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Cyber-Physical-Systems for Fluid Manufacturing Systems

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Abstract

Increased volatility continues to challenge the automotive manufacturer's production performance. More than a century after the start of mass production, changeable production systems that allow the flexibility for the economic mass production of customized products have arisen. Limitations on established production systems are driving the development of changeable production systems like the Fluid Manufacturing System (FLMS). In an FLMS, the individual production modules are mobile and consist of Cyber-Physical Systems (CPS) which can be combined ad-hoc to adapt to changing requirements. By connecting different CPS – e.g., Autonomous Mobile Robots (AMR) or smart load carriers – adaptable and flexible production will be achieved. This paper presents the first real-world initiation of an FLMS with the design and development of CPS and digital twins for production and logistics at the ARENA2036 research campus.

Keywords

cyber-physical-systems; digital twin; material flow control; human-centric production, automotive

1. Introduction

Driven by growing competition, companies need to increasingly focus on customer requirements in order to remain competitive in the long term. Exclusive differentiation based on product price and quality is no longer sufficient. On the other hand, high delivery reliability and short delivery times have become a well-recognized competitive factor. Due to their technical limitations, a traditional production system, such as the **Dedicated Manufacturing Lines** (DML), cannot achieve the required changeability to achieve these requirements especially in high mix low volume production environments. Therefore, new, changeable production systems have been developed over time. As early as in the 1990s, the term "changeability" was used to describe the ability to adapt quickly to changing influences. Since then, the term has been one of the key success factors for manufacturing companies and various systems have been developed. The **Flexible Manufacturing Systems** (FMS) enables the adjustment of production capacity and functionality within a fixed flexibility corridor (e.g., a family of parts). This requires the use of predefined functionalities, which leads to additional costs and higher complexity. The retooling of an FMS beyond the flexibility corridor takes several weeks or months [1–7]. FMSs are thus configurable within a corridor, but not reconfigurable

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beyond it. The **Reconfigurable Manufacturing Systems** (RMS) can resolve this limitation. In contrast to FMS, an RMS allows the adaptation of the production system across fixed flexibility boundaries. Koren refers to this as customer-specific flexibility. RMS thus combines the advantages of DML and FMS [8,9]. According to Koren, the productivity of an RMS is higher than that of a line, for example in large complex systems [10]. However, efficient algorithms are necessary for the real-time control of an RMS. These are also correspondingly complex [11,12]. **The Matrix Manufacturing Systems** (MMS) consists of flexibly-linked, usually dedicated process modules. Each process module provides predefined sets of technological functionalities necessary for production. An MMS enables new production control functions, as each product can determine an individual production path by selecting its process modules, depending on the available process module functionalities, the assembly precedence graph, and the current state of production resources. The cycle times of the process modules are no longer uniform [13,14]. **The Fluid Manufacturing System** (FLMS) is based on the principle of ad-hoc resource allocation and reconfiguration to individual process modules for optimal manufacturing performance [15] and develops the MMS concept further. Comprehensively using the benefits of cyber-physical systems [16,17] and their capability to self-integrate and self-parametrize, process modules can be easily aggregated from single resources to advanced manufacturing systems [18]. To fully leverage the potential of FLMS, all process modules must be modular and mobile. The requirements for mobility and modularity are on-demand adjustments of capabilities and functionalities as well as adaptable production layouts. Thus, the manufacturing system is capable of being iteratively reconfigured in variable steps to the currently required product configuration. This reconfigurability requires complex production planning and control logic, considering previously unknown degrees of freedom in production system design. New degrees of freedom are the: Operation Sequence (specifies the sequence of work operations), Work Distribution (assigns the process modules to the production order), Work Content (defines the competencies of a specific process module) and Layout Position (defines the position of production equipment on the shop floor). These freedoms affect both the planning and control complexity of the order management. Order management thus defines the new understanding of production planning and control (PPC) in which the fulfilment of customer orders is the central goal [19]. Order management covers the planning, control and monitoring of all activities (including orders, resources, ...) along the value chain from customer inquiry to shipment [20,21]. The remainder of this paper is organized as follows: Section 2 provides an overview of the state of the art, Section 3 presents various developed CPS for FLMS, Section 4 presents the initiation of the FLMS. Section 5 concludes the key points of this paper and provides an outlook.

2. Designing and Development of Cyber-physical Systems

CPS connect the physical world with the virtual world by allowing mutual control and information exchange via the internet, also known as the Industrial Internet of Things (IIoT) [22,23]. They are commonly used in engineering, manufacturing and logistics. Moreover, CPS are providing benefits for manufacturers by utilizing sensor generated data [24]. However, the boundary conditions and the new levels of freedom in an FLMS have resulted in new requirements for future CPS. These requirements affect several production assets, e.g., AMRs, machines and sensors. Some of these requirements are related to the design and others to software [18]. In the next step, each requirement for CPS in an FLMS will be described in detail.

Reconfigurability is the ability to change and evolve rapidly in order to adjust productivity, capacity and functionality [10]. Therefore, CPS have the task of enabling these requirements. For example, by adapting to different products and parts with a wide range of measures, different weight sizes, etc.

Modularity is the integrating element directed at highly customizable manufacturing engineering structures [25]. In an FLMS, all units, including CPS, are modular and can be combined ad-hoc to new resources.

Asset Administration Shells (AAS) are necessary for communication amongst the individual I4.0-components. This is embodied in the approach of this paper through the concept of submodels which broadly

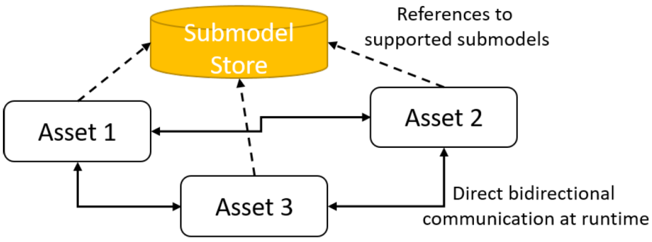

Figure 1: Communication between assets based on known submodels

describe features and capabilities. One submodel precisely explains one technical feature. Submodels are published in a central location that is accessible to each partner in order to ensure that this shared understanding is as clear as possible and is used by as many I4.0-components as possible [26]. An I4.0-component must introduce itself and specify one or more supported submodels in order to make its attributes and capabilities known to others (see Figure 1). An I4.0-component consists of the following objects:

- Submodels: An I4.0-component's technical details are specified by one submodel only. In order to achieve this, the submodel explains the traits, occasions, and actions connected to this feature.
- Properties: A submodel can specify any number of properties. A property describes a static or variable property, e.g., a position, color or serial number. If an I4.0 component communicates a property, the specification is assumed to be valid until the component sends an update.
- Events: Unlike properties, events have a unique time reference. The event contains a timestamp. Examples for events are the arrival of an AMR at the destination or the completion of an assembly process. Events also have a unique name and can communicate with other data fields. Each data field is specified in the same way as a property.
- Operations: While properties and events describe outgoing communication, operations specify services that can be called upon by other components. For example, a manufacturing process can be triggered. Operations are identified by their unique name within the submodel. Optionally, parameters can be specified. Unlike events, a return value can also be specified, e.g., to report a successful operation.

Creation of a digital twin: Representing a CPS with an AAS raises the possibility of representing any asset from the real world as a copy in the digital world. Visualization, simulation, etc. are just some examples of what can be done by utilizing the given data from an asset.

The orchestration of CPS in an FLMS is realized by Node-RED. Node-RED is a browser-based, graphical, open-source programming environment. Processes can be modeled in the form of so-called "flows" and are then processed in a server-side engine. A node is a data processing step. It is always triggered when new data is present at the input. Node-RED is designed to be supplemented with its own node types to fulfill application-specific tasks. A service ensures that, for each submodel that is currently in use, a node type is automatically created for its properties, operations and events. In this way, processes can be modeled in Node-RED that can access all the elements of the management shells and thus all assets.

Service-oriented architecture (SOA) allows IT system services to be structured and used more efficiently. At the same time, business processes can be mapped more flexibly, which reduces maintenance efforts and costs. The basis for this is the decomposition of complex business processes into their individual steps. SOA is not only comprised of components required to interact with an AVG or AMR, which can be represented as an AAS, but value-added services can also be set in this format. Utilizing this approach has an impact on the development of different services.

3. Cyber-physical Systems for FLMS

According to the requirements in the following chapter, different prototypes of CPS for FLMS and a concept for human-centric production have been developed. In the following sections, the implementation process and the concept are described in detail.

3.1 Human-centric production

In human-centric production, the user interfaces allow the easy operation and commissioning of the CPS. In addition, collaborative assistance systems enable the worker to perform simple maintenance tasks without prior training. Human-robot collaboration also makes it possible to parallelize the processes in the process modules and thus reduce cycle times [18]. In the context of the ARENA2036, a shared safety concept for human-machine collaboration in an FLMS has been developed. Taking machine safety into account, a sensible approach for automated guided vehicles (AGVs) to drop-off or pick-up locations, which are protected with safety devices, can only be realized if those devices are switched off. This entails potential hazards for workers in the working space. However, since this must be excluded by the machinery directive, additional hardware in the form of separating safety devices or additional sensors are necessary. If an AGV approaches the storage location and a Safety and Control Unit (SRU) with the safety devices switched off, there may also be a blind spot (Figure 2) behind the AGV that the laser scanners miss. A person could be behind the AGV and enter the danger zone of the SRU. This must be absolutely excluded. The designed concept provides four steps to counter the problem described. In the first step, the second asset, the SRU, controls the AGV. In order to transfer the control of the AGV to the SRU, it is necessary to clearly identify the two assets, as there may be several assets of the same design in a real environment. Initially, the transfer takes place manually. Therefore, the AGV takes a picture of the asset and sends it to a worker for confirmation, who then releases it on his smart device. In addition, approaches for the automatic handover are examined in more detail. To enable the transfer of the control functionality from the AGV to the SRU, a safe switchover is required, which is carried out via a safe operating mode selector switch. This puts the AGV into manual mode and provides the laser scanner data of the AGV via AAS (Figure 2).

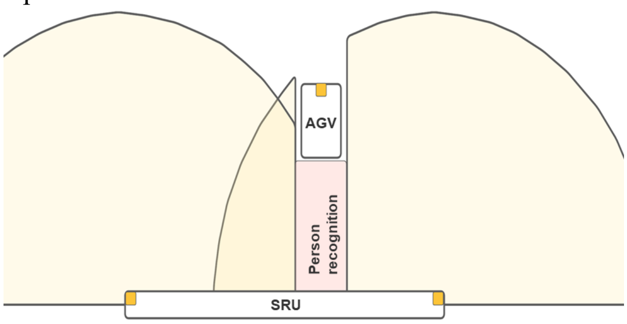

Figure 2: Person recognition in front of the AGV

In order to adjust the safety devices, it is necessary to open a corridor in front of the AGV in the area of the laser scanner of the SRU. In this way, the entry of the AGV does not trigger a system stop of the SRU. At the same time, the data of the laser scanner of the AGV, which is turned away from the SRU, must also be evaluated via AAS. Thereby, a person can be prevented from entering the safety area of the system. In addition, person detection is performed in front of the AGV in order to additionally secure the muted area. The last step of the concept is undocking and restoring the original state. Therefore, the AGV must be navigated out of the danger zone and then, as soon as the AGV is in the warning zone of the SRU, the muted zone must be reactivated before finally switching to autonomous operation again. In general, the concept was designed generically in order to combine a wide variety of assets and their safety devices. A first prototypical implementation has already taken place.

3.2 Fluid Production Logistics

In order to use the full potential of an FLMS, adaptable and flexible logistics systems are needed. Therefore, a smart load carrier and an AMR have been developed. Furthermore, different approaches for a decentralized material flow control system have been designed.

The aim of the development of **AMR** was to enable the transformation of an Autonomous Guided Vehicle from its task-based applications to an autonomous, smart and safe mobile robot platform. The AMR is an autonomous logistics unit, which is responsible for pick-up and transportation tasks as an essential part of FLMS. Depending on the size and the task, the AMR is able to transport different sizes of load carriers and car bodies. This enables more flexibility and further benefits in the logistics and production process, e.g., modularity and reconfigurability. The mobile robot system consists of two drive-rotation-axis units, which enables the AMR area-moving kinematics. Compared to differential kinematics, it is possible for the AMR to drive in the Y-direction as well as to change orientation during the drive. In addition, the AMR has two safety laser scanners, which can be used for the safety field and navigation. In order to transform the AMR into a CPS, the following key issues are considered for this purpose, which will be illustrated in the following sections: communication interface to Industry 4.0, higher-level control and target-oriented navigation. For a unified semantic description, the interfaces of the AMR are realized via an AAS. Figure 3 shows the first Version of the AAS of the AMR with its submodules, which was later expanded with further Submodules for the order management to realize the use cases in section 4.2 and 4.3.

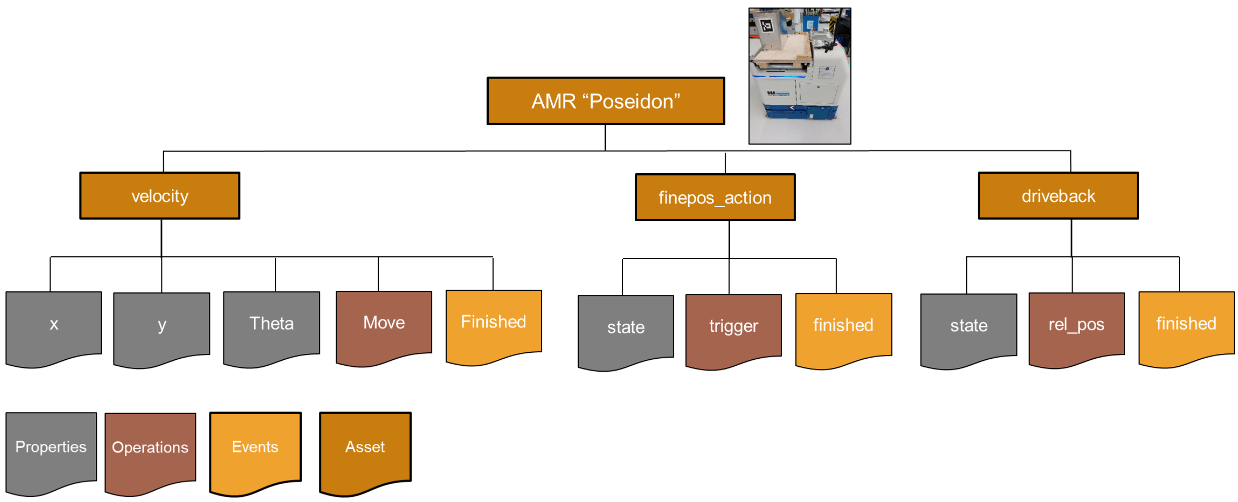

Figure 3: First Version of the AAS for the AMR “Poseidon”

An advantage of the AAS is that any size of data can be implemented in the description. Thus, the interface can be severely limited or allow full access at all levels of the control hierarchy down to the sensor level. Likewise, it offers the possibility to the other participants in the network to receive information on the components as well as to send control commands like, for example, different movements or the fine positioning of the AMR. The higher-level control system has the task of planning and coordinating AMRs within a production area. In general, it is a master control or fleet management which is used with the help of the VDA 5050 recommendation for AMRs/AGVs [27]. With this standard, it is possible to coordinate several AMR among the others, independently of the manufacturers. Navigation is an important part of the AMR, which can be described as one of the main features for the transformation into a CPS. Localization and route planning go hand in hand. The aim is to determine the current starting position in relation to the specified target position autonomously and without collision. The Robot Operating System (ROS) offers a wide range of packages so the navigation of the AMR can be safely achieved. It offers the navigation stack via a navigation algorithm by using different information such as laser scanners. The move_base requires a map of the environment which is recorded using the laser scanners and the wheel odometry of the AMR. For localization, the ROS offers different software packages. In this case, the mobile robot system uses the slam_toolbox, which has the modes "mapping" and "localization". With this combination of localization and navigation, the AMR can approach its respective workstation in the FLMS.

Smart Load Carriers are load carriers which are equipped with different sensors and computing devices to provide smart services, e.g., tracking & tracing or condition monitoring In order to fulfill an adaptable and flexible logistics system in an FLMS, the following requirements for a smart load carrier have been defined: (1) Reconfiguration for different load carrier sizes and materials, (2) Storage and visualization of condition monitoring data, (3) Decentralized control of the material flow, (4) Localization for a location-flexible material supply and (5) Provision of master data, e.g., bill of material, CAD model. Based on the requirements, several physical and virtual Smart Logistics Modules have been developed. This includes modules for Condition Monitoring, Container Management, Localization, Power Management and the Master Data via an AAS, as shown in Figure 4 [24].

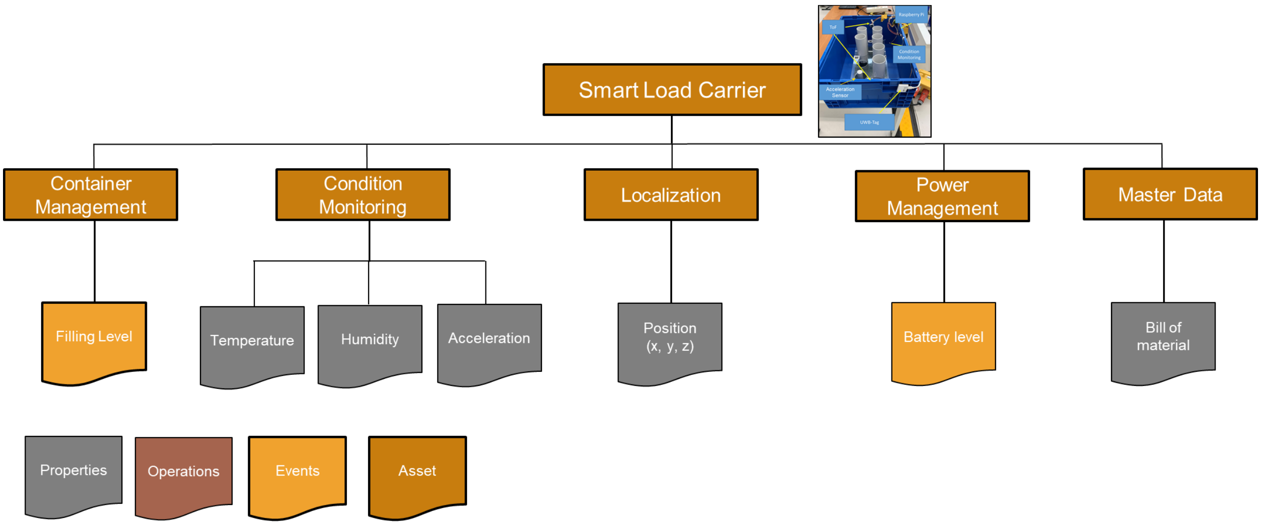

Figure 4: Modelling example for the AAS of the Smart load carrier

The smart load carrier is reconfigurable to different sizes of load carriers and parts. Moreover, it contains different interfaces for the connection and interaction with other CPSs, e.g., AMRs and Smart Products.

3.3 Assembly Process

Smart Sensors are an important part of meeting requirements for reconfigurability, fast ramp-up and flexibility in an FLMS. For this purpose, the existing sensor technology needs to become significantly more flexible and integrated more strongly into the overall system. For example, by expanding the interfaces, communication can take place across devices and systems. Thus, a fast reconfiguration to a new use case can take place within a minimal time. The Balluff Smart Camera BVS002F is used as a CPS. It is characterized by a CMOS chip of the size 1/1.8" and the recording of the image using the global shutter method. This enables better image capture with moving objects. The camera captures color images with a resolution of 1280 x 1024 pixels. The control and readout of the images is realized via Gigabit LAN. For the application positioning tasks (see Chapter 4.1), the largest possible angle of view is required in the close-up range. Therefore, a lens with an 8mm focal length for wide-angle images is used especially for the close-up range. This enables a large depth of field, so the entire working area is always sharp and refocusing the lens is not necessary. The images and results from the camera are sent to the Raspberry via an FTP interface for further evaluation and processing. The Raspberry Pi can extract the information and make it available to the other CPS components. The camera can also be reconfigured by calling various operations. Hence, it is possible to switch between different inspection programs and configurations. This allows, for example, adaptation to environmental conditions in strong or weak light conditions or switching between different use cases. The Smart Camera can perform the following operations directly on the camera: (1) Object inspection, (2) Color analysis, (3) Measurement within the image, (4) Object recognition and (5) Barcode, 2D, OCR identification, QR code. The asset administration shell of the camera provides the two properties X-position and Y-position of an object in meters (see Figure 5).

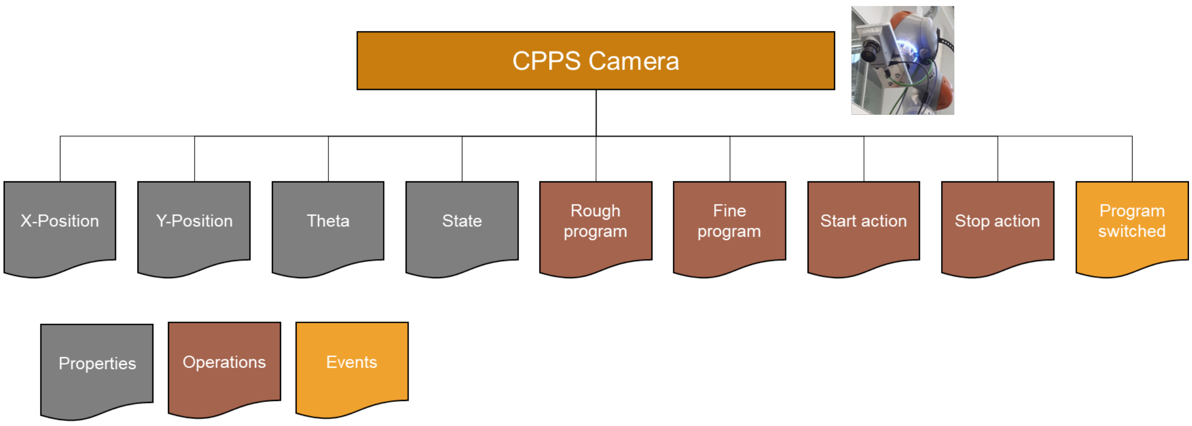

Figure 5: Modelling example for the AAS of the smart camera

In addition, the theta angle, i.e., the displacement of the object towards the camera, is output. The operation used here is the switch between the two programs Fine and Coarse Positioning on the camera. These programs can each be controlled by means of the two start and stop operations. As soon as a program change has been carried out successfully, an event is sent with a message about the change.

Smart Assembly Modules: An important aspect in the realization of FLMS is the modularization of the assembly processes involved. In classical manufacturing systems, the assembly processes and components involved are usually permanently integrated and difficult to adapt. The initial investment cost as well as the cost of changes are usually very high. An FMLS can profit from the usage of versatile and reconfigurable manufacturing concepts, in which the individual processes or components can be changed in a rapid and efficient manner. The usage of smart assembly modules (also called Mechatronic Objects (MO)) presented in this section precisely enables this modularization. The modularization considers aspects such as electrical engineering, mechanics, process technology and IT and captures them systematically at the component-level of the MO. With this modularization, an MO is standalone, possesses its own control and can be easily integrated into a higher-level manufacturing system as a part of the overall process orchestration. The overall system, in which the MOs are an integral part, is called CESA^{3}R. In the context of the project, CESA^{3}R stands for Concept for Engineering free, Scalable, Advanced Automated Assembly system for Rapid ramp up. An MO can be described and set up in a process-specific manner (see Figure 6) and usually consists of two important parts: (1) a standardized process carrier, and (2) a Process Unit that can be especially designed and constructed according to the process demands.

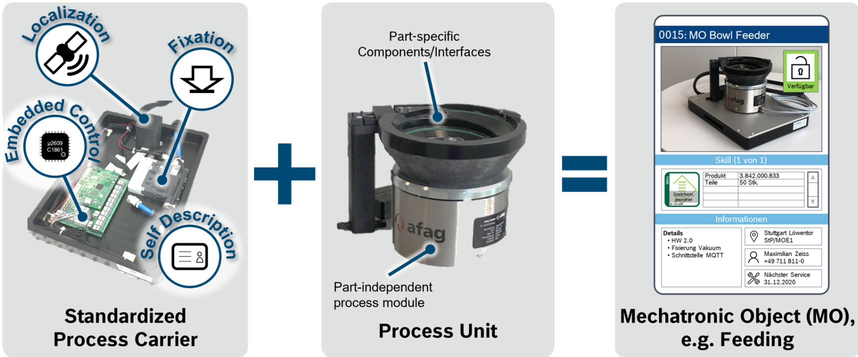

Figure 6: Structure of a Process Module

For instance, Figure 6 shows an example of a vibratory bowl feeder designed for the feeding process. The feeder is divided into a part-independent process module and a part-specific component, which can be adapted to suit different parts.

The standardized part of the MO serves as a functional sample for all MOs. This standardized process carrier is comprised of a fixation system to fix the MO during operation and a localization system to determine the position of the MO in the working area. In addition, the MO is equipped with an embedded Control which handles the inputs and outputs (IO) as well as the external communication. Finally, the MO comprises data about itself in a self-description file. The self-description integrated in each MO can provide different static and dynamic data that are useful for the overall process orchestration as an important feature of a cyber-physical system. For example, some fundamental static information, such as the identification (ID) of the MO, the available work positions and the geometry data are made available. Other dynamic data that are updated consistently during operation include, e.g., the real-time coordinates and the current operational state of the MO. For an effective standardization of the self-description, standardized data modelling for the MO is required. The data modelling used for the MO is based on the concept of the AAS. In relation to the AAS, an MO may also be described as an asset. The AAS is based on so-called submodels, which provide a standardized description of the technical aspects of an asset. A submodel can be structured into properties, events and operations.

- **Properties** describe the static and dynamic characteristics of an MO (asset). Those cover, among other information, the above-mentioned ID of an MO or the dynamically measured position of the MO origin.
- **Events** are used to communicate changes in the state of the MO to other assets. This may include the completion of a specific assembly task or a notification that an operation call has been received.
- **Operations** offer predefined functionalities for the respective MO, which can be triggered by external modules. Those operations may be used e.g. to request information or to execute a motion command.

To enhance the reusability, a single submodel should only cover a single functionality, e.g., the position data. Thus, the submodel can be used for different assembly modules and a single MO can integrate many submodels handling a variety of functionalities. Figure 7 introduces the concept of an MO using the example of a bowl feeder

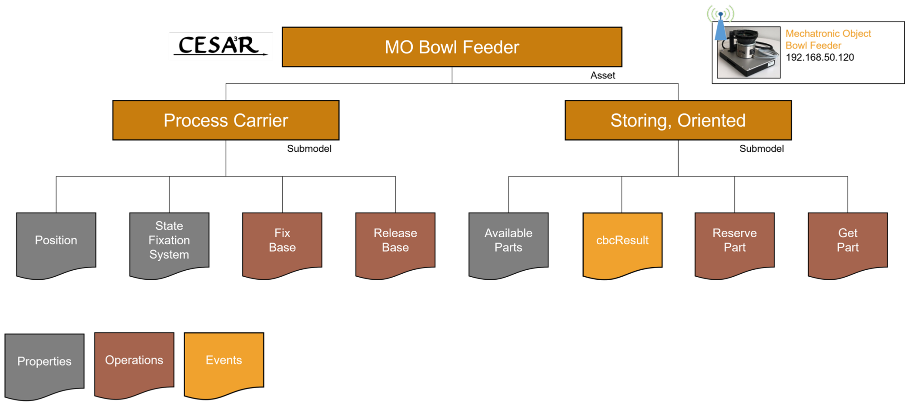

Figure 7: Modeling example for the AAS of a mechatronic object for the storage or provision of parts with the two submodels "Process Carrier" and "Storing, Oriented."

The submodel diagram shown in Figure 7 visualizes the corresponding submodels. Each MO has a submodel for the Process Carrier and one or more additional submodels, depending on the necessary skills of the equipped process unit. The introduced bowl feeder MO therefore contributes a Storing, Oriented submodel. Each submodel provides MOs defining properties such as the current position, events such as Basis Command (CBC) Result and finally operations which allow other modules and assets to reserve a part or fix the base. The reservation of a respective part guarantees that it is only used once in the process. The fix base operation allows an MO to be fixed on its current position and disable any further adjustment of its position. The MO can also be enhanced or extended with other submodules, if any functionalities should be added.

4. Instantiation of the FLMS

In the context of the project, different use cases were developed and tested. The aim through the composition of the individual use cases was the instantiation of an FLMS.

4.1 Use case – Assembly System (CESA^{3}R)

In order to verify the concepts and modules introduced with the CESA^{3}R system, a demonstration product was defined. The Battery Management System (BMS) is an easy to assemble product that provides a great use case to prove the functionality of the CESA^{3}R system. Figure 8 gives an overview of the MOs and assets involved in the assembly task.

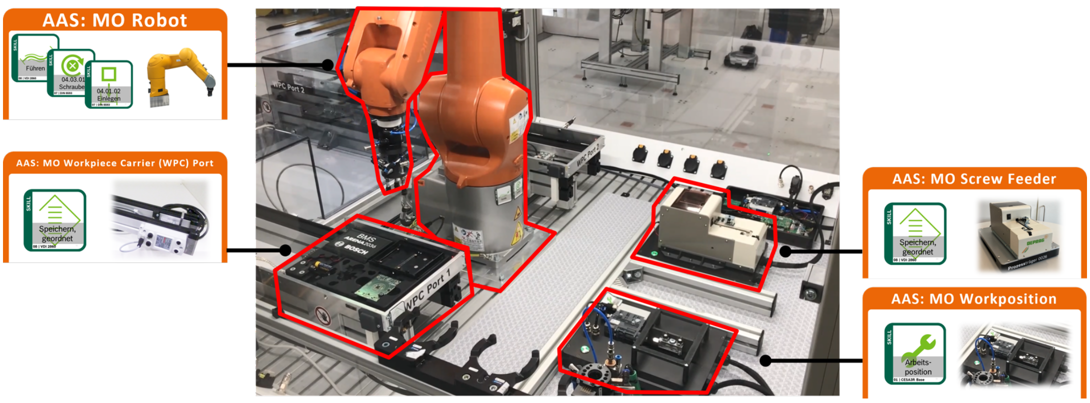

Figure 8: FluPro demonstrator and mechatronic objects (MO) for assembling the printed circuit board of the Battery Management System (BMS) demo product.

The assembly of the BMS requires a great variety of skills from robotic guidance to screwing and dispensing. For this assembly demonstration, the assembly of the printed circuit board (PCB) was chosen. Therefore, four MOs have been developed which provide the required skills:

- MO Robot for Pick&Place tasks
- MO Workpiece Carrier (WPC) Port for suppling the necessary workpieces
- MO Screw Feeder for suppling the screws used for fixing the PCB
- MO Workposition for providing a work position during the assembly procedure

The assembly starts by collecting the BMS case from the WPC Port and fixing it on an MO with the corresponding workposition skill. The PCB is attached to the BMS case using four screws. The screws are provided by the corresponding MO. The assembled case is then placed back on the workpiece carrier which is automatically moved out of the robot cell for further assembly tasks.

4.2 Use Case – Robot-based Assembly

For a fluid manufacturing process, it is important to communicate with different assets to get more flexibility. Therefore, the following use case was defined to test a precise positioning process for a robot assembly station using the AMR. For most transport processes, the accuracy of the AMR is sufficient for positioning. In order to achieve higher accuracy, an additional sensor is needed. Therefore, a flexible camera on a robot is used. Figure 9 provides an overview of all the assets involved in the positioning task.

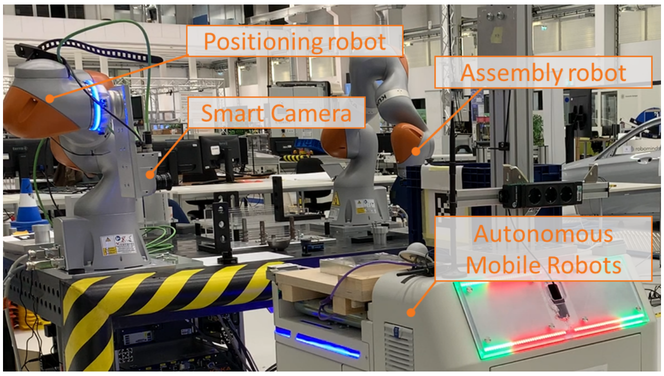

Figure 9: Use-case: accurate positioning for the assembly station, Bär AMR and Balluff Smart Camera.

Rough positioning: An ARUCO marker is attached to the carrier on the AMR. This enables the alignment and the distance of the carrier and AMR to be determined. Since the camera does not directly support ARUCO marker detection, only the raw images from the camera are used and processed for this use case. Figure 10 provides an overview of the individual AAS assets and the communication channel. Data from the evaluation of the ARUCO marker are output via the AAS to the MQTT rough_position topic. The AMRs subscribe to this topic and derive the necessary driving command from it. The X-position (displacement right/left in the image) and the Y-position (distance camera - AMR) are used here, each specified in meters. Furthermore, the theta angle, which indicates the rotation of the AMR in the image, can be used to derive the driving command. The camera and the AMR use different coordinate systems, so a transformation of the data is necessary. This transformation is performed before transmission via the AAS and allows the AMR to use the data directly for the driving commands. Once the AMR has arrived at the rough target position, the position of the camera is changed using the positioning robot. The following fine positioning is performed by positioning the camera directly vertically above the AMR with the workpiece.

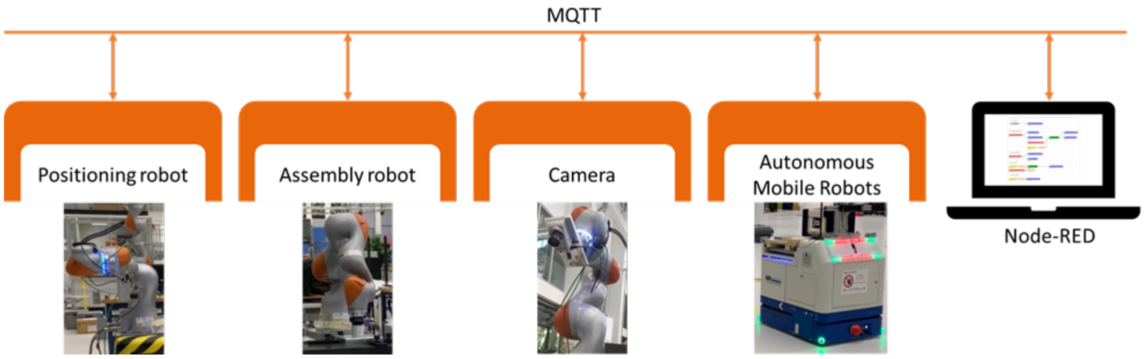

Figure 10: Overview of the asset administration shell for the use case.

Fine positioning: As soon as the robot with the camera has reached the new position, then the inspection program on the camera is switched over to an operation of the AAS. For fine positioning, the image processing algorithms running directly on the camera can be used. This is possible since the distance between the camera and the workpiece does not change during fine positioning. In order to perform fine positioning, the current position of the workpiece must be determined. The first step is to search for the workpiece in the image and then calculate the deviation from the center of the image. This results in the x and y deviations as well as the theta deviation from the learned target state in the center of the image. Driving commands for the AMR are derived from these deviations. The AMR receives the movement commands for the fine positioning via the call for operations of the Raspberry Pi of the camera. This directly addresses the operations of the AMR with the current data. The AMR attempts to minimize these deviations as far as possible by means of driving maneuvers. If the positioning robot with the mounted camera moves in the direction of the table, these deviations become larger, and the AMR must readjust by following the movement of the positioning robot. As soon as the positioning robot reaches its final position, this is reported via an event. The AMR drives the remaining distance to the desired final position and remains there for further assembly.

4.3 Use Case – Decentralized Material Flow

The aim of the logistics use cases is to demonstrate an event-based decentralized material flow-control via the interaction of several CPS. A decentralized material flow control is the capability of system elements to interact with each other and make autonomous decisions [24, 28]. In an FLMS, the material flow can be triggered by different events [29]. In the first use case, the smart load carrier triggers the material flow on a pull principle like the e-Kanban concept. If the material is removed from the smart load carrier, the time-of-flight sensors initiate the "material reorder" event followed by the "transportation" operation for the AMR. In the next step, the empty smart load carrier will be transported [24]. In the second use case, the material flow is trigged by a condition-monitoring event. If a sensor detects a deviation in temperature, humidity or a high acceleration, it publishes an event. Afterwards, the "transportation order" operations are published and the defective material is transported away [24]. In third use cases, the material flow is triggered by the BMS. The BMS uses an infrared interface to transmit information about the condition of the product to the Raspberry Pi installed in the battery case. Subsequently, the information is transmitted via AAS to the MQTT broker. If the BMS is completely assembled on the battery case and connected, it triggers the "connected" event, followed by the "material reorder" operation and "transportation order". In the last use case, the material flow is triggered by a condition-monitoring event of the BMS, similar to the second use case. Then, the product is transported via an AMR either for rework or quality inspection.

5. Conclusion and Outlook

In this paper, the development of CPS for FLMS is presented and tested on a defined product. The various CPS are elements of the FLMS, without rigid coupling of stations, routing and location flexibility. In order to ensure the scalability and technological adaptability of the production system, a planning logic for the design and development of a production system consisting of flexibly linked process modules were implemented. The interoperability of the CPS, fast, intuitive and the ad-hoc creation of process and assembly modules are supported by plug-and-produce approaches. Further, the presented approach will help to master a change in automotive production especially on the human work force in production. The separation between production and logistics and also between product and production will be further eliminated due to the increasing merging of systems. Value-adding processes will take place in all areas of production.

In the next step, to fulfil the premises of the FLMS, the CPS will be reconfigured for a second product, which is unknown at the start of the production. It represents the core point of the validation of versatility in FLMS, since it will show that a second product, which is not known at the time of planning, can be included in production. In addition, the presented concepts and logics in logistics and human-centric production will also be tested and validated on the second product. Moreover, the efforts on the reconfiguration of CPS in an FLMS will be measured and evaluated for future research.

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