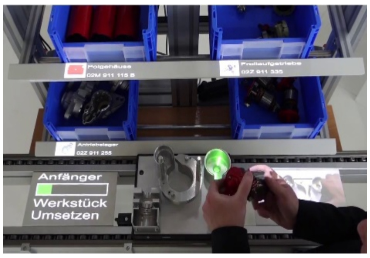
Project / Participants	System Components	Main functions
 **Motion EAP Project** Universität Stuttgart, hciLab	• Depth camera • Projector	➢ Motion detection ➢ Picking detection ➢ Object recognition ➢ In-situ projection ➢ Pick-to-beamer
 **Plant@hand** Fraunhofer IGD	• Mobile trolley • Display • Smart watch • Motion and touch sensors	➢ Tool detection ➢ Gesture control ➢ Gesture recognition
 **Operator Support System** TNO	• Projector • Motion controller Kinect MS	➢ Pick-to-beamer ➢ In-situ projection

Table 1: Overview of assistance systems for research applications

2.2.2. Examples from the industry

The DESC System by DE software & control GmbH [15] is a modular system that provides the assembly workers with all necessary information at their workplace. As depicted in table 1, the DESC assistance system is composed of various modules that allow the adaptive guidance of the assembler (e.g. Beamer, pick-by-light, RFID, Touchscreen). Added to that, a smartphone application offers an augmented reality solution that gives more precise information to the worker, if there is some doubt concerning the correct positioning of the part.

Der Assistent by Ulixes Robotersysteme GmbH [16] is an all-in-one system that covers the requirements of the assembly worker and gives the possibility to download or even develop more adequate applications to the specific assembly situation through its open app-platform. A multi-sensor camera controls the assembly process and a beamer allows the in-situ projection of work instructions and a pick-to-beamer functionality. Additionally, other components are available to guide the worker and prevent him from being confused or overwhelmed.

Der schlaue Klaus by OPTIMUM data management solutions [17] offers an image processing software that allows the object detection through image recognition. The image processing results are displayed on a screen or a tablet in order to prevent the worker from mishandling and ensure a good product quality. No tools are connected to the system, although tool detection is possible with the camera system.

ActiveAssist is a system developed by the company Bosch Rexroth [18]. The assistance system comprises a camera, a beamer, a pick-by-light system, RFID, a touchscreen and other components. The camera allows quality control and hand tracking. And through the beamer, the in-situ projection and the pick-by-light system, the worker is assisted in every step. Error detection in real time is henceforth possible. In addition, the Sarissa tool module enables the detection of tools and control of the correct tool. The system accesses information from upper level IT systems such as manufacturing execution systems or enterprise resource planning systems and provides the worker with individual assembly instructions.

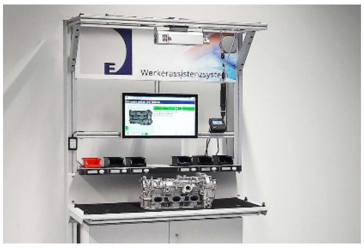
Product / Vendor	System Components	Main functions
 **DESC** DE software & control GmbH	• Touchscreen • RFID • Laser • Beamer • Screwdriver • Scale • Smartphone	➢ In-situ projection ➢ Pick-by-light ➢ Pick-by-voice ➢ Gesture recognition ➢ Augmented reality to visualize the correct position
 **Der Assistant** Ulixes Robotersysteme GmbH	• Projector • Multi-sensor camera • Touchscreen • Hand scanner	➢ Pick-to-beamer ➢ In-situ projection ➢ Gesture recognition
 **Der schlaue Klaus** OPTIMUM data management solutions GmbH	• 2D Camera • Monitor or tablet	➢ Object identification ➢ Quality control
 **ActiveAssist** Bosch Rexroth AG	• Projector • Touchscreen • RFID • 3D Camera • Intelligent screwdriver • Barcode scanner • Sarissa Tool Module	➢ In-situ projection ➢ Pick-to-light ➢ Hand tracking ➢ Quality control ➢ Nutrunner positioning

Table 2: Overview of assistance systems used in the industry

2.2.3. Summary

A wide range of assistance systems was presented in the last section, from demonstrators in the research-field to industry-ready off-the-shelf solutions. All systems presented are designed to guide the worker during manual assembly tasks. Different HMI and sensor technologies are used for that sake: from Displays to Augmented Reality and from simple proximity sensors to AI-based camera-systems.

Several assistance systems use in-situ projection of the work instructions, which is supposed to minimize mental load at high working speeds, others simply display the information on a touch-screen. Few systems offer the option of a head-mounted display to visualize instructions and to highlight regions of interest, which is especially useful in mobile applications, for example in maintenance or plant construction. [19].

In this work, we decided to go on with a touch-screen, taking into account the restrictions of the two other possibilities: (1) the performance of today´s beamers can be in some cases affected by lighting conditions, which could probably annoy the worker and lead to confusion, and (2) the fact that head-mounted displays could cause cyber-sickness such as headache or nausea [20].

For the recognition of the production context and progress, some of the systems work with 2D or 3D cameras based on image processing while others are using RFID technology, barcode scanners and binary sensors to track the assembly process. The multi-sensor camera systems are used for motion detection and object recognition which allows detecting many handling errors before the assembly task is carried out. Picking detection is mostly realized via a pick-by-light system composed of LEDs and light barriers or pick-to-beamer thanks to hybrid laser led technology. Due tothevarious advantages and drawbacks of different approaches and technologies, there is no ideal assistance system that suits every application. Rather, the specific requirements for a certain use-case and the respective objectives need to be considered, when the actual system is introduced.

The presented solutions mainly focus on the frame conditions of series production with medium lot sizes in a workshop environment or in manufacturing islands, like well-defined and mature processes. The time pressure on the worker in such scenarios is usually higher than in the prototype production to reach certain productivity goals, while still allowing the worker to consume and process information provided by the assistance system. In a highly optimized continuous flow production like the automotive series production, cycle times are so short and the workers require extensive training to be able to complete the assigned tasks in the given time. In such environment, assistance systems need to provide minimal information, i.e. the current variant in a very simple manner. For prototype assembly, which forms the scope of this work, the frame conditions and requirements is analyzed in the following chapter, in order to develop and compile an adequate worker assistance system.

3. Sensors in the manual assembly

Without sensors, today´s technology, both in industry as well as in our everyday personal lives, would not be possible. In DIN 1319-1 [21], which defines standards for measurement technology, a sensor is defined as a part of a measuring system that directly responds to a physical or chemical stimulus. It forms the first element in the measurement chain. By leveraging physical or chemical effects, various physical and chemical values can be measured, including temperature, light, sound, pressure, magnetism, motion, pH-value, etc. [22]. Miniaturization, new materials and innovative sensor concepts as well as cost-effective mass-production have enabled the integration of sensors in challenging environments and a broad field of applications, from highly critical industrial control systems to portable consumer entertainment devices. At the moment, the trend in sensor technology is moving from simple analog detectors to smart sensors with local intelligence, integrated measurement processing, extended pre-processing functionalities, digital signal output and wireless communication capability [23]. A large variety of smart sensors is already available in the electronics market. However, the challenge is to choose the most suitable sensor technology and system architecture for a specific application. For the presented use case, there are mainly two tasks that shall be accomplished leveraging sensors integrated into an assembly Assistance System:

- Track the assembly process to ensure adherence to process instructions and to detect and avoid human errors
- Observe and measure values that indicate the assembly process quality to evaluate the maturity and fitness for application in the series production, like i.e. the physical strain on the worker

In order to define requirements and prepare the selection of adequate components, in the following chapter the prototype assembly is analyzed.

3.1. Manual assembly tasks and frame conditions in the prototype production

Assembly activities consist in building a system of higher complexity from manufactured or delivered individual parts, which fulfills desired functions. This must be done in a defined period of time [24]. According to the VDI guideline 2860, the assembly is described as "the totality of all processes, which serve the assembly of geometrically determined bodies". In addition to the joining of parts, this also includes

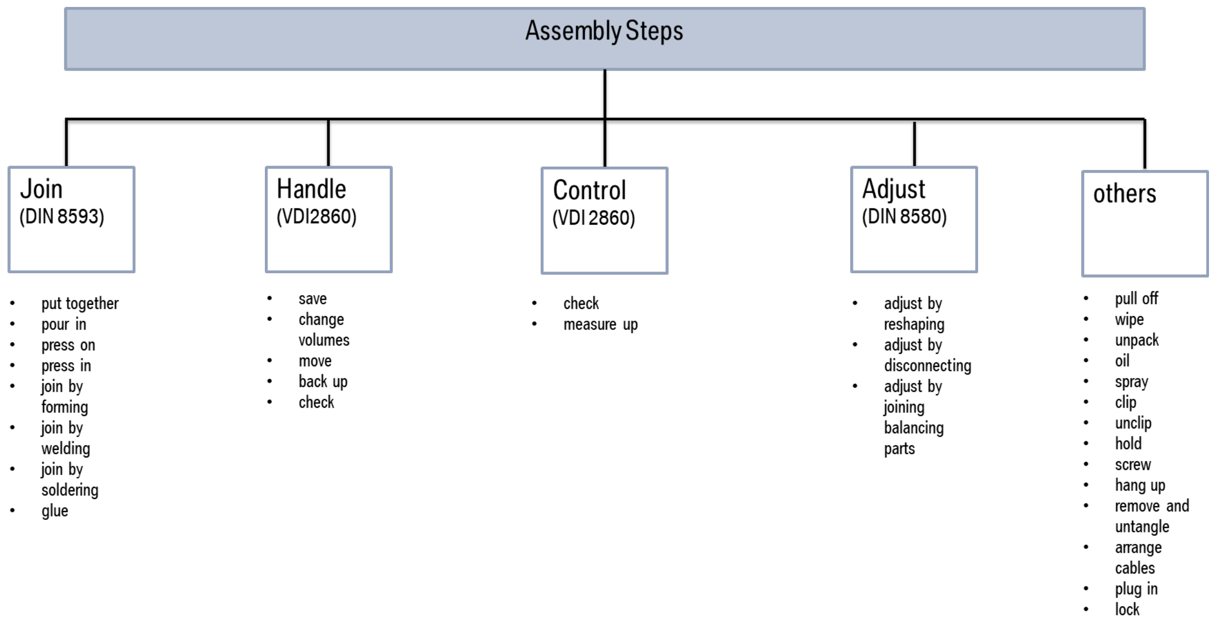


Figure 2: Assembly steps according to DIN and VDI guidelines

processes of handling materials and tools or special operations, such as unpacking, marking and inspecting parts. **Error! Reference source not found.** shows the different assembly-related actions.**Error! Reference source not found.**

Deleted:

In order to ensure a 100% correct execution of the assembly process and to provide the worker with context-aware instructions, the assisting system should ideally be able to detect, evaluate and document all the operations shown in Figure 2. That would probably be possible with extensive use of various sensor technologies. However, with today's state-of-the-art, such a system would be highly complex, difficult to design and realize, error-prone and hard to maintain. Consequently, many processes in manual assembly are usually composed of simple tasks that can be easily tracked by sensors. Some can be sensed with binary sensors or position and motion sensors or by tracking involved tools. However, there are also complex tasks that are hardly detectable with conventional sensors, like i.e. unpacking and handling of a part. Semiconductor image sensors in combination with computer algorithms might be able to offer a solution in those cases. . However, using this new, complex technology is not possible in all cases and the visual surveillance of the workplace raises privacy concerns.

Therefore, following the Pareto-principle, in this work the approach to focus on the most frequent, critical and easy to track tasks and process aspects was pursued.

To gain a better understanding regarding the various manual assembly tasks and their relevance for the production of vehicle prototypes, the steps involved in the cockpit preassembly of a BMW M440ix, a test vehicle that was used for evaluation purposes in the research project, are examined in detail. Around 132 assembly steps are required in order to assemble the cockpit of a BMW 440ix. This number depends on the optional equipment chosen of by the Research and Development department or

Total of partial operations	Picking	Part Ident	Positioning	Screwing	Clipping	Plug in	Other
132	56	102	65	27	33	24	13

Figure 3: Number of specific assembly tasks relevant to the assembly process of a BMW440 ix

the end customer. A categorization of the assembly partial operations based on the type of activity permits to derive the most common actions to be sensed by the W-A-S.

As shown by the analysis results in figure 3, the most frequent task is part identification, with 102 scanning actions needed over the 132 partial operations mentioned above. 59 of the 102 scanning actions are not relevant to the series. This emphasizes the difference between the prototype development and the series production. These extra steps are due to the lower time pressure compared to the series and tend to ensure a better documentation of the process for an accurate process evaluation and a precise failure location.

The other assembly activities, present in the assembly of the cockpit, are in order of decreasing frequency: Positioning, picking, clipping, screwing and clipping. These assembly actions represent the most relevant actions of the prototype assembly and are therefore to be taken into consideration for the implementation of the W-A-S.

Several properties of these processes need to be considered to determine, whether a process is mature and ready for application in the series production. Among these so called process aspects are the mountability, which itself contains i.e. the geometric consistency of the product, the assembly sequence and the accessibility of connection elements, the completeness and correctness of work instructions and process parameters, the capability of tools, and so on.

In the following, the specific frame conditions in the automotive prototype assembly are discussed. Thereby, important differences between the prototype assembly and the series production are highlighted.

1. <u>Product development and process planning not completed:</u>

   Due to ongoing product development, throughout the prototype assembly phase, a multitude of changes concerning parts and joining concepts are committed by the R&D department. For the first batches of prototypes, and due to low part quality, poor dimensional accuracy or deficient concepts, extensive additional work, like mechanical adjustment and rework of parts is frequently required. Those unforeseen tasks are obviously not specified by the assembly planning department. Also, the planned and specified series processes might be incomplete or flawed.

In contrast, by the time the series production is started, product concepts are thoroughly tested and fixed, adequate part quality is assured and assembly concepts and processes are mature and optimized. Therefore in the series production, changes regarding product or processes occur by far less frequent and to a smaller extent, and are planned well ahead.

2. <u>Novelty of product and processes</u>

   In the prototype production, new products and assembly concepts are evaluated for the first time in hardware. Especially with the trend towards new drive concepts and autonomous driving, which also demand for new production concepts, the complexity is dramatically increasing. The workers have to assemble the prototypes without extensive prior training.

3. <u>Low number of repetitions:</u>

   In a mid-sized series-plant, between 500 and 1.500 vehicles of the same model are produced per day. The training of employees for series production usually requires several weeks of intensive schooling in separate environments as well as supervised practice directly in the production line. During the prototype development, depending on the complexity and novelty of the product, regulatory requirements, etc. about 20 to 500 vehicles are produced over a period of several months. Therefore, the number of times a certain process is repeated remains relatively small, which together with the high frequency of changes (see 1.) and the high degree of novelty (see 2.) emphasizes the necessity of an adaptive, context-aware assistance system.

4. <u>Automation and time pressure:</u>

   As the purpose of prototyping is not to achieve a cost-effective mass-production but to produce a relatively small number of highly customized experimental vehicles for the R&D departments and to test and evaluate certain aspects of the manufacturing process, throughput times in prototype production are much longer than in series. While the degree of automation in the series assembly is already low compared to the press or body shop, in the prototype assembly, almost no automated systems are used due to the high costs, which are not justifiable for the low numbers of vehicles (see 3.).

5. <u>Higher cost compared to the series production:</u>

The total costs of a prototype is several orders of magnitude higher compared to the series products. Scale effects do not apply for the prototype production, since the production volume, as explained above, is low. Thus, the average unit cost does not decline and remains high. Labor cost is also accordingly high.

6. Documentation of the prototype components and assembly process:

   In order to ensure and prove the validity of test results, to facilitate the analysis in case of problems and due to regulatory requirements, a thorough documentation of the materials, parts and the assembly process is necessary. In the series production, only selected security relevant parts and processes need to be documented, as many potential errors are avoided by design of the production system.

7. Numerous and wide range of problems:

   Due to the ongoing product development and continuously changing assembly processes, a variety of problems can occur during the prototype assembly. First, these problems need to be documented rigorously and comprehensively. Next, a problem has to be classified in order to determine, whether a conceptual deficiency is at hand. In such cases, the subject has to be communicated to the respective product development or process planning department so that further analysis can be induced and corrective measures initiated.

3.2. Analysis of the requirements

Based on the state-of-the-art similar systems and current research presented in chapter 2, the analysis of the cockpit preassembly processes, the process aspects and the frame conditions in the prototype assembly, the following requirements regarding the use of sensors in combination with a worker assistance system is derived.

The system shall provide detailed contextual instructions. This means, that at the beginning of a task, the assistance system should at first explain precisely and clearly every assembly step thanks to and illustrations displayed on the screen in order to allow hands-free use and direct the worker through the whole process. The next prerequisite would be to track the production state to determine the progress of the work and save all the collected data for an instant or an upcoming analysis. Whether it concerns the tool used or the picked-up component, all assembly-related information are of importance for a thorough assistance of the employee. Added to that, the system should be able to notice if the worker does not respect the assembly sequence. For safety issues and in order to ensure a good product quality in the prototype production, ensuring screws are correctly tightened in the right sequence is essential. That would be possible by observing the position of the screwdriver for example and processing the collected data in order to confirm the correct screwing sequence or even by observing the position of the screw itself. Since assisting systems should ultimately provide a more adequate working environment, the ergonomic assessment is also of great importance. For that purpose, a gyroscope-based motion capturing system for the identification of body postures was used by Gudehus [25], while Bellman et al. preferred using a camera-based solution to record and analyze data [26]. Both of these approaches intend to evaluate the workstation and derive possible improvements of the workplace. Thus, the integration of such a system to the W-A-S would be of great interest.

Although assembly times are not of major importance for the prototype production as explained in 3.1. execution times must be recorded and analyzed. However, the aim of recording completion times depends on the application scenario of the assistance system. On one hand, if the system is used by an apprentice for training purposes, recording throughput times would be to strengthen its motivation by providing him with a summary of his results after completing his tasks. On the other hand, if an experienced worker is guided by the system, then saving assembly times would be an essential part of the evaluation of the process maturity. Nowadays, process-related times are determined by one or many experts or by the assembly operator himself through self-recording [27]. This method is far from being as precise as an automatic time calculation through the assembly assistance system and can lead to an erroneous process evaluation.

Obviously, errors must be documented and analyzed. Error reports are essential for the optimization in small and fast cycles of production processes before the series production is reached. Today, errors are mostly documented in paper form. This includes lengthy delays and long quality control loops. The traceability of errors causes is hampered by the time gap and that lead in most of the cases to knowledge losses.

To sum up, the sensors integrated into the W-A-S must allow the system to:

- track the production context to provide the worker with situation-related assembly information;
- control the assembly sequence;
- detect deviations from the process such as the incorrect attachment of clips;
- record and evaluate the physical workload on the worker; and
- record time required to finish task in order to evaluate the process.

Therefore, the following requirements have been considered as determinant for the selection of the components that need to be integrated into the W-A-S.

Index	Functional requirements
A1	Identify a part the worker picks up
A2	Identify a tool the worker picks up
A3	Control the placement position of part and / or Tool
A4	Control correct tightening of screws
A5	Control correct placement of clips / plugs
A6	Track motions of the worker, grip forces and weight

Table 3: The functional requirements relevant for the W-A-S

3.3. Selection of system components

Various sensor systems are analyzed in the course of this project. The choice of the components for the considered use-case presented in this section is based on the analysis of frame conditions in the prototype assembly described in chapter 3.1 and the derived requirements summarized in Table 3.

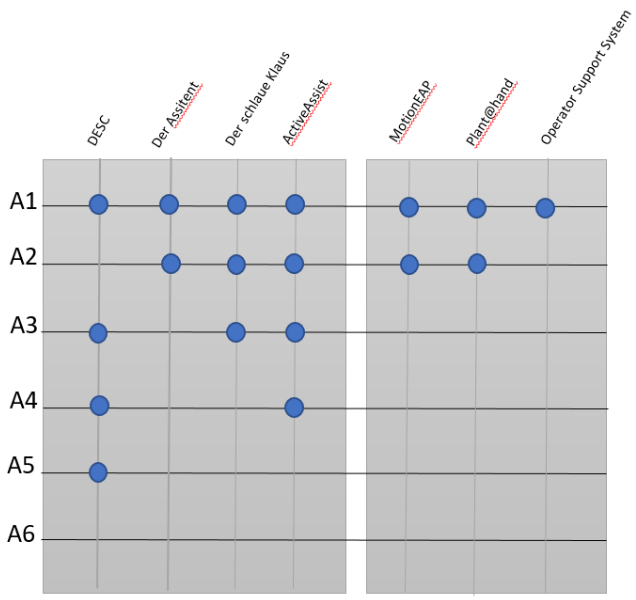


Figure 4: Matching between the assisting systems proposed in the section 2.2 and the requirements derived in section 3.3

Figure 4 depicts the ability of the assisting systems presented in section 2.2 to cope with the chosen requirements (A1 - A6) explained earlier. All the systems offer the possibility to identify a part the worker picks up and five from seven identify the tool the worker is using. A1 and A2 represent the key functions of assisting systems. In order to provide the user with context-aware instructions, it is compulsory to track and detect the assembly parts and tools at first. Three systems fulfill the requirement A3 and two of them fulfill A4. Controlling the correct placement of clips is very specific to the assembly scenario of this thesis, thus, just the DESC may allow the detection of clip attachment with its augmented reality interface. To finish, none of the systems stated above does allow an ergonomic assessment by measuring grip forces and the weight of the user. The choice of sensor modules will be explained according to the six requirements stated in section 3.3:

Deleted:

A1) As specified earlier, the detection of assembly part could be possible thanks to a pick-to-light solution and scanning systems or via a camera solution. For the assembly of prototypes, the first solution was considered as more adequate. The worker usually has enough time to scan all the assembly parts. In case of the availability of RFID tags, the RFID reader would automatically detect the part the employee picks up and a notification would be displayed on the touchscreen. The pick-by-light system could be replaced by a pick-to-beamer although the resolution could be sometimes deteriorated by the environmental lighting conditions. In addition, according to the context of the assembly, the boxes cannot be placed under the top-mounted projector due to lack of space, hence, the choice of the pick-by-light.

A2) Tool grasping detection could be possible with RFID in the context of a body-worn solution as explained in the section 2.1. Nonetheless, body-worn-sensors could bother the employee and prevent him from doing his job smoothly. The camera solution is also relevant for this purpose, however, a more cost-effective and a trustworthier solution was chosen. It consists in an intelligent support that is equipped with a proximity sensor to detect the presence or absence of the tool.

A3) In order to control the screwing sequence, the placement position of parts or tools should be detected by the W-A-S. For that purpose, a Sarissa tool module was attached to the nutrunner linked to the ActiveAssist to monitor and record the correct sequence of each individual screw connection, while a camera-solution was chosen for the OPTIMUM datamanagement solutions assistive system and the DESC. A more convenient solution was though integrated to the W-A-S. The chosen screwing-system offers the possibility to detect the screw locations via a monochrome camera attached to its tip by the mean of image processing.

A4) As explained in section 3.2, the correct tightening of the screws should be directly controlled by the system. A torque limit is set up, so that the screwing system automatically stops when this limit is reached and protects the screw/part from potential damage.

A5) A smart glove developed at the Clemson University in collaboration with BMW group have been tested for the detection of correct clipping. As shown in Figure 5 , the system is composed of two sound sensors, 4 force sensors, an inertial measurement unit, a real-time clock and a microcontroller. Through this sensor-system, the attachment of clips or plugs could be detected and sent in real time to the W-A-S. However, since the prototype is still under development, the final integration of this smart glove to the W-A-S was postponed to the next quarter. Another cause of delaying its integration is that wearing such a glove is inconvenient for other assembly activities. For the test, two workers participated to the demo in order to avoid detecting irrelevant actions which could lead to an erroneous process evaluation.

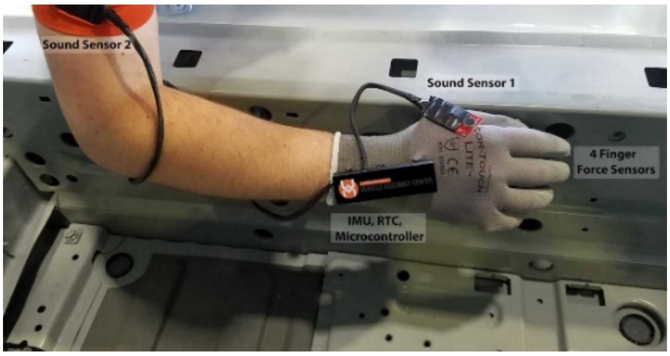


Figure 5: Wearable embedded sensors for future manual assembly

A6) In order to prevent work-related health risks, physical workloads such as wrong postures and heavy lifting during manual handling operations have to be analyzed before series production is started. Such evaluation is carried out nowadays by experts in dedicated workshops. Therefore, this is time-consuming and subjective. The Xsens body-worn motion capturing solution is capable of detecting body posture, movements and joint angles. Thereby, it allows for an automated and accurate evaluation. The strain of the neck, the shoulder-joint and the hull are automatically recognized. To complement the data for a complete ergonomic evaluation, furthermore a pressure-measuring insole system and a force-measuring glove are used. The W-A-S provides the information about the current assembly process and establishes the link between the measurements and the process steps. However, this ergonomic assessment solution is still not an integral part of the W-A-S. The possibility of data exchange between the W-A-S and the Xsens is verified and validated. The integration process is still ongoing. An explanation of the prototypical implementation of the sensor-based worker assistance system should follow,

Figure 6: Xsens suit calibration and test in real environment

starting from the concept for the integration of sensors arriving to the general system architecture and hardware design.

4. Concept for the integration of sensors into W-A-S

An assembly assisting system is based on automatic activity detection. However, a great deal of effort is required to integrate different sensors and interpret the collected data. The challenge here is the necessity of implementing a flexible and adaptable system that handles the change change of drivers and easily adapt to different production scenarios. Having an automated interpretation and integration of the sensors as a goal, the provision of abstract information instead of sensor-specific values, which can be interpreted by all systems, is essential. The basis for this is the semantic modelling of the sensor technology and the work instructions according to a uniform methodology.

4.1. Analysis of the non-functional requirements

Regarding the integration of sensor modules or more general cyber physical modules into a cyber physical system, the functional requirement basically comes down to allow for the communication among the modules as well as the communication between the modules and central software components. Apart from the functional requirements, which precisely define what shall be accomplished, for the conception and development of a solution, also non-functional requirements play a decisive role, as they form the basis for the selection of appropriate designs and implementations among the myriad of existing solutions [28], how the specified functions will be achieved and what the resulting properties will be. Non-functional requirements (NFRS) designate system attributes also known as quality attributes that impose constraints on the system design. The choice of these system quality attributes (such as security, reliability, accuracy, performance etc.) may vary from one software system to another regarding its functional requirements and its application scenario, however, determining the nonfunctional requirements generally tend to ensure usability and performance [29]. An enquiry about the required nonfunctional requirements for the worker-assistance-system and the potential challenges was conducted in order to set up the foundation for the W-A-S development.

1. <u>Interoperability</u>

   Interoperability can be defined as the ability of distinctive systems, modules or applications to exchange services in an organized manner, without additional effort from the end user [30]. This nonfunctional requirement represents a characteristic of a system, which modules are meant to share services and interact with other systems or products without constraints. Syntactic interoperability, also known as structural interoperability, is considered the most relevant type of interoperability for the W-A-S, as it is relevant for systems that interoperate through compatible formats and protocols [30]. Various sensor modules can be attached to the W-A-S to assist the assembler depending on the workplace, car model and the according assembly tasks. Devices should be able to share data and interoperate between themselves. Quint et al. [31] indicate that standardized semantic description is needed to enable interoperability between sensor modules. Mingh [32] proposes a solution to interoperability issues based on the idea of upper ontologies Gezer et al. [33] ensure that using widely-used standards such as MQTT and TCP/IP increases interoperability among devices.

2. Flexibility

Flexibility refers to the ability to cope with internal and external changes in a timely-effective manner without affecting their value delivery. In other words, a design is considered flexible if it easily responds to uncertainty in a way that its added value remains unchanged or even increases. Uncertainty represents a key element in the definition of flexibility [34]. It can be a source of opportunities as well as risks in a system. Thus, emphasizing the need for flexibility in system engineering. In the case of the W-A-S, the simple integration of various sensor systems of different vendors is a crucial criterion since the assembly processes and therefore the functional requirements regarding the complete system are constantly changing. In fact, flexibility yields the connection of multiple devices to the system so that it could be tailored to target environments and a better awareness of the production environment could be achieved.

3. Modularity

Modularity is defined as separating the functionality of the program into modules. Each of these modules execute only one aspect of the functionality but has the possibility to interact with other modules through clear-cut interfaces. According to Baldwin et al. [35], modularization has three main targets. It tends to make complexity controllable as well as parallel work possible. It also adapts future uncertainty. Uncertainty can be accommodated by changing the elements of the modules as long as the design rules of the modular architecture are respected.Since modules can be reused for the same tasks, a lot of time can be saved in the development and configuration of a system and the construction of large software programs is therefore facilitated. When the program is built up according to the modular principle, the developer is able to effect change on one part of the system without affecting other components.

4. Scalability

A scalable system is a system that can handle a growing amount of resources and users without causing throughput bottlenecks. By adding resources, the load increases. The system should be able to increase performance proportionally. Scalability is a system attribute that describes the capability of a system to manage changes and adapt to increased demand. This NFR is often a sign of system stability as it mirrors the ability of the system to face the increased productivity trends and changing need. [36] The worker assistance system should be designed in such a manner that its operability is ensured independently from the number of system users and connected resources. The scalable design of the W-A-S would allow to use the developed system in several production stations and cope with a multitude of application scenarios, which automatically increases the number of users and connected sensor modules.

5. Fault tolerance

Fault tolerance is a property of critical systems that ensures the proper working of the systems even despite failures of some of its components. While the W-A-S is not critical in the sense that a malfunction or outage can jeopardize the workers physical health, a production that is heavily reliant on such a system might have to reduce or even halt production, causing high financial losses and causing delays in downstream departments. In a networked environment like the worker assistance system, an error in one system can affect another system and propagate among interconnected systems. Thus, fault tolerance should not be restricted to individual systems but it should also concern their communication environment [37]. According to Kant [37], graceful degradation is a strategy to maintain a degraded performance with reduced service level in the event of failure by reallocating the functionality of the defect subsystem to another one. Thus, the system can be referred to as fault tolerant. Latash et al. [38] propose to use redundancy as a way to ensure fault tolerance. Redundancy in system engineering is defined as the duplication of system components or the inclusion of unnecessary extra modules in order to provide backup in case of failure.

6. Usability

Usability is a quality attribute that is defined as the ease of use of a system. It is mostly related to the user interface and the amount of training required by the user to understand how the system works. Usability is inversely proportional to the degree of training needed. As mentioned in section 2.1, the W-A-S would be used by assembly workers with different experience levels. It would be ideal if even the apprentice could intuitively use the system without the need for an initiation to the W-A-S. In regard to the sensor system, the user should be quickly able to gain a basic understanding of the core functions.

The software and hardware design decisions should be based on these requirements. The challenge at hand lies in the selection of an architecture that allow the W-A-S to meet all these requirements. Therefore, an enquiry regarding system design principles, so called paradigms, and architectures and existing frameworks in the area of control systems and the internet of things was done in order to derive a suitable approach that resolves the challenges and fulfills the requirements stated above. The NFRs discussed above define part of the criteria which the whole system needs to be evaluated against. An evaluation of the concept will be done in section 6.1.

4.2. Paradigms, architectures and existing frameworks

In order to get an overview of the existing solutions regarding the integration of heterogeneous modules to complex cyber physical systems, common paradigms, architectures and frameworks in the domain of software engineering will be presented and discussed.

The word “paradigm” is defined and re-defined in many areas to the degree that its meaning has become overburden and vague [39]. It is commonly used to refer to a group of entities that have a common characteristic [40]. For the presented work, especially software design paradigms, which describe models for building applications sharing common properties are relevant. In the area of software design paradigms, four building blocks can be distinguished: Design patterns, components, software architecture and frameworks [40]. Design patterns represent a structure of communicating objects that is intended to solve a particular problem. Components are logical and changeable parts of a system that have to communicate with a variety of other components. Software architecture refers to the high level structure of a software system. It defines the components of a solution and conceptualizes their interrelations and properties. Finally, frameworks are reusable architectures that provide the generic arrangement and context of abstractions with their relations and use within a certain domain [41]. A software architecture must conform to the system´s functional requirements as well as NFRs. Numerous and diverse architectural styles are applicable, such as the data flow architecture, the data-centered architecture, the hierarchical architecture or the distributed architecture. Each style describes a category of system that comprises a set of components of multiple types, communication enablers, semantic limitations and a topological layout of the system components. Detailed information about these different architectural styles can be found in [42].

A distributed architecture is selected in this work as a reference architecture, since in this type of architecture, components can communicate with one another over a communication network and the data processing is not restricted to a single central system but is rather distributed over different system components. In addition, this style of architecture generally favors the fault tolerance of the system, the concurrent processing, which increases the system performance, and it also allows for adding new resources that leads to a bigger throughput.

Relying on existing frameworks can make the development process easier and allows the developer in some cases to save valuable time. To sum up, results from our research on existing approaches including five frameworks with different software architectures is discussed:

1- The Calvin framework [44] consists of a hybrid framework for internet of things and cloud computing applications that is developed following theories from Actor model and Flow-based computing. It establishes a runtime programming interface for the communication between runtimes and actors and divides the development process into four aspects: describe, connect, deploy and manage. The use of a cloud system allows a high flexibility. However, system security issues have been reported. Added to that, a proprietary programming language named Calvinscript is required.

   SOCRADES [45] is a service-oriented framework for web service enabled smart devices in manufacturing industries. Based on the service oriented architecture paradigm, this framework is composed on four parts: a device layer, a middleware, a Manufacturing Integration and Intelligence component and a user interface. It is designed to support device integration into ERP systems, like it is the case for the assembly assistance system ActiveAssist presented in section 2.2 as a state-of-the-art project. As a downside to this approach, problems related to the central enterprise service bus can compromise the entire system. This is known as single point of failure, which could be a source of hindrance to the use of such a system in business critical scenarios, due to concerns regarding reliability and security.

2- FRASAD [46] is a multi-layered model-driven architecture-based framework that uses sensor node domain concepts. A model transformation process automatically generates the application code from intial models thanks to an Operating System Abstraction Layer (OAL). The sensor node architecture is characterized by the presence of two layers (the OAL and the application layer) that tend to amplify the level of abstraction. That is possible through the modeling of the sensor nodes with a domain specific language and isolating the application from the operating system.

3- AllJoyn [47] is an open source framework that allows detection and interoperability of mobile devices and permits a dynamic configuration of the network. In addition, sensor systems can be integrated via this framework regardless of their communication protocol, operating system and vendor. AllJoyn is composed of two main components: (a) the AllJoyn Apps, with its code, service framework and core library, and (b) the AllJoyn Routers that offers a communication platform for the different Apps components through three common patterns: Bundled Router, Standalone Router and Router on a different device.

4- Arrowhead framework [48] is an IoT-based automation framework that consists of a collection of matching services, systems and interfaces. By abstracting the IoT as services, it enables interoperability among devices. Arrowhead´s architecture is based on the local clouds concept, which offers a set of basic core services such as service discovery, service registration, authetication etc.. For its architecture, two implementation alternatives were considered: (a) a service oriented architecture based on web services and (b) a SOA based on MQTT [49].

The five frameworks present different approaches to software architecture such as the model driven architecture and the service oriented architecture that are relevant to distributed systems or applications. By design, each of the presented frameworks has inherent advantages and restrictions which are mainly related to implementation patterns. Due to the respective restrictions, none of these frameworks is fully adaptable to the case of the assembly assistance system. Therefore, a proprietary approach inspired from the ideas and methodologies of the frameworks described above was developed to create an appropriate architecture based on a service oriented design.

4.3. Concept approach

In order to build a flexible and adaptive framework for the W-A-S, the inspiration comes from two service-based architectures: (1) the microservices architecture and (2) the service oriented architecture (SOA).

Microservices architecture could be compared with SOA, as they both focus on service use. However, the architecture characteristics and service capabilities are completely different. For instance, Microservices has an Application Programming Interface layer, while SOA has a messaging middleware that has a multitude of additional capabilities such as routing and protocol transformation [50]. Besides, MSA attempts to reduce the number of remote access protocol to one, wheareas SOA promotes the propagation of multiple heterogeneous protocols through its messaging middleware component [50]. Further information about the difference between the service oriented architecture and microservices architecture can be found in [51]. The decomposition of the system into several processes facilitates the interaction between the different services and allows a better understanding of the system, which makes the distributed systems architectural style ideal for the Worker-assistance-system.

The reference architecture for the W-A-S is a service oriented architecture based on Publish/subscribe pattern. According to ISO standards [52], MQTT (ISO/IEC 20922:2016) is a simple packet agnostic messaging protocol that runs over TCP/IP. The publish/subscribe message pattern guarantees a 1-to-n message delivery through the three following qualities of service (QoS): At most once, at least once and exactly once. The MQTT client can be on one hand any device that connects to a broker over the network in order to receive messages on specific topics, by sending a SUBSCRIBE message. On the other hand, the client can also publish messages on a topic to the broker, which pushes the messages to the subscribing clients. Should the connection of a client be disrupted, the broker buffer the messages and sends them to the subscriber as soon as it is back online. Thus, the choice of this messaging protocol to secure the bidirectional communication between the sensor modules and the W-A-S backend.

Figure 7 depicts how services are classified into 2 categories: functional and non-functional. Functional services represent the operational functions of the sensor system such as the detection of environmental variables. Non-functional services are

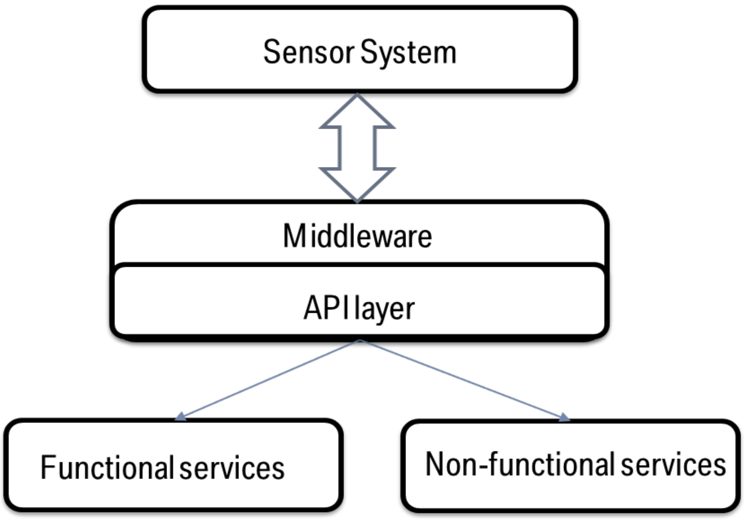


Figure 7: Service classification of the sensor systems

not less important and are of great importance in ensuring system reliability.

They consist in the non-operational tasks such as logging, authentication, life-acknowledgment, connection status provision etc. Some of these services are exposed to the user, such as the connection status of the screwdriver in order to warn the assembler as soon as a disconnection is noticed and thusly avoid assembly delays. Services provided by the sensor systems are exposed by the application programming interface (API)through a set of predefined resources and heterogeneity of services is resolved by middleware. Middleware is required in order to coordinate the distributed sensor systems of the worker assistance system. Software engineers rely on middleware products to build systems that are distributed across a local-area network [53]. A study on existing middleware has to be done in order the best suited solution according to the nonfunctional requirements described above. Middleware can be classified in several categories such as transactional middleware, message-oriented middleware, procedural middleware etc. [53] . The message-oriented middleware is chosen as reference in this work as this class is well-suited for publish/subscribe-based architectures and facilitate message exchange. The message can be event-triggered or a request for service execution from a client with service parameters included. Added to that, asynchronous message delivery is possible by leveraging this class of middleware, thus, a better scalability can be achieved. The reader is invited to know more about middleware, their classification and their added-value in software programming in [53]. Functional services such as sensing relevant environmental variables and reporting the right information to the system ought to be described in details. The evaluation of the effectiveness of the sensor system is done according to the pre-established requirements. Thus, well understanding the purpose and the aim of adding a new sensor module is a very important step when designing a cyber-physical unit. Specifying the interacting variable(s) between the sensor module and the central system is the next step. Then, an information model is built for each sensor module attached to the W-A-S, following the models presented in Figure 8.

Deleted:

The structural model represents all the assets/components relevant to one module,

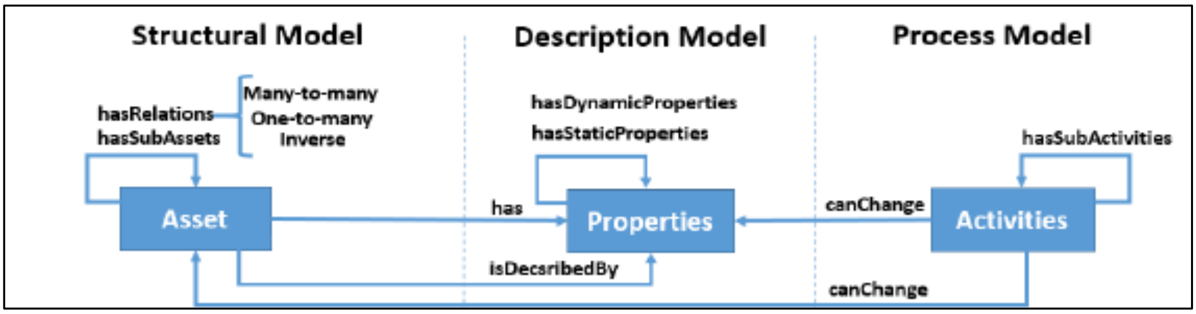


Figure 8: The relation between the structural model, the description model and the process model [5]

while the description model encompasses all their properties. These models are the basis for the design of the hardware that was chosen earlier. The process model describes the assembly process and remains unchanged whether a sensor module is removed or added. The information model developed is used as reference to develop the right ontology for the sensor modules. Finally, classes of services and devices are coded according to their interrelation, with an emphasis on attributing services to different devices based on the device-Ids, so that if a certain device is defect or unavailable, an alternative solution would be available. That is intended to magnify the flexibility and fault-tolerance of the W-A-S. Besides, a special attention was made on the utilization of unified, unambiguous and easily understood terminologies.

5. Application for the implementation of the W-A-S

After defining the concept approach for the integration of sensor systems into W-A-S, the software and hardware design is described in this chapter.

5.1. General system design and architecture

As shown in Figure 9 , the system architecture of the W-A-S is composed of four main components: sensor modules, messaging server, user browser and backend.

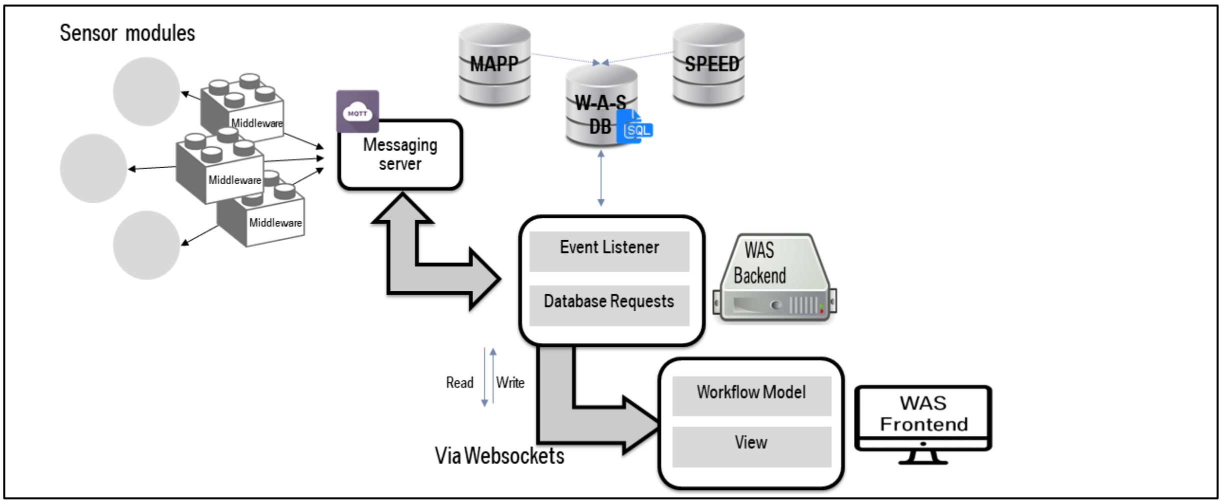


Figure 9: W-A-S software architecture

The workflow model is represented in the frontend. It encompasses states and their interrelations for a certain activity. The backend is composed of two principal modules: one enables extracting/storing data from/in the according database with SQL and the other monitors the events triggered by the sensor modules and sends them to the frontend for further processing. Finally, based on the current state of the assembly task, instructions are displayed on the visualization device (a stationary touchscreen and/or a mobile tablet). The W-A-S is built in Javascript and is responsible for the decentralized acquisition and processing of production-related data. The assistance system implemented in this work requires a combination of three different databases. The assembly process is extracted from two BMW Databases MAPP (to acquire the assembly sequence) and SPEED (for the list of all the components) and an internally developed database named W-A-S DB on which an event-triggered registration or extraction of data occurs. The messaging server is an MQTT broker. It connects all sensor modules and permits the exchange of data between the sensor systems and the W-A-S backend through their middleware. A more detailed explanation of how the modules communicate with the W-A-S is proposed in the next subchapter.

To sum up, a Four-Layer architecture is proposed in this work (see Figure 10).

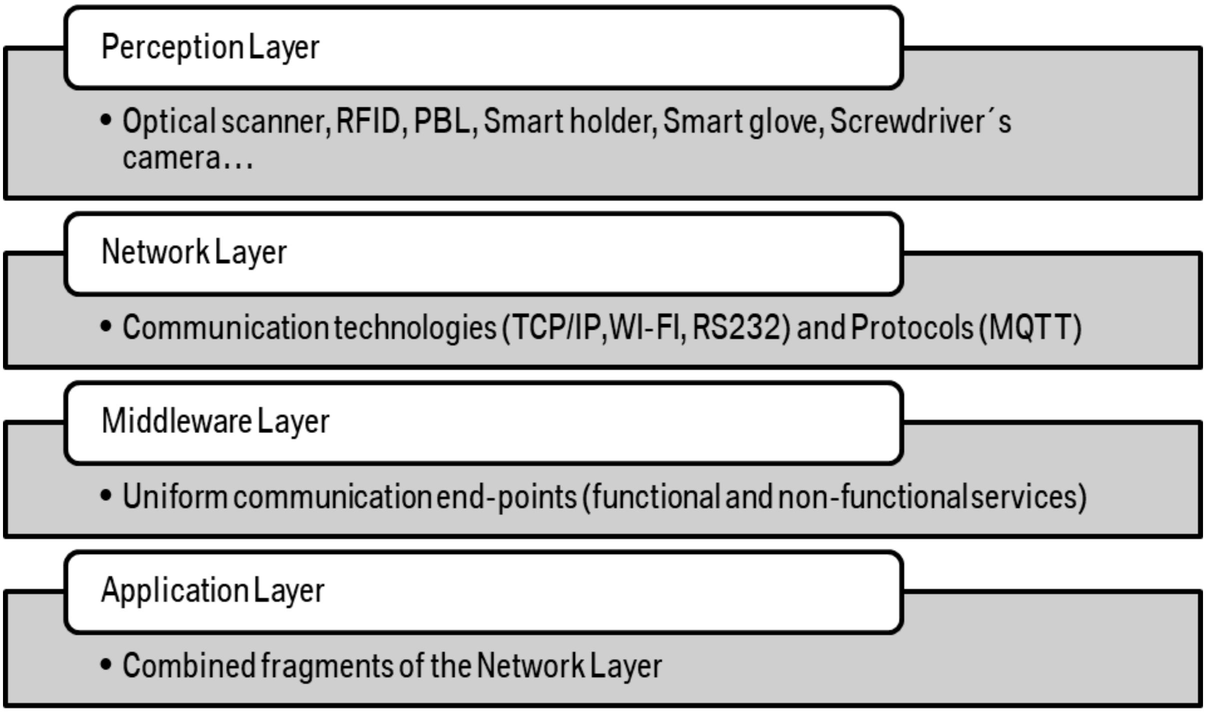


Figure 10: Four layer Architecture of the W-A-S

A Perception Layer consisting of a variety of sensor systems is present in the W-A-S. Environmental data are collected and physical objects are identified and annotated. A Network Layer transpors information from the perception layer to the Middleware Layer. In the Middleware Layer, heterogeneous data is normalized and a uniform interface is derived from the chosen ontology. The Application Layer processes the normalized web services and API endpoints exposed by the Middleware Layer in order to offer the right information to the W-A-S user.

The W-A-S can be constantly expanded with new functions. Besides recording and evaluating all work results, the system ensures transparent processes and creates a reliable source of information for other users.

5.2. Hardware and communication design

The pick-by-light (PBL) system

The PBL system built in the course of this work is composed of nine LEDs over the nine boxes containing different screws. Nine photoelectric proximity sensors are placed on the side of every box in order to ensure the correct detection of gripping actions. A programmable logic controller (PLC) is used to control the pick-by-light system. PLCs are digitally operating electronic systems adapted for industrial environments with programmable memories for internal storage of user-oriented control instructions. Specific functions such as logic control, sequence control, timing, counting and arithmetic functions can be implemented to control different types of machines and processes through digital or analog input and output signals (IEC 61131-2). For this project, a WAGO PF 100 PLC is used. It allows for an easy I/O configuration thanks to its graphical CODESYS-based runtime environment. In the first step, system variable identifiers are assigned to the corresponding inputs and outputs of the PLC. As shown in Figure 11, digital input signals are linked to the light barriers while outputs are assigned to the light emitting diodes.

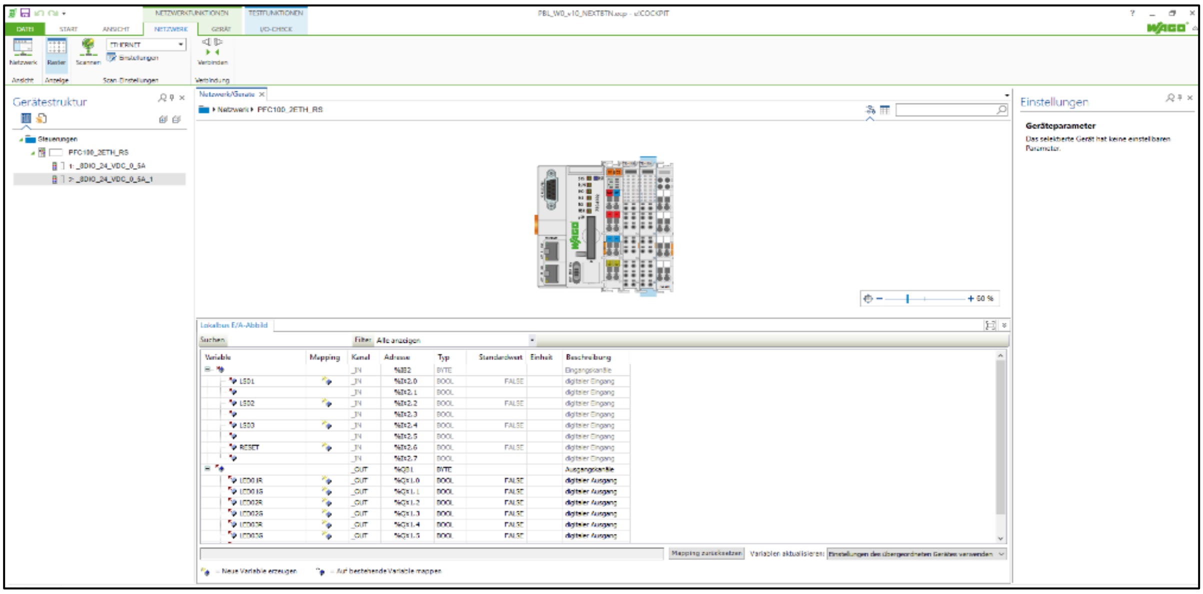


Figure 11: WAGO !eCockpit PLC device structure interface

The PLC allows a direct communication to the backend via MQTT. Thus, 3 modules are programmed in Structured Text (ST), one for the main logic and the two for the MQTT messaging protocol. As shown in Figure 12, the three modules are created in order to implement an operational PBL: MQTT_Publish, PLC_PRG and MQTT_Subscribe. As soon as the PLC boots, a connection to the MQTT broker is established and the PLC subscribes to the defined topic. While the connection is online, a heartbeat is sent to the W-A-S backend every 15 seconds. If a part has to be picked in the assembly process, a JSON message containing the pick-request is sent from the backend to the PLC. The message is then parsed using functions from the

WagoAppJson library and the output corresponding to the according container-id (a green shining LED) is activated.

The main PLC program represents the process logic of the pick-by-light system. Two colors are utilized to signal the worker. Red shining LED means that the worker gripped

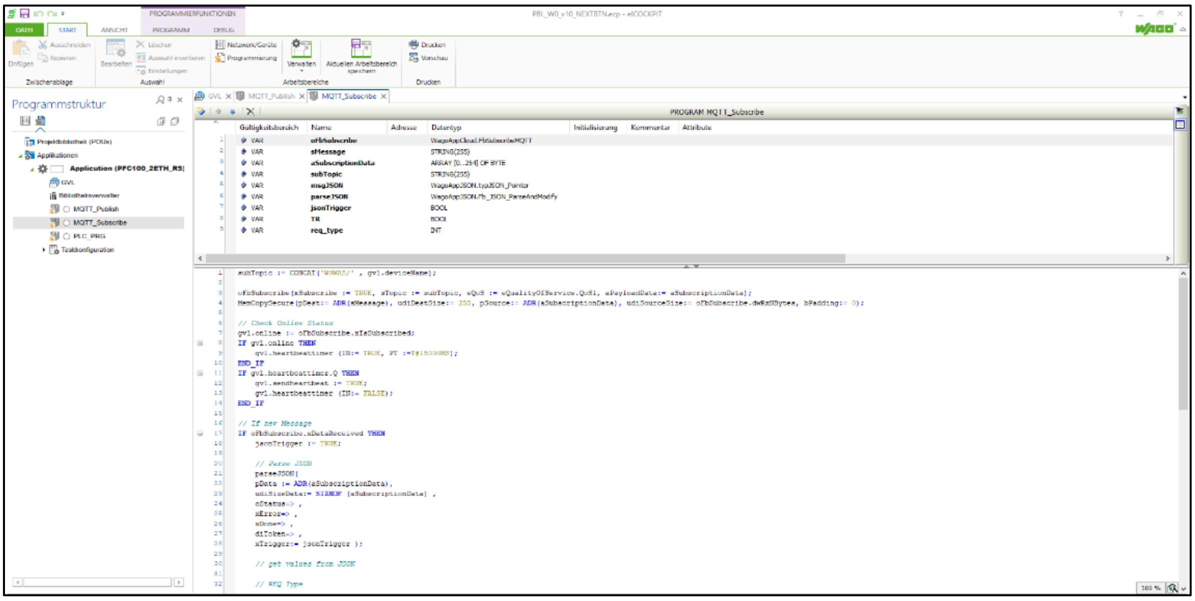


Figure 12: WAGO !eCockpit PLC programming interface

the wrong screw, while a green LED indicates the right shelf to pick. If the right part is picked, the LED blinks for five seconds and then turns off, the worker receives a confirmation of the correct gripping in form of an acoustic signal and a textual instruction on the W-A-S screen as shown in Figure 13. The bin-number is the information that needs to be verified in order to react properly. The choice was made on a JSON that contains the PBL_Id, the screw-Id, its change index and a request type. A comparison between the global variables ShelfPicked and ShelfToPick occurs in the PLC. With the MQTT_Publish module, the JSON is sent to the topic, on which the W-A-S server subscribed. Depending on the request type contained in the generated JSON, the gripping action performed by the worker would be identified by the W-A-S. In the case an error is detected, all the LEDs start shining in red and an error message is shown by the W-A-S.

Scanning components is an important part of the prototype production as explained earlier. Two scanning systems were chosen so that the scanning of all the assembly parts would occur without being a chore to the employee. Some parts are detected by the system through the RFID technology and some others are acknowledged manually with the barcode scanner. The worker gets notified when there is the need to use the barcode scanner and whether the scanning part is correct. Otherwise the part gets scanned automatically via RFID and the relevant information is displayed on the touchscreen.

The handheld barcode scanner

As explained above, a handheld optical barcode scanner is integrated to the W-A-S in order to control the assembly process. The scanner is connected to a raspberry pi 3

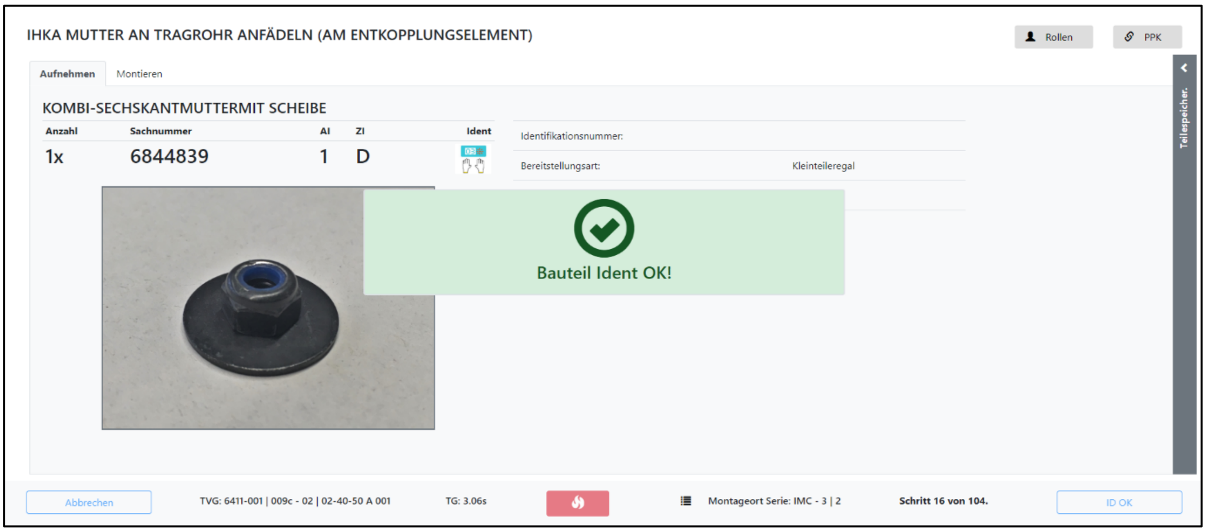


Figure 13: The W-A-S interface after picking the correct part

Model B computer via RS232 over USB. Using Node.JS, a program written in Javascript is running on the Raspberry pi. The program establishes a MQTT connection to the broker, converts ASCII text incoming from the scanner to a JSON message and sends it to the W-A-S backend.

The server compares the barcode detected by the scanner to the one expected. If correct, a success message is displayed on the screen followed by the assembly instruction. Otherwise, the worker is informed that the scanned component does not match the production manual.

The RFID reading system

As mentioned already, a HARTING RFID reader is attached to the W-A-S for the automatic detection of safety- relevant parts equipped with RFID Tags. As soon as the employee holds a component and brings it to the assembly workplace, the RFID antenna identifies it and the reader sends, instantaneously, the corresponding data via TCP packets to the RFID middleware. Thus, a confirmation can be displayed.

This RFID reader offers a user-friendly interface for its configuration according to a specific application. Up to four antennas can be connected to the reader to cover four different workstations in one assembly zone with one reader unit. In order to be able to send messages to the W-A-S backend, the reader´s Ethernet interface has to first be configured for the local area network. Figure 14 shows the LAN configuration interface.

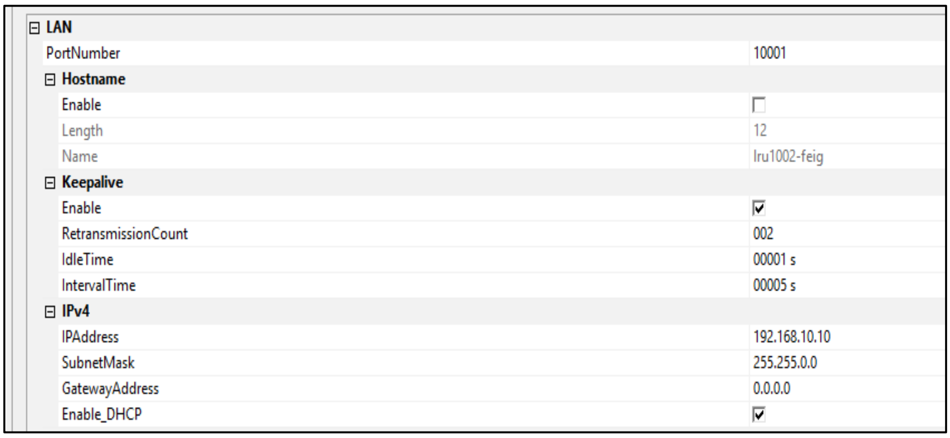


Figure 14: LAN configuration

The Ha-VIS RF R400 RFID reader can then operate in three operating modes:

- A bufferedRead mode, in which the reader detects tags and records them in local memory until a request is received. Only then, it does send the recorded data to the server.
- A notification mode, in which the reader sends a message to a configured destination as soon as it reads a tag. Therefore, there is no need to actively request data.
- A scan mode, in which the reader awaits a request to start the scanning process. On a second request, the reader stops scanning and transmits all the discovered data to the server.

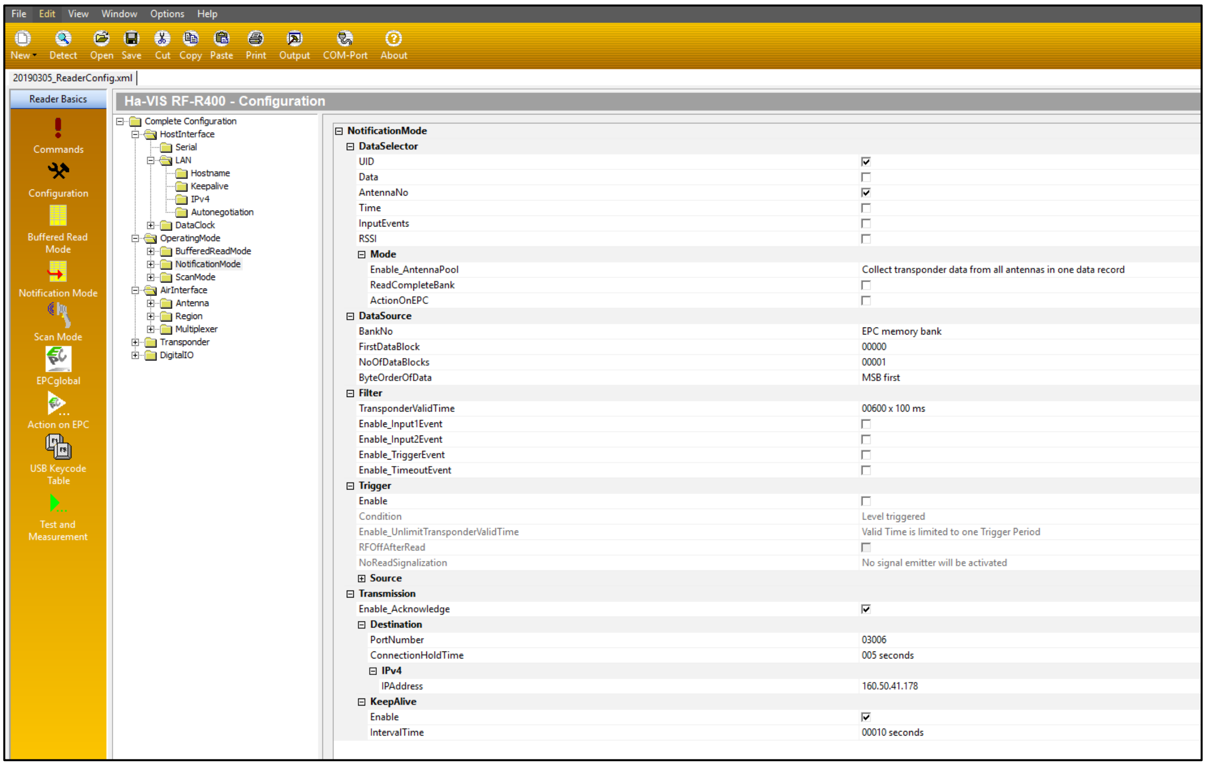


Figure 15: Configuration of the chosen operating mode

Since W-A-S must be able to detect all activities that do not comply with the assembly process, the notification mode is chosen for the presented use case. The configuration of the operating mode is shown in Figure 15. The last step is to regulate the reader´s detection range which is proportional to the output power of the antenna as shown in **Error! Reference source not found.**. It is set to 0,1 W, the lowest possible power, which largely covers the assembly workplace. Deleted:

Figure 16: Configuration of the air interface

The screwing system

The screw system represents a solution for smart connected assembly operation. For its connection to the W-A-S, a ST Middleware with an MQTT interface from one side and a TCP/IP interface from the other needed to be programmed. For that purpose, two packets are available: a net packet for the TCP/IP communication (port and IP address) and another named MQTT for the MQTT protocol. Figure 18 shows the communication between the W-A-S, the ST Middleware and the intelligent screw system.

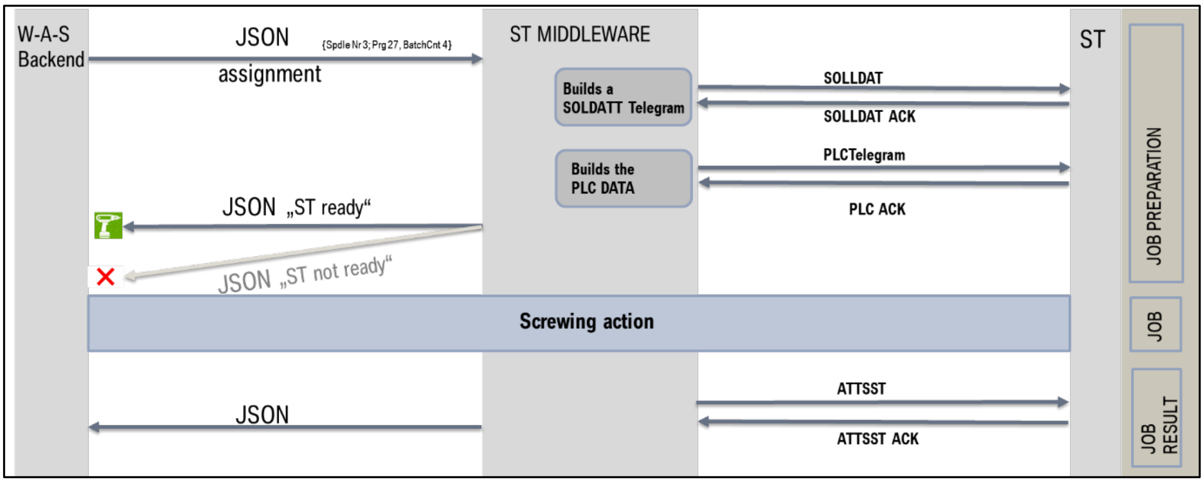


Figure 17: Communication logic of the screwing system

As soon as the TCP server is online, the ST subscribes to the MQTT broker and sends a LIFE telegram that is responded with a LIFE ACK telegram. After checking the connection status with a timeout, that fails if the MQTT broker is unreachable, a JSON assignment is sent to the middleware. The latter builds a SOLLDAT String according to the specifications from the JSON message (tool-Id, program number) and sends it to the ST, which responds with a SOLDAT ACK telegram if the assignment has been correctly understood. Then, following the assembly sequence, the middleware builds a PLC telegram to inform the ST that a screwing activity has to be done. Directly after receiving a PLC ACK, the middleware builds a JSON message and sends it to the W-A-S backend to indicate that nutrunner is ready. As there are three screw-drivers connected to the ST, the relevant one emits a sound before and after the completion of the screwing and shows the batch count on a small display attached on it. That permits to further assist the employee and avoid his confusion. An extra module for the recognition of the assembly sequence was added to the W-A-S. The screw driver is namely equipped with a camera that permits to detect the location of the screw and subsequently verify the screwing sequence in real time.

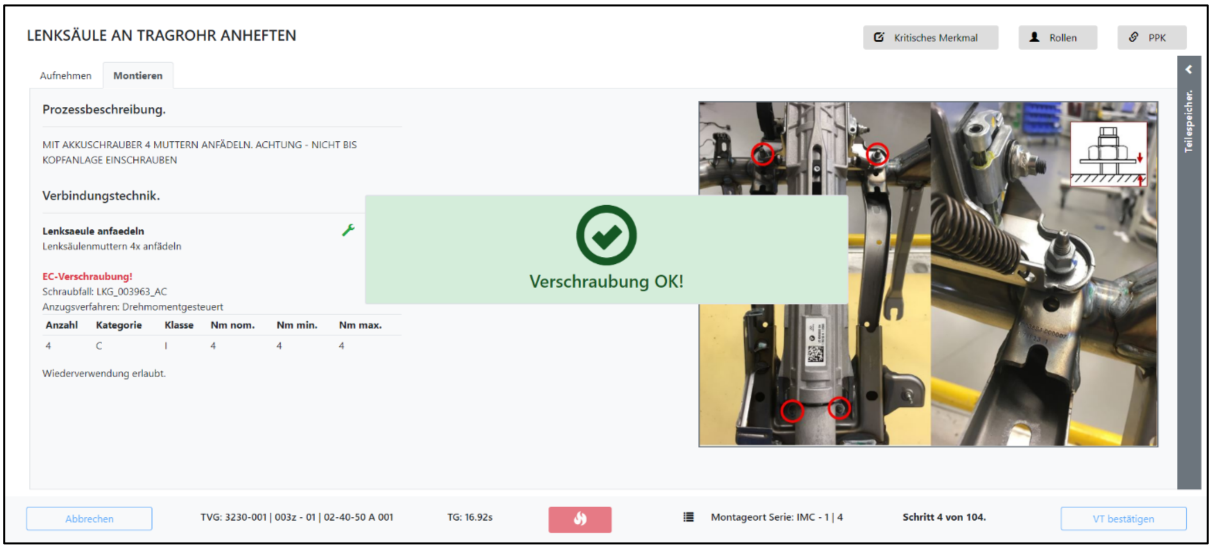


Figure 18: The W-A-S interface after correct screwing

The sequence has namely to be respected for safety issues. With this extra module, the W-A-S warns the worker in case he does not follow the correct order until he does. A confirmation of the correct screwing is then displayed on the screen as depicted in figure 18.

The smart tool-holder

The detection of picked tools is crucial of an effective tracking of the production context and a precise determination of assembly times. For that sake, a smart tool-holder is implemented in the course of this work. It consists in a light barrier attached to the scanner holder and connected to the PLC via a connector. The smart holder detects the presence/absence of the tool and generates a Boolean signal. According to the smart holder main program, a timer is activated when the assembler picks the scanner and is stopped directly after the worker puts it back on the holder. This can be considered as an accurate way to calculate the duration of the scanning action. A JSON message containing the tool Id and the scanning time is sent to the W-A-S via MQTT. If the duration of the scanning activity is too exceeds the estimated time frame, a signal tone notifies the worker of that and the following textual instruction is displayed on the screen: “Please do not forget to put the scanner back in its place!” Low battery issues can thus be prevented.

The smart glove

The smart glove, as already mentioned, permits the detecting of clip attachment. A Boolean signal is generated to indicate if the action was successful or not and the data collected is registered within a BMW IoT tool. Clipping errors are therefore recognized by the system and the worker receives a warning signal in order to redo the same action in a correct way. However, this sensor module does not just participate in monitoring the assembly process but offers also the possibility of determining the time required for every clipping actions, and thus, evaluating the process before it reaches the series production.

As soon as a clipping action has to be done, the W-A-S activates a timer, which turns off immediately after the system realizes that the worker has finished attaching the according clip. The W-A-S has access to this information thanks to the real-time transmission of the acquired data from the IoT tool. The data collected with the sensing glove is analyzed and the detected times are compared to the estimated ones. If the mean value of the processing time is higher than estimated, then a redesign of the assembly process would be required and more realistic times need to be attributed.

A resume of the W-A-S components according to their operating principles, their Inputs/Outputs and their connection to the W-A-S is presented in the Table 4.

W-A-S components	Action	Input	Output	Connection type
Power focus Hand scanner	Illuminates the barcode with red light and detects the reflected light through its sensor, then generates an analog signal with varying voltage. Its converter changes the analog signal to a digital one which is interpreted by the decoder and converted into ASCII text	Reflected light	ASCII text	RS232 connection to a raspberry pi
Raspberry Pi 3 Model B	It converts the ASCII text into JSON and sends it to the backend via MQTT	ASCII text from the scanner	JSON message	Ethernet/ MQTT
Pick-by-light	Detects the gripping action with a SICK photoelectric proximity sensor (WTB27-3P246) that detects the light reflected by the object to be detected and activates a LED in accordance to the correctness of the gripping action.	Reflected light	Boolean	Connector linked to the WAGO PLC
Harting RFID	Uses electromagnetic fields to create an adaptable interrogation zone in which it emits interrogator signals and receives authentication replies from	Authentication replies from tags	Base 6 encoded ASCII String	Ethernet/ MQTT

	passive tags attached to assembly parts			
Copco Atlas screwing system	It controls three wireless nutrunners equipped with cameras. Depending on the user´s needs, the most appropriate nutrunner is activated. The system receives a message from the server via the MQTT broker and publishes an acknowledgment on the same topic.	JSON string with program-number, tool-number, screw count	JSON String with the same data and response “ok” or “not ok”	Ethernet/ MQTT
Wago PLC	Is an IoT controller that assigns a signal to every sensor and every LED of the pick-by-light, communicates data in JSON files with the Backend via MQTT and ensures an encryption of the link using TLS.	JSON containing shelf number	JSON response “ok” or “not ok”	Ethernet/ MQTT
Smart tool holder	Detects if a tool is picked with a SICK photoelectric proximity sensor (WTB27-3P246) that detects the absence/presence of the light reflected by the tool	Reflected light	Boolean	Connector linked to the WAGO PLC

Table 4: resume of the W-A-S components according to the I/Os and connection type

6. Evaluation

In this chapter, an evaluation of the W-A-S according to the NFRs of subchapter 3.2 is presented. The two main targets of implementing the W-A-S described in the introduction, namely, the assembly process tracking and its evaluation, are verified in the next subsection.

6.1. Verification

Designing a sustainable engineering system that fulfills the NFRs described above is a challenging task. As explained earlier, interoperability, flexibility, modularity, scalability, fault tolerance and usability should be met by the worker assistance system in order to obtain a reliable solution for digitalizing the prototype assembly at the BMW plant 0.

The worker assistance system was designed in a way that ensure syntactic interoperability among devices. Although the current sensor modules do not interact with each other but communicate with the W-A-S server, which coordinates all the services, the possibility to have sensor systems that exchange data through the MQTT broker is available. All the exchanged messages in the W-A-S are written in JSON and a unique communication protocol is relevant to all chosen modules. Each component can subscribe or publish on a random topic. In case one sensor module subscribes to the topic, on which another module publishes messages, it will be able to receive these messages and react accordingly. A simple reconfiguration of the code of the according controller is needed. Translating module specific protocols to the W-A-S protocol allows the changeability of the system, as sensor modules could be added to the system independently of their vendors. This changeability refers to the flexibility of the system, which was tested by adding two optical scanners of different brands. The plug-and-produce feature of the system was confirmed. The worker assistance system is decomposed into various manageable subsystems. Each module carry out a specific function separately without directly interfering with other subsystems. Thus, when needed, changes can be applied on one module without affecting other parts of the assembly system. For instance, other LEDs and light barriers can be added to the pick-by-light with a simple reconfiguration of the hardware and a registration of the new bins in the database. This do not disturb the functioning of the system and other sensor modules can keep on operating in parallel, which accentuates the modularity of the system and offers an infrastructure favorable to fulfilling scalability. The worker assistance system is designed to operate in several assembly stations simultaneously.

The Javascript runtime Node.js is used in this work. It is based on an event-driven architecture capable of asynchronous I/O, which enhances throughput and scalability in web applications [54]. The data model of the W-A-S was designed according to the abstraction design tactic in order to create a flexible, robust and scalable design. Details were removed in order to make services applicable to a wide class of devices despite their difference. For every sensor device, a device class was created according to its functional and non-functional services, as mentioned above. A task class is available to every assembly action that has to be captured by the W-A-S such as <Part-identification> for instance. In order to achieve this service, three device-classes are available. A class was implemented for each of the RFID, the hand scanner and the pick-by-light, with the possibility to integrate several devices with different device-Ids, as shown in figure 19, although just one device from each is currently linked to the W-A-S. Figure 19 depicts the flexibility and modularity of the W-A-S, as a multitude of other devices could be added to the W-A-S in just few steps and a favorable framework would be already available.

Although the task class <detect-tool> is implemented in a way that the tool used can be detected by three different sensor systems as shown in figure 19, the smart tool holder is currently the only module that is responsible for this service, as it is the most practical and cost-effective solution. Nonetheless, in case of failure of the smart holder, the system provides the worker with another option which is scanning the tool if a barcode is accessible or an automatic identification of the tool would occur in case it is equipped with a RFID tag. This could be referred to as an example of how the system fulfills the fault tolerance attribute.

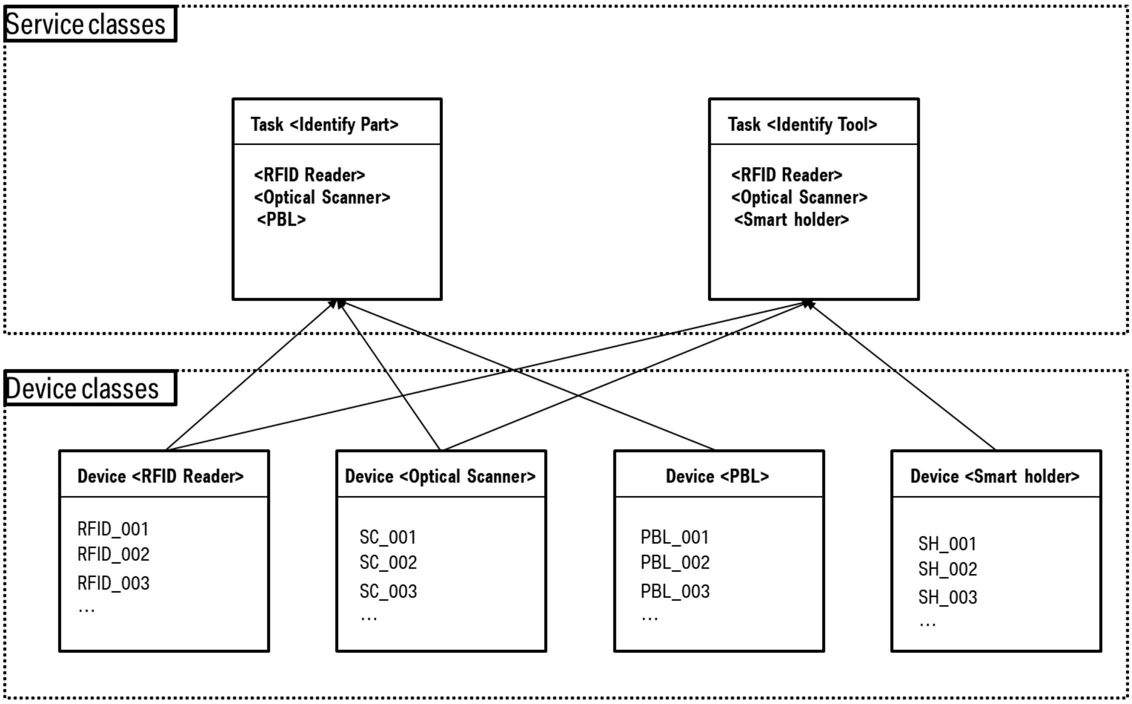


Figure 19: Service classes and device classes (example)

In addition to fulfilling the above stated requirements, the user-friendliness of such a system also plays a major role in productive use. The system usability scale (SUS) is used to evaluate the reporting concept and to test usability requirements. This is developed by John Brooke [55] in order to evaluate the usability of a system objectively and with little effort. It is a questionnaire with ten questions that are evaluated by volunteers using the Likert scale (from "do not agree" to "fully agree"). The questions relate to different areas of usability, such as complexity, incorporation and system support. Each question is considered proportionately to calculate the SUS score. The sum of the individual scores is multiplied by 2.5 to reach a scale value between 0 and 100. [56]

The questions of the System Usability Scale are the following:

1) I think I would like to use the system frequently.

2) I found that the system unnecessarily complex.

3) I found that the system is easy to use.

4) I think that I would need the help of a technical person to use the system.

5) I found the various functions in this system were well integrated

6) I thought there was too much inconsistency in this system.

7) I can imagine that most people learn how to use this system very quickly.

8) I found the system very cumbersome to use.

9) I felt very confident using the system.

10) I needed to learn a lot of things before I could get going with this system

The evaluation gives an average value of 85.3. The highest rating was 92.5. The lowest score was 80. Evaluations of 5000 subjects in over 500 studies achieve an average rating of 68. With a rating of over 80 points, the system is therefore among the top 10% in comparison. [57]

6.2. Validation and discussion

Since cockpit assembly takes place in single-station assembly, this workstation is considered suitable for a first prototypical implementation. The worker does not have to move around or even under the vehicle, but can work and watch the screen with the provided instructions. Context awareness is the backbone of assistive systems. Although some of the current IoT solutions are subjected to poor context awareness caused by the incorrect choice of semantics and various unfairly distributed ontologies, the approach adopted in this work allowed the implementation of a context sensitive system based on an organized device-service classification, as explained earlier.

The W-A-S is composed of different sensor modules and output systems, which purpose is to make the information available to the employee at all times. The interactive system is able to indicate errors and intervenes to correct them, so that the quality standards can be met and reworking time can be reduced. Additionally, the assembly process, that is tracked and evaluated by the W-A-S, is compliant with the process of serial production. The aim is to test, optimize and validate assembly processes before they reach the series production so that no major problems remain undetected before the transition from the development to the series plant. Thus, a greater use of the prototype production is noticed. On one hand, several sensor modules are connected to the W-A-S, having process tracking as main role. The optical hand scanner, the RFID and the pick-by-light ensure the control of the assembly process by tracking assembly components, as explained earlier.

Monitoring the process is also accomplished by detecting picked tools and correct attachment clips. These two tasks are respectively verified by a smart tool holder and a smart glove. On the other hand, a software timer, a body-worn solution and an error reporting feature are added to the W-A-S in order to provide a process evaluation platform. The assembly process evaluation belongs to the main targets of this thesis. For that purpose, an ergonomic assessment of the workplace according to the assembly activities is imperative. The Xsens body-worn solution was chosen as an effective solution for the posture recognition. To validate the approach, the complete System was tested in a real production environment in collaboration with the departments for work safety and industrial engineering, but still, the definitive integration of this system to the W-A-S is not yet relevant as some complaints about the intrusive character of the body-worn solution have been reported. The next step for a thorough evaluation of the process including the ergonomic assessment would be visualization based. However, using a camera system for the ergonomic assessment is still being discussed due to privacy issues, even though the camera solution can be an accurate solution to prevent work-related health risks and harmful physical workloads.

A software based time calculation was programmed. By the mean of timers, the duration of every assembly activities can be retrieved and compared to initially estimated durations determined by the planning engineers. Nevertheless, many tests must be done under real conditions including different levels of employee experience in order to determine the optimal maximum time frame of each activity. For that sake, the introduction of the W-A-S in the prototype production plant of BMW should start in the next quarter. The number of participants and the prototype model to be assembled are still to be discussed. In fact, a comprehensive process evaluation is not possible without the involvement of the worker. Note that the worker assistance system allows extracting the knowledge of the experienced assemblers through the error reporting button. The worker can report process inconsistences by writing a short descriptive text and take a relevant picture by mean of a tablet. The error report is then archived and can be sent in real time to the planning engineers. However, the problematic of how to classify the problems and to whom should they be addressed is not relevant to this thesis.

7. Summary and outlook

The earlier conceptual problems in series development can be identified, the easier it is to intervene and derive measures. Additionally, resources can be procured with more foresight, further reducing the cost that has to be incurred for troubleshooting.

The idea of a W-A-S for the prototype assembly is derived with this intention. The approach presented in this thesis provided great benefit during the series development: Manual assembly processes planned for the series production can now be effectively tested and evaluated during the prototype assembly in order to correct conceptual problems early on and improve efficiency and effectiveness. Thus, the maturity of the processes and the fitness for series production can be ensured with little additional effort. Instrumentation of the manual workplace with the W-A-S provides the assembler with relevant information while avoiding human errors. At the same time, through the collection of data, the system allows real time tracking of the assembly process and the evaluation of certain process quality aspects.

The system proposed in this work was, as explained earlier, is tested on the assembly process of the cockpit preassembly of a BMW M440ix. Clear instructions, pictures and CAD images are displayed on the touchscreen. The estimated processing time and the real processing time is displayed to the worker to allow for self-control. In addition, the assembler has the possibility to call report problems directly via the W-A-S if needed. Such functionality ensures the precise documentation of problems and, thereby facilitates the problem solving process.

A pick-by-light, a screw driving system, an RFID reader and a barcode scanner are currently available to monitor the production process, facilitating the workers job, while also ensuring adherence to the defined processes. At the time of the submission of this thesis, the integration of the smart glove and the ergonomic assessment system is still ongoing due to some technical challenges. Further work will be carried out to add new sensor modules and functionality based on worker feedback and as required by new assembly techniques.

Additional features are evaluated and they are planned to be integrated following the first tests of the W-A-S under real conditions. For instance, a wearable lightweight scanner will be added to the system in order to save precious time and achieve better efficiency. Furthermore, a smart watch or a smart glass can be integrated into the W-A-S in order to support the worker and provide him with feedback in assembly situations where a screen is not applicable. Another feature that could be added to further support the assembler is an “assistance request” button. This feature would allow the worker to ask for support when needed. The team leader would be informed via the smart watch about the station number and the nature of the problem and may act accordingly.Once the W-A-S has been rolled out to the BMW prototype assembly lines, it would be interesting to follow-up on this thesis by evaluating the reliability of this implemented system when used in different stations simultaneously and the actual improvements in the process quality that can be achieved.

8. Bibliography

[1] M. McDonald, „Digital Strategy Does Not Equal IT Strategy," 2012.

[2] A.-W. Scheer, *Whitepaper - Industry 4.0: From vision to implementation,* 2015.

[3] „Reuters," [Online]. Available: https://www.reuters.com/article/us-bmw-results-strategy/bmw-ceo-puts-digital-trends-at-center-of-strategy-review-idUSKCN0Q91HH20150804. [Zugriff am 08 03 2019].

[4] W. Apt, M. Schubert und S. Wischmann, „Perspektiven und Herausforderungen für den Einsatz in Industrie und Dienstleistungen," 2018.

[5] J. D. H. Halswanter und B. Blazevski, „Experiences with an Assistive System for Manual Assembly," 2018.

[6] S. Hinrichsen, A. Unrau und D. Riediger, „Assistance Systems in Manual Assembly," 2016.

[7] J. D. H. Haslwanter und B. Blazevski, „Experiences with an Assistive System for Manual Assembly," New York, USA, 2018.

[8] A. Singh, F. Quint, P. Bertram und M. Ruskowski, „Towards Modular and Adaptive Assistance Systems for Manual Assembly: A Semantic Description and Interoperability Framework," in *UBICOMM, At Athens, Greece*, Greece, 2018.

[9] C.-B. Zamfirescu, B.-c. Pirvu, D. Gorecky und H. Chakravarthy, „Human-centred Assembly: A Case Study for an Anthropocentric Cyber-physical System," in *Procedia Technology*, 2014, pp. 90-98.

[10] A. Singh, F. Quint, P. Bertram und M. Ruskowski, „Towards Modular and Adaptive Assistance Systems for Manual Assembly: A Semantic Description and Interoperability Framework," 2018.

[11] T. Stiefmaier, D. Roggen, G. Orgis, P. Lukowicz und G. Trüster, „Wearable Activity Tracking in Car Manufacturing," 2008.

[12] „Motioneap," 31 12 2016. [Online]. Available: http://www.motioneap.de/. [Zugriff am 18 03 2019].

[13] J. Voskamp, „fraunhofer-innovisions," Fraunhofer-Institut für Graphische Datenverarbeitung IGD, 03 08 2012. [Online]. Available: https://www.fraunhofer-innovisions.de/usability/wissenstechnik-fuer-praktiker/. [Zugriff am 12 03 2019].

[14] T. Bosch und G. V. Rhijn, „Fast, Flexible and Faultless Assembly with projected work instructions," [Online]. Available: https://www.tno.nl/SMARTINDUSTRY. [Zugriff am 12 03 2019].

[15] „de-group," [Online]. Available: https://www.de-group.net/portfolio/werkerassistenzsystem/. [Zugriff am 19 02 2019].

[16] „derassistent," [Online]. Available: http://derassistent.de/. [Zugriff am 12 03 2019].

[17] „optimum-gmbh,“ [Online]. Available: https://www.optimum-gmbh.de/der-schlaue-klaus.html. [Zugriff am 09 03 2019].

[18] [Online]. Available: www.boschrexroth.com/en/xc/products/product-news/assembly-technology/activeassist. [Zugriff am 08 03 2019].

[19] P. Bertram, M. Birtel, F. Quint und M. Ruskowski, „Intelligent manual working station through assistive systems,“ 2018.

[20] H. Heo, E. C. Lee, K. R. Park, C. J. Kim und M. Whang, „A realistic game system using multi-modal user interfaces,“ 2010.

[21] D. Ralph, DIN 1319-1 Fundamentals of metrology - Part 1: Basic terminology, 1995-01.

[22] T. Rose, „Anwendungen von Sensorik,“ muenster, 2010.

[23] J. Sauerer, „Smart sensors,“ 2013.

[24] J. Henke, Eine Methodik zur Steigerung der Wertschöpfung in der manuellen Montage komplexer Systeme, Stuttgart, Germany, 2015.

[25] T. Gudehus, Gudehus T. Entwicklung eines Verfahrens zur ergonomischen Bewertung von Montagetätigkeiten durch motion-capturing. Kassel: kassel university press GmbH; 2009, 2009.

[26] V. K. Bellmann, M. Ansari, S. Nyhius und P. Brede, „Development of a System for a Real Time Ergonomic Assessment,“ 2017.

[27] S. Kärcher , E. Cuk, T. Denner, D. Görzig und L. C. Günther, „Sensor-driven Analysis of Manual Assembly Systems,“ 2018.

[28] L. Chung, B. Nixon, E. Yu und J. Mylopoulos, Non-Functional Requirements in Software Engineering, 2000.

[29] „ScaledAgileFramework,“ [Online]. Available: https://www.scaledagileframework.com/nonfunctional-requirements/. [Zugriff am 18 04 2019].

[30] R. Margareth, „SearchMicroservices,“ 2014. [Online]. Available: https://searchmicroservices.techtarget.com/definition/interoperability. [Zugriff am 12 04 2019].

[31] F. Quint, L. Frieder, M. Orfgen und D. Zuehlke, „A System Architecture for Assistance in manual tasks,“ 2016.

[32] A. Singh, „Modular and Adaptive Assistance System for Manual Assembly – Engineering a,“ 2017.

[33] V. Gezer, J. Um und M. Ruskowski, „An Extensible Edge Computing Architecture: Definition, Requirements and Enablers,“ in *UBICOMM 2017, The Eleventh International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, Barcelona, 2017.

[34] O. Perminova, M. Gustafsson und K. Wikström, „Defining uncertainty in projects – a new perspective,“ 2008.

[35] C. Y. Baldwin und K. B. Clark, „Modularity in the Design of Complex Engineering Systems,“ in *Complex Engineered Systems* , pp. 175-205.

[36] „Technopedia,“ [Online]. Available: https://www.techopedia.com/definition/9269/scalability. [Zugriff am 18 03 2019].

[37] K. Krishna, Computer based industrial control, New Delhi, 2010.
[38] M. L. Latash und V. M. Zatsiorsky, Biomechanics and Motor Control: Defining central concepts, 2016.
[39] E. Göktürk und A. M. N., Paradigm and Software Engineering.
[40] „coronet,“ 2006. [Online]. Available: https://coronet.iicm.tugraz.at/sa/scripts/lesson01.htm. [Zugriff am 01 06 2019].
[41] TU Graz, „coronet,“ [Online]. Available: https://coronet.iicm.tugraz.at/sa/swp_res.htm. [Zugriff am 01 06 2019].
[42] „tutorialpoints,“ [Online]. Available: https://www.tutorialspoint.com/software_architecture_design/distributed_architecture.htm. [Zugriff am 10 02 2019].
[43] O. Uviase und G. Kotonya, „IoT Architectural Framework: Connection and Integration Framework for IoT Systems,“ 2018.
[44] P. Persson und O. Angelsmark, „Calvin – Merging Cloud and IoT,“ in *The 6th International Conference on Ambient Systems, Networks and Technologies (ANT-2015), the 5th International Conference on Sustainable Energy Information Technology (SEIT-2015)*, 2015.
[45] L. M. Sá de Souza, D. Guinard, M. Köhler, S. Karnouskos und D. Savio, „SOCRADES: A Web Service Based Shop Floor Integration Infrastructure,“ in *The Internet of Things p50-67*, 2008.
[46] X. T. Nguyen, H. T. Tran, H. Baraki und K. Geihs, „Frasad: a framework for model-driven Apllication Development,“ in *Internet of Things (WF-IoT), 2015 2nd World Forum*, Milan, 2015.
[47] S. M. Kala, V. Sathya, S. Magdum und T. Vamshi, *Designing Infrastructure-less Disaster Networks by Leveraging the AllJoyn Framework,* 2019.
[48] Arrowhead, „Arrowhead,“ [Online]. Available: https://www.arrowhead.eu. [Zugriff am 10 03 2019].
[49] P. Priller, A. Aldrian und T. Ebner, „Case Study: From Legacy to Connectivity Migrating industrial devices into the world of smart services,“ Austria, 2014.
[50] S. Tuli, „Dzone,“ 16 05 2018. [Online]. Available: https://dzone.com/articles/microservices-vs-soa-whats-the-difference. [Zugriff am 10 05 2019].
[51] T. cerny, J. Pechanec und M. J. Donahoo, „Disambiguation and Comparison of SOA, Microservices and Self-Contained Systems,“ in *the international conference*, 2017.
[52] „ISO,“ [Online]. Available: https://www.iso.org/standard/69466.html. [Zugriff am 28 02 2019].
[53] W. Emmerich, „Software Engineering and Middleware: A Roadmap,“ 2015.
[54] H. Sun, F. Schiavio, D. Bonetta und W. Binder, „Reasoning about the Node.js Event Loop using Async Graphs,“ in *019 IEEE/ACM International Symposium on Code Generation and Optimization (CGO)*, 2019.
[55] S. C. Peres, R. Phillips und T. Pham, „Validation of the System Usability Scale (SUS),“ 2013.

[56] J. Brooke, „SUS - A quick and dirty usability scale,“ 1996.

[57] J. Sauro, „MEASURING USABILITY WITH THE SYSTEM USABILITY SCALE (SUS),“ 2011. [Online]. Available: https://measuringu.com/sus/. [Zugriff am 02 05 2019].

[58] T. Ochs und U. A. Riemann, IT Strategy Follows Digitalization, Germany, 2019.

[59] P. Guillemim, F. Berens, O. Vermesan, P. Friess, M. Carugi und G. Percivall, Internet of Things Position Paper on Standardization for IoT technologies, 2015.

D. Appendix