μPlant: Model factory for the automatization of networked, heterogeneous and flexibly changeable multi-product plants

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Abstract

In the Department of Measurement and Control of the University of Kassel, the model factory μPlant was developed and built up. It permits testing new automation concepts for networked, flexibly changeable plants with distributed heterogeneous control systems close to industrial practice. Moreover, students are trained on modern instrumentation and control system technologies. μPlant is composed of modular, automated units for fluid processing, discrete manufacturing, and storage purposes. Material flow between the units is realized using autonomous mobile robots

1 Motivation

Production facilities typically consist of a set of processing, manufacturing, logistic and auxiliary units. These have been tighter integrated regarding energy, material flow and automation systems in order to improve operational effectiveness, efficiency and flexibility. The reduced buffer storages increase the coupling strength and require extending the system boundaries to sufficiently capture the system dynamics for control system design. The modularization of processing plants using package units with standardized process and information/automation interfaces is another trend. In addition, a quest towards a larger variety of specialized or even personalized products can be observed, tagged as “lot one production” at the far end. Recently, networked production systems received major interest under the label “Industry 4.0”. To enable testing new automation concepts and algorithms that answer such trends without endangering plants, people or environment, the model factory μPlant was developed. In addition, μPlant permits undergraduate and Ph.D. students to get hands-on-experience on state-of-the-art robotics and automation technology.

The model factory μPlant represents a networked, changeable scale-production plant with industrial instrumentation and automation systems but miniaturized processing components. It is composed of several heterogeneously automated subsystems for continuous fluid pro-

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cessing, discrete manufacturing, warehousing and material flow using mobile robots. Commercially or public domain automation and information systems are used augmented by own applications/software components. Different hardware platforms (PLCs, industrial PCs, office PCs, Micro-PCs) and operating systems (Microsoft Windows 7, Linux/Ubuntu 14.4, and ABB AC700 OS) are employed. All subsystems are integrated to permit an autonomous plant operation and to access all operational data for analysis. Section 2 gives an overview of the model factory. Details of the plant units are recorded in section 3. Section 0 is dedicated to the control systems. Section 5 concludes this article.

2 Model factory overview and utilization

2.1 Plant layout

The guiding design principle was to obtain a modular factory that integrates different production types: fluid processing systems, blending and storage systems, discrete manufacturing systems as well as industrial robots and mobile robots. In order to avoid hazardous waste and relax safety requirements, μPlant works with water but no additional chemicals and temperatures are kept below 60 °C. The product is filled into 0.8 l bins. Small polymer balls of different color can be added to a bin to represent different products. Intermediate product can be transferred by the 0.8 l or by larger 3.5 l bins. Finally, water and balls are automatically separated and reused as raw material again permitting to run the plant in a loop without producing any waste.

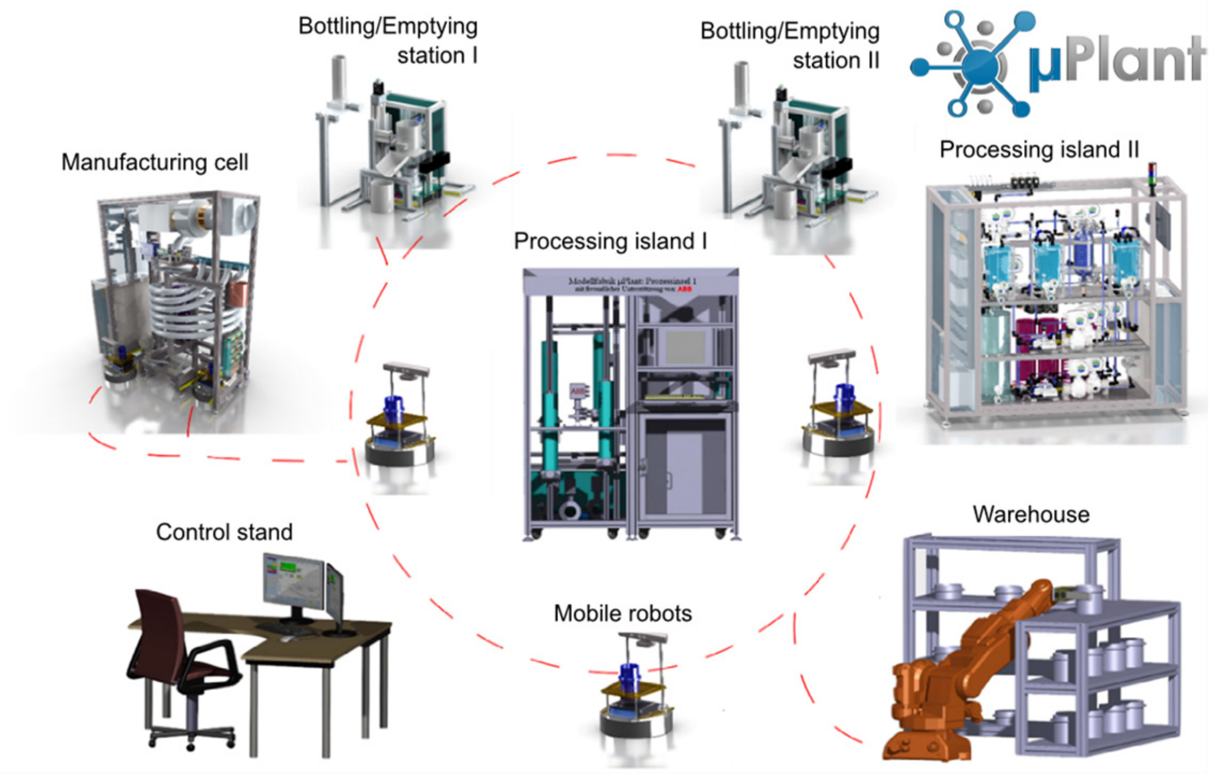

Fig. 1: Schematic sketch of the model factory μPlant

The model factory works fully autonomous to permit unmanned test runs. μPlant consists as shown in Fig. 1 of seven subsystems: 1) a processing unit with several chemical reactors to produce intermediate products (PI II), 2) a processing unit with 10 flexibly connectable tanks e.g. for blending intermediate products to the final liquid product (PI I), 3) two bottling and emptying stations to fill the liquid produced in PI I and PI II into bins that are carried by mobile robots (AuE I/II), 4) a discrete manufacturing cell that can add balls to the product (FZ), 5) a high bay warehouse with material handling by an industrial robot (LZ), 6) four omni-drive mobile robots that transport the bins from unit to unit (TS), and 7) a control stand to enter orders, supervise plant operation and carry out engineering tasks (LS).

2.2 Use in research and teaching

In contrast to many other model factories, μPlant is a complete own development incl. steel works, process equipment, instrumentation and control systems. About 45 student projects were involved besides the work of scientific and technical staff. μPlant is currently used in the coursework as PLC programming (for a fluid processing island) and as industrial robot programming laboratory (for the warehouse). It is deployed for public demonstrations e.g. on occasion of the "Tag der Technik". Regarding research, μPlant serves as a test bed for data-driven methods in modeling, control and supervision. For instance it is currently used in the BMBF project "FEE" (http://fee-projekt.de/) that addresses the early detection of and decision support in critical situations in industrial production facilities. For academic test-systems, it represents a large-scale system. The use of industrial instrumentation and control systems resembles the situation in commercial plants. To mimic operation with component failure or degradation, adjustable typical instrumentation malfunctions have been installed. Examples are reference pressure shift of hydrostatic level measurements, gas loaded fluids passing electro-magnetic flow sensors, pump efficiency degradation and electrical failures. The knowledge of source, severity and time instance of occurring abnormalities as well as the repeatability of experiments for statistical analysis are advantages of the model factory.

3 Production system details

3.1 Processing island I

Processing island I (PI I), see Fig. 2, was the first realized unit of μPlant. It was designed to simulate networked production systems that may structurally change over their live cycle. It is composed of 9 atmospheric product tanks and a central tank that serves as a reservoir. All tanks are made of acryl glass. The product tanks can be moved vertically for realizing hydrostatic pressure driven material flow. The liquid flows are measured by using industrial elec-

Fig. 2: Processing island I

tromagnetic flowmeters. Gear pumps, binary valves and proportional valves permit controlling the flows. These instruments can be flexibly mounted on several aluminum profiles as required in number and position for the flow sheet of interest. The tank inventory levels are measured hydrostatically using industrial pressure sensors. All components are interconnected by tubes. This enables to easily change between different flow sheets configurations. PI I is connected via pipes to both bottling/emptying stations for exchanging material with other plant units by using the mobile transport robots. Alternatively, processing islands I and II can be jointly operated using pipes, in case such an operational scenario is required. PI I is automated with a Beckhoff Soft-PLC that runs on an IPC. It has a local operator panel that gives local access the TwinCAT 3 PLC software.

3.2 Processing island II

Fig. 3: Processing island II

The second processing island (PI II), see Fig. 3, was designed to mimic typical industrial units found in chemical processing plants. The liquid raw material is processed in two parallel streams, each including preheating and each passing through a chemical reactor. Both streams are mixed in a tank with stirrer to form the final product. The production includes heat integration and material recycle (e.g. to mimic circulated solvent). Four product tanks are available for storing different products. The processing components and pipes are made of acryl glass. A glass serpent-tube liquid-liquid and a liquid-air heat exchanger are also deployed. Electrical heating is used as it avoids the utility requirements and safety risks going along with steam heating that is typically used in industrial plants. PI II was constructed with rigid pipes to reassemble typically chemical plant situation and to better cope with the higher temperatures. The same type of flow and level sensors is used as in PI I. Control valves and gear pumps permit controlling liquid flow. PI II is connected via pipes to both bottling/emptying stations. Binary values are used to direct flow e.g. to and from the respective bottling/emptying stations. As previously mentioned, PI II can also be coupled with PI I using pipes. PI II is automated using an ABB® AC 783F controller. It has a local operator panel, where ABB Freelance runs on an IPC.

3.3 Warehouse

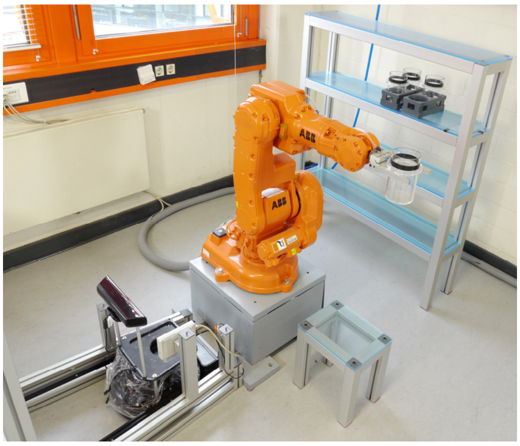

Fig. 4: Warehouse

The warehouse (LZ), see Fig. 4, was designed to reassemble characteristics of flexible manufacturing cells with high bay racking. The high bay rack has one shelve for finished products and two shelves for intermediates. Each shelve can accommodate eight palettes. A palette can be loaded with two small bins. A commissioning table is used to load (unload) bins to (from) a palette. The warehouse has two main tasks: At first, it unloads and stores a filled or empty bin once a mobile robot has entered. Before doing so, using the RFID reader the warehouse management software reads the bin ID and checks the required actions to be performed on the bin content. A palette is put on the commissioning table and the industrial robot moves the bin from the mobile robot to the palette, which is then put back onto the rack. When a product is to be delivered, an empty mobile robot enters the station. The industrial robot moves the palette with the requested product to the commissioning table withdraws the required bin and loads it on the mobile robot. The warehouse is served by an ABB IRB 140 6-axis industrial multipurpose robot with a pneumatic driven gripper and an IRC 5 robot controller with ABB RobotWare/RAPID 5.11. A docking station is used for the mobile robots in order to provide for a defined position for unloading/loading a bin. It is equipped with an RFID reader/writer system. The warehouse management system is an in-house development written in VisualBasic .NET and runs on a standard office PC.

3.4 Manufacturing cell

Fig. 5: Manufacturing cell

The manufacturing cell (FZ), see Fig. 5, represents a discrete event system and has two main functions. The first function is to add balls of different colors to the liquid in a bin to mimic different products. The second function is to empty the bins and recycle the contained water and the balls. The manufacturing cell embeds two docking stations for mobile robots: one for adding the balls and another for unloading the bins and recycling their content. For the latter, the bin is lifted by a linear drive with a lift fork and tilted for emptying. The water is collected in a tank and the balls proceed to a drying unit which is composed of a fan with integrated electrical heater. The leading ball is regarded as dry, once a pyrometer senses a specified ball surface temperature. The dried ball is relieved using pneumatically operated twin blockers and the dying process continues with the remaining balls, as long as the ball queue is not empty. Succeeding, the color of the released ball is identified using an RGB camera. Then the ball is sorted into the corresponding tube-type magazine using a series of pneumatically operated gates. To add balls into a bin at the second docking station, pneumatically operated twin blockers are used to control the ball supply. The subsystems for emptying, drying, sorting, and adding, respectively, can operate simultaneously. This allows one bin to be lifted off a mobile robot for emptying at one docking station while at the same time balls can be added to a bin on another robot in the other docking station. The manufacturing cell is automated using TwinCAT 3 PLC software running on a Beckhoff panel PC.

3.5 Bottling/Emptying stations (AuE I/II)

µPlant is equipped with two bottling/emptying stations (AuE I/II), see Fig. 6. They realize the material flow between the processing islands and all other units of the model factory. They are used for bottling the small and large bins as well as for emptying the large bins (which are not supposed to contain balls). Each AuE features a dosing and a collecting tank as well as two pumps. A linear drive is used to lift the large bins for emptying. Each AuE is connected to both processing islands. Once enough product is ready for bottling a bin, it is piped to the dosing tank. As soon as a mobile robot has docked and the presence of the expected bin has been verified by reading the bin's RFID tag the product will be filled into the bin. If a bin needs to be emptied, it is lifted using a fork lift and mechanically tilted. The fluid drains into a collecting tank and is pumped back to PI I or PI II as chosen. All tanks are equipped with hydrostatic pressure sensors for level measurement. Both AuE I/II are automated using TwinCAT 3 PLC software running on the engineering computer in the control stand: Due to the small size of the AuEs it was decided not to equip them with own control hardware.

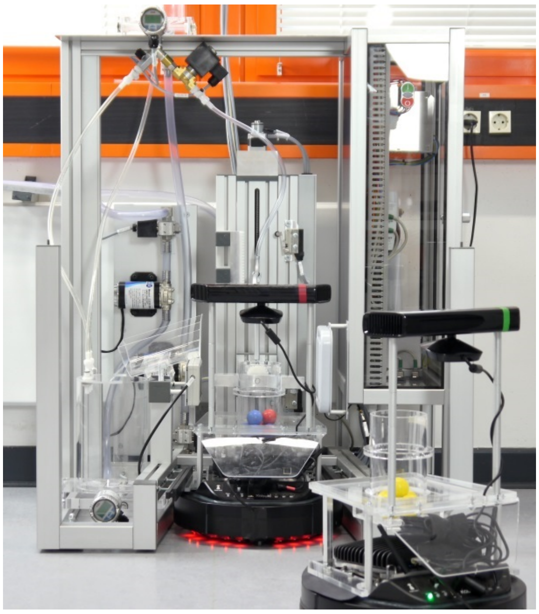

Fig. 6: AuE station II

3.6 Instrumentation and field communication

Most of the analog sensors and actors use the 4-20 mA or 0-10 V industrial signal standard. Field bus communication was discarded to lower hurdles for students and to permit maintenance without dedicated support personal. Remote I/Os are used to connect the field devices to the unit control systems using TCP/IP (Profibus for ABB Freelance and EtherCat for Beckhoff TwinCAT) with the PLCs. The PLCs communicate with each other and the operator station via TCP/IP and various protocols: Modbus/TCP, ABB ADMS, Beckhoff ADS and TCP/IP sockets. The RFID writers are connected via TCP/IP with the factory network backbone. The mobile robots use WLAN to communicate with each other and with the central robot control station.

3.7 Intralogistics/material transport

Fluid transport between plant units is realized by using mobile robots that carry the bins, see e.g. Fig. 5 andFig. 6. All units except both processing islands are equipped with docking stations that support well defined positioning of the mobile robots during loading and unloading operations. The robots are guided towards the station by an infrared beam. At present, four Kobuki Turtlebots 2 are used. Each robot is equipped with a depth camera (Microsoft Kinect) for self-localization and navigation purposes and an onboard computer (CompuLab Mintbox 2) for processing sensor data and planning movements. A carrying device is mounted on each robot to hold a bin in place during transport. Each Turtlebot can carry payloads of up to 5 kg, which leaves 2 kg for a bin with content due to the weight of the Mintbox and the carrying device. The battery is reloaded in three separate electrical charging units as well as in any docking station of the plant's units. Navigation and collision avoidance do not rely on zone control methods but are realized as self-developed ROS extension that runs on the central ROS control station (Linux/Ubuntu PC). It is based on a modified Dijkstra's algorithm. The modification permits to exclude certain regions from the permissible area as well as to avoid collisions with unplanned obstacles such as humans walking through the plant or ad hoc placed material/objects. The control station is responsible for both the coordination and the supervision of transportation tasks whereas the onboard computers run necessary drivers and robot-specific navigation programs.

3.8 Control stand

The control stand, see Fig. 7, allows to operate and supervise µPlant as well as to carry out control engineering tasks. The Freelance station serves as operator station for the overall production control system and the process island II. It is also used for the related control engineering tasks. In the middle, the ROS control station permits to supervise the four mobile robots: Their poses and movements are shown in real-time in a digital 2-D-map of the plant.

It is also used to carry out all ROS-related programming work. The Beckhoff station is used for engineering all TwinCAT 3 programs used by processing island I, both bottling/emptying stations and the manufacturing cell. It can be used to show detailed operator graphics for the respective units. Finally, it runs the PLC programs for both bottling/emptying stations. The forth station on the separate desk to the right contains the warehouse management and control system, which shows the capacity utilization of the high bay rack and the status of loading/unloading processes.

Fig. 7: Control stand and plant

4 Control and information system architecture

4.1 Control and MES functions

µPlant pursues a decentralized control strategy, therefore, a superordinate system, the production control system (PS), is used to plan the production based on incoming orders and to pass tasks on to the individual control systems of the production units. From the units' points of view, the passed tasks are orders which are transformed into individual production steps. The units carry out these production steps by handling the underlying sensor signals and actors. Therefore, the functions assigned to the different levels in the classical automation pyramid, like the operational management level, the process control level and the ground level control, are also distributed over the production control system and the unit control systems. For that reason, also the borders between the systems used for the three levels (manufacturing execution system, process control systems and programmable logic controllers are not fixed anymore. The functions of the production control system are: managing the order list, splitting each order into tasks to be carried out by the units, operating and monitoring the overall process, collecting product related data and sensor signals from the plant. On the other hand, the functions of the unit control systems are: handling the tasks coming from the production control system, controlling and monitoring the processes of the unit as well as providing feedback to the production control system. The control systems of µPlant support both batch and continuous production.

Besides the task communication with the PS and with each other, the units are working independently. Therefore, a failure or error of one of the stations will not stop the whole production. Moreover, experiments with individual units can selectively be carried out without involving the remainder. Different control systems have been selected for PS and unit control depending on the specific requirements, the offered engineering functions, the ease of use and the costs. ABB Freelance is deployed for implementing the production control system. It was selected in particular, as it was regarded as comparatively fast to adopt by students that have little previous knowledge and as it was assessed to be sufficiently functional for the small scale-production plant. The processing island I, the manufacturing cell and the bottling/emptying stations use BECKHOFF TwinCAT 3 systems. The Matlab extension of TwinCAT 3 permits to carry out Matlab programs on a PLC, simplifying rapid prototyping of new control algorithms, which was regarded as important in the conceptual phase of µPlant. The process island II uses ABB Freelance 2013. The warehouse uses a self-written VisualBasic .NET program together with ABB RobotWare. ROS "Indigo" is used for the mobile robots. It is wide spread used in mobile robotics and well supports distributed control concepts. As an example, the function of the production control system and the control system of the processing island I are described in more details in the following sections.

4.2 Production control system

The main functions of the production control system have been listed above. As interface to the operator a graphical user interface (GUI) was implemented with two main operator graphics, considering the high performance GUI standard. The first frame shown in Fig. 8 gives an overview of the model factory and the status of the production units: At the top left of the window information on the bottling/emptying stations and the electrical charging stations is shown. The status of the mobile robots themselves is visualized at the bottom. In the middle of the window information on manufacturing cell is displayed to the left, on processing island I in the middle and on the warehouse to the right. Information on processing island II is provider in the top right. Beside the main information about the production units, more infor mation can be displayed in separate windows. This first operator graphic is for visualization, not permitting the operator to control the units. The second graphic offers the possibility to create orders and to observe the progress of the order processing.

As no overlying planning and scheduling system is implemented, a new order can be created directly by the operator. It is identified by the order number and consists of the customer ID and the ordered product types with the respective amount. Based on the selected products, the order will be split into an ordered list of tasks, considering all currently inserted orders. The single tasks are then forwarded to the unit control systems and the robot control system. If a task has been finished by a production unit, the later gives an according feedback to the production control system, which initiates the next production step or parallel steps from the current order list. If an order was completed entirely, information such as product types, amount of successfully produced products, etc. are collected as printable report.

4.3 Control system of processing island I as example of a unit control system

An aim of the model factory is that the production units can operate individually without any connection to the production control system. In order to realize this, each production unit has its own local control stand. In case of the processing island I (PI I) also the flexibility of placing and connecting of the components inside the processing island has to be considered. The GUI of PI I, which is shown in Fig. 8 or an exemplary flow sheet configuration, manages the flexibly changeable interconnections between the components by loading different overviews (P&IDs) of the realized process. If besides the process representation also the controlled process is changed, it is necessary to change the control program that is implemented on the controller, too. If the PI I is operated as part of the model factory and not stand-alone, the production is executed after a task from the production control system was received. Depending on the task, PI I orders resources, proceeds with the production process and finally pumps the product to one or both of the bottling/emptying stations. During the production, PI I continuously updates the status information that can be read by the other units as well as by the production control system. At the end of a task, PI I reports back to the production control system. Also, PI I continuously sends a status signal and the updated measurement values for the overall visualization to the overlaying system for visualization.

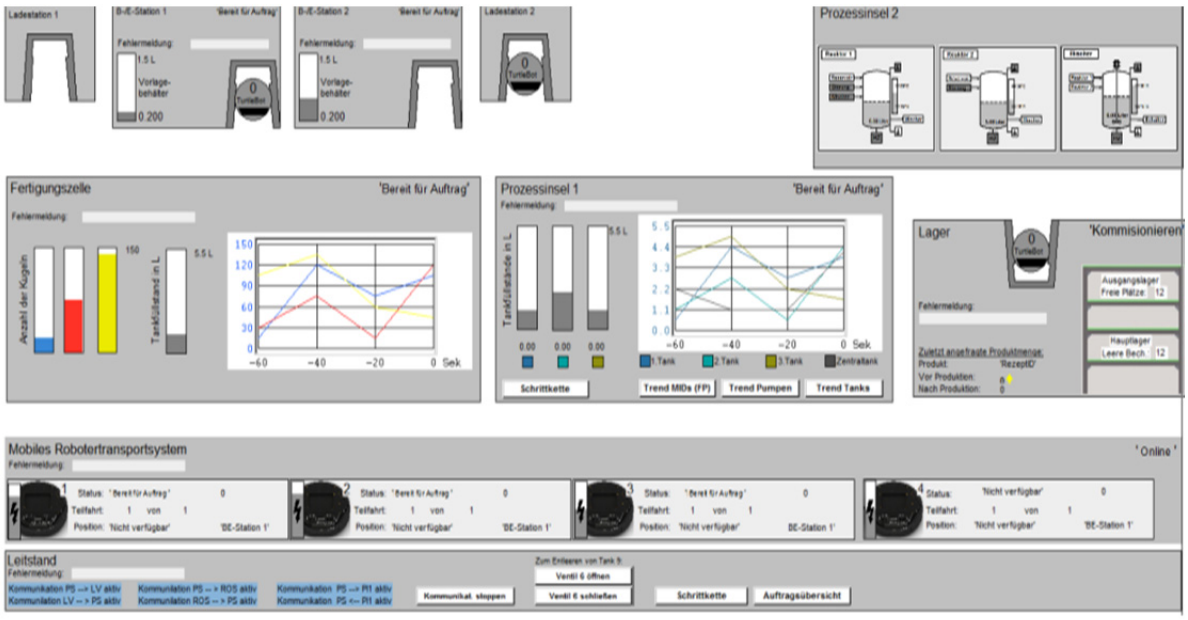

Fig. 8: Overall visualization of the model factory

4.4 Control system architecture

As a distributed control concept is implemented, the production control system and the individual units are equal agents. The individual control systems are able to communicate with each other and also global information, like the master recipes, is available for agents within the communication structure. To realize the communication, the units use different interfaces and protocols like Beckhoff ADS, ABB ADMS, and Modbus/TCP, see Fig. 9. The main communication bases on TCP/IP enabling a fast communication between the agents. Between the control systems of the units and the underlying I/Os, different protocols (EtherCAT, Profibus, ABB ADMS and TCP/IP) are used depending on the respective control system. To integrate the warehouse system, the robot control system, and the RFID reader/writer systems to the agent communication, a server PC is used, where the individual protocols are converted into each other.

4.5 Use case example

This section describes a production scenario where 0.5 l of lemonade *A* and 1.0 l of lemonade *B* are ordered. PI I, FZ, LZ, AuE I, AuE II and three transport robots are involved in the production task. The initial situation is as following: the warehouse has none of the ordered product on stock, but contains at least 3 empty bins. The three mobile robots rest in the FZ, the AuE I and in one of the charging stations, respectively. There is no inventory in PI I. The use case starts with the operator entering the order into the Freelance-based order management user interface. Then, the production request is automatically generated by the operator station. Secondly, the warehouse is queried whether some of the required products are already on stock, such that only the remainder has to be produced. The warehouse answers that no finished product is available and the operator station issues a production order to PI I. In parallel the operator station sends transport requests to the mobile robot system: three robots move to the warehouse and are loaded with an empty bin one after the other. Before a robot leaves the warehouse the RFID tag of the loaded bin is written with order information (order ID, product ID, customer ID, and bottling state). Two robots move into bottling/emptying stations AuE I and AuE II, while the third one queues. In parallel, PI I produces the intermediate products for lemonade *A* and *B*, which is mimicked by pumping the required quantity of liquids each through a different tank network of PI I into the intermediate product storage tanks. Each of the AuE is requested to handle one of the products: The 0.5 l intermediate product *A* is pumped to AuE II, and the first 0.5 l of intermediate product *B* is pumped to the AuE I. When the dosing tank of an AuE is filled and its RFID reader reports that a robot carrying the ordered bin has docked, this bin is filled. This way two robots have received their loading and leave towards the manufacturing cell (FZ) while the third robot receives the second half of intermediate product *B* into its bin in AuE I. The mobile robots transport the intermediate products to the manufacturing cell. There a product-specific set of colored balls is added in order to form the final product and to finalize the production of lemonade *A* and *B*. Product delivery and usage is mimicked as following: the robot with product

A moves to the other docking station of the FZ, where the bin is directly unloaded, lifted, emptied and liquid as well as balls are recycled. The two robots with product *B* move to the warehouse, where they are unloaded. Both bins are placed in a single palette and stocked on the rack for finished product. Then the bins are unstocked and successively loaded onto two mobile robots that carry their freight to the FZ for unloading and recycling. The empty bins are transported back to the warehouse, unloaded and stored. The mobile robots move back to the three docking stations where the use case started from such that the later plant returns to the state it started from.

5 Conclusions and outlook

The model factory µPlant is a test facility for automation, modeling, supervision and data analysis concepts targeting networked, heterogeneous and flexibly changeable multi-product plants. It features fluid processing systems with slow continuous dynamics and many analog signals, discrete manufacturing systems with majorly logical signals and discrete event character, a robotized warehouse and mobile robots with discrete events and Cartesian data. µPlant's assembly of heterogeneous production and automation systems makes it a true "system of systems" and puts it into a unique position in the landscape of scale plants. Processing island I was commissioned as first unit in 2013 and used for novel methods for dynamic analysis of distributed production systems. Building on that experience, µPlant was successively extended. Processing island II was built up as the last unit and it is currently being integrated into the entire plant operations. The "start-of-production" of the entire plant is planned for fall 2016. µPlant received great interest of students in terms of labs, student projects and student assistant jobs. After commissioning, µPlant will at first be used as test bed for novel methods addressing predictive alarming and operator decision support systems. The future use will include data-driven modeling and big-/fast-data analysis and other topics to come. At present the automation concept is under revision several improvements are implanted.

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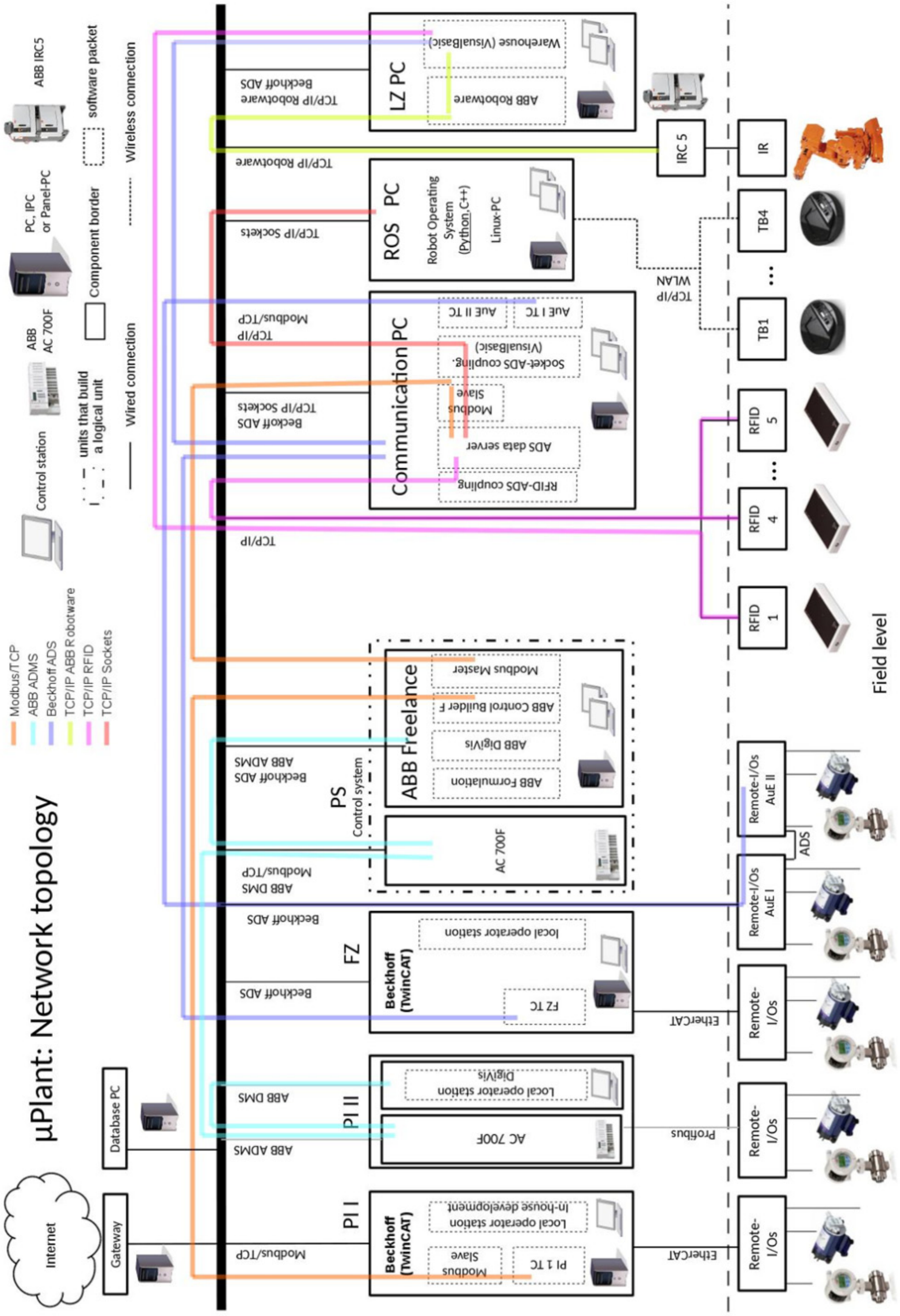

Fig. 9: Network topology of the model plant