Towards Mixed Reality in SCADA Applications

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Abstract: The purpose of this paper is to explore the opportunities of Mixed Reality (MR) as a complementary tool to Supervisory Control And Data Acquisition (SCADA) systems and to demonstrate the potential benefits on an experimental set-up. The set-up represents an automated logistic process that is highly integrated in a Computer Integrated Manufacturing (CIM) structure. MR is realized through the collaboration between a vision application and a SCADA system and both the opportunities of Augmented Reality (AR) and Augmented Virtuality (AV) are being explored. This results in a monitor based AR supervisory tool on the shop floor and enhanced SCADA functionalities through AV.

Keywords: Mixed Reality, SCADA, Augmented Reality, Augmented Virtuality, Supervisory Control.

1. INTRODUCTION

Ever since the introduction of 3D computer graphics and the ever increasing capabilities of hardware and software, Mixed Reality (MR) has spurred the enthusiasm of researchers in many fields. MR refers to visualization techniques where elements of the real world are blended with computer generated objects. In order to acquire a better understanding of the concept, the Reality-Virtuality (RV) Continuum introduced by Milgram et al. (1994) is shown in Fig. 1. The Continuum describes a scale that spans from the real environment to the complete virtual environment. Many authors have adopted the definition of Virtual Reality (VR) from Benford et al. (1998) to describe the virtual environment. VR systems are computer systems in which users are immersed in a virtual, computer-generated world.

All possible compositions between both extremes of the RV Continuum represent different variations of mixed reality. Augmented Reality (AR) is a subset of MR whereby the user's vision of the real world is extended with additional information of virtual objects. According to the generally accepted definition provided by Azuma (1997), AR systems have distinct characteristics: 1) combines real and virtual, 2) interactive in real-time and 3) registers (aligns) real and virtual objects with each other. The second subset of MR is defined as Augmented Virtuality (AV) (Khan et al. (2011)).
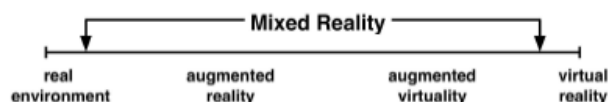

Fig. 1. The RV Continuum (Wursthorn et al. (2004))

Different studies can be found in the literature that pinpoint areas of application for MR systems. A study con-

ducted by Constanza et al. (2009), refers to the manufacturing industry and remote collaboration. Azuma (1997) focuses on AR and proposes six classes of potential AR applications under which manufacturing & repair and annotation & visualization. AR tools for the manufacturing assembly domain have shown promising results. Tang et al. (2003) showed that AR instructions in a specific assembly task reduced the error rate by 82% compared to a classic printed manual.

On the opposite side of the RV continuum, Ferrarini and Dedè (2009) point out that 3D graphical visualization tools, which can be interpreted as AV systems, are a mean to model flexible manufacturing systems. These systems are possibly used for commissioning, for supervision purposes and for diagnosis and maintenance. Supervision of production processes is traditionally realized with Supervisory Control And Data Acquisition (SCADA). SCADA systems display process information to the user based on data exchange with the Programmable Logic Controller (PLC) which controls the automated process. In automated logistic systems, sensors are placed strategically across the installation and traditional SCADA systems will update the visualization display when a sensor is reached. The user has no idea of the state of an object between sensors and has to wait patiently until the object reaches the next sensor to validate the location of the object.

As quoted from Mekni and Lemieux (2014), the challenge in the industry is to design and implement integrated MR systems that could enhance manufacturing processes, as well as product and process development, leading to shorter lead-time, reduced cost and improved quality. MR is in many ways still in its early stages and there are many technical restrictions to deal with. Fite-Georgel (2011) studied the readiness of Industrial AR (IAR) by collecting all scientific publications the author could gather related to the subject. The conclusions were clear: only two

applications broke out of the lab and only one was still used in the field by non-developers at the time of the study. Research on MR is mainly focused on proof of concept styled results and on addressing case specific issues.

In this paper, a holistic approach is adopted to present some opportunities of MR as a supporting tool for SCADA applications. The goal is to integrate different concepts of MR on an experimental set-up that is used to simulate automated logistic processes. Both sides of the RV continuum are investigated. In the first place, AR is achieved by augmenting a web cam feed of the scene. The application is made interactive by integrating a computer vision algorithm that tracks the objects on the logistic path. By selecting an object, the AR tool provides support for the user in the form of virtual elements projected in the display feed. Secondly, an approach based on AV is used to monitor the system. For this the software Experior is used instead of a traditional SCADA system. Experior is an emulation software with a 3D graphical visualization tool and is typically used for Virtual Commissioning (VC) of automated systems. This results in a user friendly 3D visualization of the process. Classical sensory inputs coupled with the vision based tracking algorithm allow the user to evaluate the state of the process at a glance.

The main purpose is to present an integrated demo in order to show potential benefits of MR in the field of supervisory control and support on the shop floor. As stated above, MR is fairly new and therefore relatively unknown in the industry. Even though research on case specific issues is essential in order to make progress, this work is designed to trigger the enthusiasm of the industry by presenting a complete demo and integration with existing elements of production control. In order to achieve these goals, a fixed camera is used to avoid specific issues related to dynamic camera viewpoints when AR hardware devices like Head Mounted Displays (HMD) are used. More information related to this topic, is given in section 3.1. As research advances to solve remaining hurdles, the application can gradually be upgraded to integrate new evolutions in hardware and software.

The remainder of this paper is organized as follows. Section 2 presents an overview of the set-up with hardware and software components. Section 3 focuses on the vision application with AR and tracking algorithm while section 4 highlights SCADA and AV. In the last section, conclusions are drawn and guidelines for further research are formulated.

2. SET-UP

A simplified, schematic view of the set-up is shown in Fig. 2. The tracks represent internal logistic routes and the trains represent Automated Guided Vehicles (AGV). The set-up is PLC driven and the controller is connected with I/O devices through industrial fieldbuses. The PLC can read inputs from induction sensors dispersed around the track switches and can write outputs for pneumatic or infrared control. Induction sensors are used for train detection, pneumatic cylinders for changing the track switch direction and infrared for controlling the train speed. In order to integrate MR in the setup, a low cost webcam which captures the scene, is mounted on a fixed

position. The live feed with a resolution of 640x480 is processed by the vision application and displayed on the laptop. The primary functions of the vision system are tracking of the trains and augmenting the webcam feed with virtual information. These functions can be seen in the schematic overview given in Fig. 3.
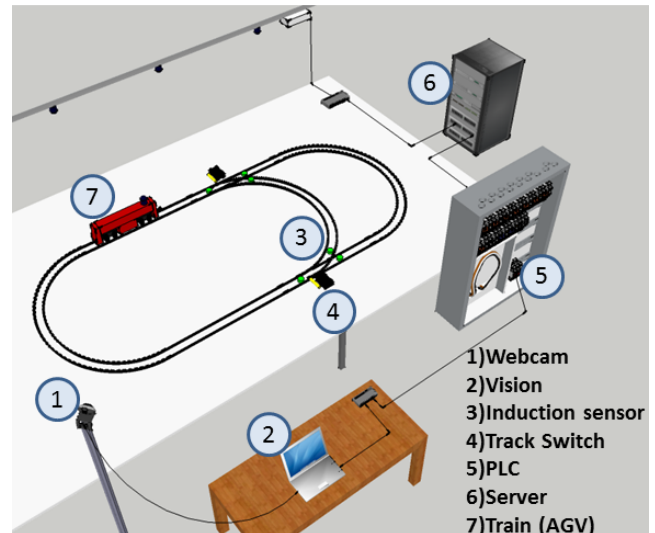

Fig. 2. The set-up

A standardized schematic overview helps to break down the complete software project into functional modules and to describe the information flows between them (Cottyn et al. (2011)). To emphasize the industrial context, the modules have been structured according to the functional hierarchy model as described in the ISA 95 standard (ISA (2000)). The Logistics Execution System (LES) above the full line, is part of level 3 in the hierarchy model which groups together all modules involved in the management of the logistics operations. The LES processes a schedule from the ERP and sends operational commands to the PLC.
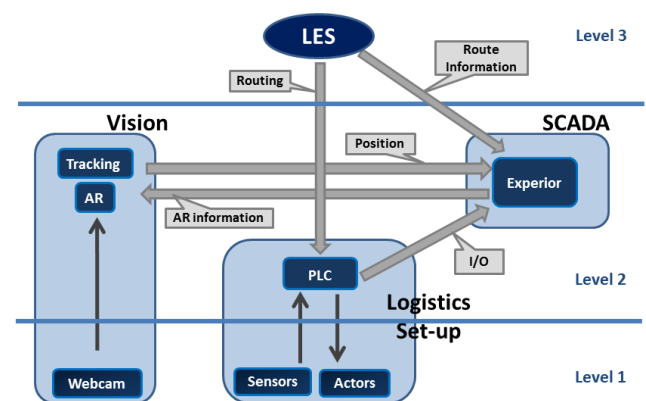

Fig. 3. Schematic overview of functional modules

The PLC, SCADA and vision application fall within level 2. This level represents the modules involved in the production control of automated processes. Experior, as a SCADA system, plays a central role in the communication flow. First of all, SCADA monitors the process by accessing the PLC I/O as is customary. In the next section, it is explained how this sensory input makes a valuable

contribution to the robustness of the AR application. Secondly, the LES database stores information about route planning, transported goods, etc.

This information can be retrieved by Experior and transmitted to vision upon request of the AR application. In the opposite direction, the tracking algorithm in vision supplies location information that is used to augment the virtual model in Experior. Level 1 in the hierarchy model represents the sensing and manipulation of the production process (e.g. the induction sensors and track switches).

3. VISION

The development of the vision application is primarily based on the C++ libraries of the open source software OpenCV for computer vision applications. OpenCV is aimed at providing the tools needed to solve computer-vision problems and contains a mix of low-level image-processing functions and high-level algorithm (Pulli et al. (2012)). Since this work's purpose is to reach out to the industry, OpenCV is an interesting choice in terms of extendability, portability and cost.

3.1 Tracking

The tracking algorithm plays an important role as sensory input for the AR application and for augmenting the Experior model. As stated by Raghavan et al. (1999), it is an essential element of an AR system to possess one or more sensors to monitor the state of the world. Depending on the complexity and the nature of the AR system, different combinations of sensors have to be considered. Constanza et al. (2009) differentiate tracking systems as either active or passive. A passive system detects an object with sensors surveying the object from a distance. Active systems on the other hand, require the object to be equipped with some type of tracking device such as GPS, Radio Frequency Identification (RFID), visual marker, magnetic and inertial sensors or a hybrid system.

Some caution about the terminology is advised when tracking is mentioned within AR systems. In many papers tracking refers to the localization of the camera's viewpoint. From this perspective, tracking is closely related to the registration process which defines the correct alignment of virtual and real images so that the illusion is created that the 2 worlds coexist (Azuma (1997)). Good static registration, as mentioned by Klein (2006), refers to the pixel-perfect alignment of virtual and real elements when the user or the camera remains motionless. Since the camera is fixed, no tracking of the viewpoint is necessary. Good dynamic registration means that the user's viewpoint must be tracked at all times so that no jitter is created between real and virtual objects. This is an especially critical and difficult task in the case of HMD's where fast head movements with 6 degrees of freedom (DOF) occur. Determining the orientation of a user is still a complex problem with no single best solution, even though research on hybrid tracking systems with visual and inertial sensing shows promising results (van Krevelen and Poelman (2010)).

In this paper, tracking refers to object detection on the logistic path and not to the location of the camera's viewpoint. The set-up is an example of static registration realized with marker detection. The first step consists in the camera calibration in order to calculate the intrinsic camera parameters such as the radial and tangential lens distortions, focal length and principal point. In the second step, the markers are detected using a contour analysis algorithm. After detection, the extrinsic camera parameters can be computed since the world coordinates of the markers and the corresponding pixel coordinates are known. The extrinsic parameters consist of a rotation and translation matrix which make the link between the camera's viewpoint and the 3D world coordinate system. Since the camera position is fixed in the set-up, the extrinsic parameters have only to be computed once during the initialization of the camera. After that, virtual elements with known 3D coordinates can be projected in the image and pixel coordinates of tracked objects can be translated into real world coordinates.

Different parameters had to be taken into account in order to choose the tracking algorithm. The algorithm must fulfill multiple tracking in real-time, initialization without manual intervention and robustness against changing environment conditions. The camera is a low resolution camera of 640x480 and is subject to a significant amount of noise. Furthermore, the covered area is very large compared to the size of the objects. Depending on its position on the tracks, an object is sometimes represented by just a few pixels. This means that the possibilities for feature extraction are limited. Feature extraction is the starting point for tracking algorithms and the algorithm can only be as good as its feature detector (Islam and Kamir (2013)). Popular methods for feature extraction such as SIFT and SURF, could not find sufficient repeatable key points. Other established algorithms like optical flow and KLT tracker, also failed to track the objects.

Two algorithms proved to be successful in tracking the objects: Camshift and Background Subtraction (BGS) based on the work of Zivkovic (2004). Both algorithms use color as the detected feature. Camshift requires that the user provides an initial search window to locate the object which makes the system unmanageable. The popularity of BGS and the amount of research towards it, has led to a plurality of models. The result of a BGS algorithm is a binary output where the detected objects appear as blobs. As shown in Fig. 4, results between different algorithms can vary significantly.

(a) Input frame (b) Zivkovic (c) Temporal Mean (d) BG Learning FG mask (e) Static frame (f) OpenCV MoG
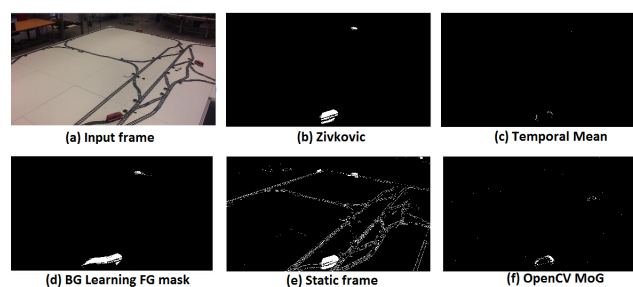
Fig. 4. Output of different BGS algorithms

The model of Zivkovic showed the best mix of results in terms of detection and real-time processing. The algorithm is an improvement of the Mixture of Gaussians (MoG)

algorithm proposed by Stauffer and Grimson (1999). The MoG algorithm models every pixel of the image with a fixed number of Gaussians which are each classified to be either representative for the background or for a foreground object. At every new frame, each pixel intensity I_t is compared to its Gaussians in order to classify the pixel as foreground or background. Next, I_t is used to update the Gaussians. This way, the background is made dynamic so that changes in the environment will ultimately be integrated in the background after a learning period. Zivkovic extended the MoG concept to dynamically adapt the number of Guassians per pixel instead of working with a fixed number of distributions. This extension increases the algorithms computational efficiency and can improve performance when the background is highly multi-modal (Parks and Fels (2008)).

BGS is only the first step in the detection algorithm and is followed by post-processing logic (see Fig. 5). In this step, morphological operations are applied on the BGS binary output to eliminate noise and to improve the quality of the blobs. At this stage, the exact 3D location and orientation of the object cannot be known because mathematically, the equation is indeterminate. Therefore, the degrees of freedom need to be reduced. In order to achieve this, the overlap between the blob and the tracks is found as displayed in Fig. 5. The resulting blob lays in the plane of the tracks and a contour analysis can be performed to find the center point and the direction of the blob represented by the center lines in the bounding box. This way, all 3D information about the object is available except for the height.

Fig. 5. Postprocessing

The post-processing step will deliver for each frame, a list of center points and direction vectors to the blob analysis which is the last step in the detection algorithm. The blob analysis essentially keeps track of the blobs between frames and sends the position coordinates to Experior. It also detects false blobs in the list. False blobs are an undesirable side effect of the dynamic background model. If a moving object stops, it will eventually be taken up into the background. If the object moves again, not only the object is detected as foreground but also the place where the object stood still appears as a blob since the pixel intensities no longer match with the background gaussians. The false blobs may, in particular cases, make the AR application unstable or at least not robust enough to be used as a stand alone application in an industrial context. Recovery issues may also arise when drastic changes in the environment occur such as sudden variations in illumination.

The robustness of the system is achieved through communication with Experior. Each time a train reaches a sensor, Experior sends the system ID of the train and the location of the sensor to the tracking algorithm. The algorithm compares the data with its current model and correction measures are applied if it proves to be necessary.

3.2 GUI AR application

The Graphical User Interface (GUI) of the AR application allows for production monitoring of the automated system. A wire frame is projected around the detected objects on the logistic path as shown in Fig. 6. The way the virtual frame aligns with the real object shows the precision of the registration process. This requires high accuracy and real-time processing of different elements combined such as the tracking algorithm and the extrinsic and intrinsic parameters. For dynamic registration, the camera's viewpoint has to be tracked on top. This explains why the registration process is considered to be the technical hurdle in implementing AR systems (Azuma (1997)). Small misalignments are sufficient to destroy the AR experience.

Different functionalities make the GUI interactive. Each user must enter a login which determines the information that will be displayed. The wire frame and the object ID are displayed for all users and the color of the wire frame indicates the state of the object. By selecting an object, specific information is rendered depending on the login of the user. Vision sends an information request to Experior which queries the LES database. Three user groups are targeted: the logistics operator, the maintenance technician and the production manager. These have been inspired by examples or ideas found in the literature, as discussed below.

As pointed out in the introduction, one of the most promising applications of AR is in the traditional manufacturing assembly domain. From the three user groups, the maintenance technician performs actions that are very similar to classic assembly tasks. When the technician selects an object, first he receives technical information about the train, such as battery life and number of days till next service. An icon gives the user the possibility to play a video, which leads him step by step through the maintenance procedure of the next service and the assembly related actions that need to be performed.
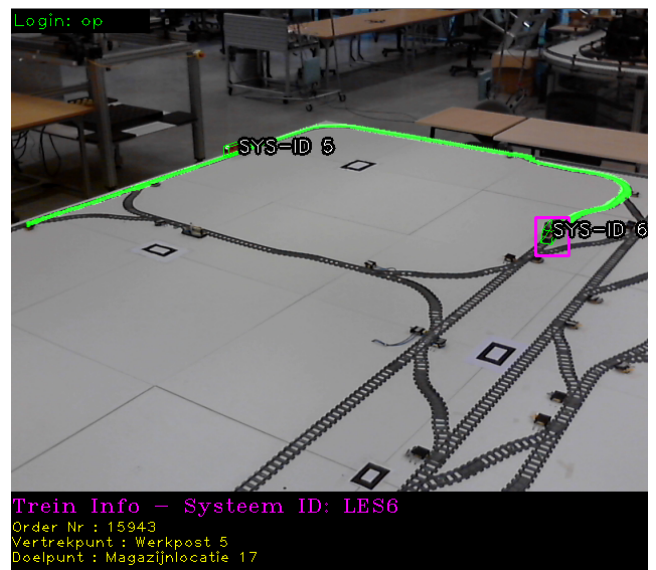

Fig. 6. AR GUI logistics operator

Besides maintenance, logistics is also cited as a field of interest for AR applications in the industry (Fite-

Georgel (2011)), in particular pick by vision. Based on the principles of pick by vision, the logistics operator receives information about start and endpoint of the AGV, which can be a storage location or a workstation and the path to destination is highlighted as shown in Fig. 6. This information can be used to optimize routing or to reroute the train if a problem is detected on the path. The last user is the production manager who receives information about delivery dates, customer details and Key Performance Indicators (KPI), e.g. the Overall Equipment Effectiveness (OEE) of the train.

Even though the scenarios are fictional and performed on an experimental setup, they show the opportunities of MR to reduce lead times and improve efficiency and quality for different user groups. Under stable circumstances, the AR application can be deployed as a fully equipped monitoring tool on the shop floor. Additional functionalities, for example alarms and warnings, can easily be added.

4. SCADA

In section 1, AV was situated on the right side of the RV Continuum. Milgram et al. (1994) define AV as completely graphical display environments to which some amount of (video or texture mapped) 'reality' has been added. The use of brackets in the definition is not detailed by the authors, but it is clear that some form of reality must be added to augment the virtual world. From this perspective, SCADA systems show characteristics of AV systems since graphical displays are augmented with real world information captured through sensors in the physical set-up. However, graphical SCADA displays remain often basic and will mostly show an abstract and schematic view of the reality. In this case, the user does not have the impression of looking at a virtual world through a window-on-the-world (WoW), a term used by Milgram et al. (1994) to describe monitor-based systems.

In this work, the purpose is to enhance the SCADA visualization in such a way that the user experiences it to be a virtual copy of the real world. This way the system can, not only by definition, but also in essence be considered as AV. The first step towards this goal, consists of using the right software tool. Different parameters have to be fulfilled such as: 1) 3D rendering platform, 2) real-time interface with PLC and 3) other communication interfaces. These characteristics are found in the software Experior which is used for VC applications as mentioned in Section 1.

VC works by replacing the physical set-up by a virtual model that emulates the behavior of the automated system. Based on game engine technology, forces like gravity can act upon the elements in the model. By interfacing the virtual model with a PLC, it is possible to test the control software through simulation before the real system is realized (Hoffmann et al. (2010)). Besides the 3D visualization tool and the PLC interface which make up the core functionalities of VC software, Experior also 1) provides extended libraries for 3D building blocks of logistic systems, 2) offers the possibility to program custom functionalities and 3) integrates different communication protocols whether industrial (e.g. Siemens S7 functions, Beckhoff ADS, Modbus, etc.) or non-deterministic (e.g.

TCP/IP). Fig. 7 shows the virtual copy of the set-up in the Experior GUI. The user can change the viewpoint as he wishes, zoom in on particular parts of the set-up and manipulate objects if necessary.
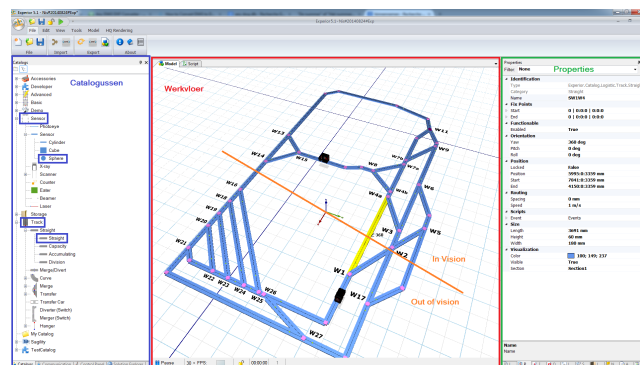

Fig. 7. Experior

The second step in order to duplicate the real process in the virtual world created in Experior, is to know the position of the trains at all times. This is realized by the tracking algorithm in vision which sends the coordinates of the tracked objects at a rate of 30 fps. The positions are processed in Experior and the trains move accordingly in the display. However, the set-up is not completely covered by the camera. The part in Fig. 7 above the orange line lays in the camera's view, while beneath the line the process can only be monitored through sensory feedback. The result above the line is a virtual world which replicates the behavior of the trains as in the real world. The user can quickly evaluate the state of the different objects such as their speed or blocked trains on the tracks. Below the line, the trains jump visually from one sensor to the other as no other information is available. The impression of a virtual world mimicking the real world disappears and the user has less information resulting in a higher cognitive effort to grasp the state of the process.

5. CONCLUSION

By creating a functional AR monitoring tool and enhancing traditional SCADA functionalities with AV, a complete demo has been realized in order to expose the potential benefits of integration between MR and SCADA systems. The focus is set on the end result and to achieve this, proven technology has been used such as a static camera, monitor based displays and marker based recognition of the real world. It is clear that the practical relevance of this work would further increase if the developed concepts were to be exported to mobile devices, e.g. tablets and smart phones. The hardware capabilities of mobile devices have grown rapidly the past years and the next generation will most likely speed up the development and use of AR applications. An example is Project Tango from Google© which is a mobile device in development specifically designed and equipped to understand space and motion.

But the ultimate goal is to directly enhance the view of the operator working in the production hall with minimal inconvenience of hardware. The enhancement of the direct view is actually realized through HMD's of which the practical use is not yet commonly accepted. Future hope

lies in compact glasses that would be capable to integrate the technology to support AR enhancement. This way, each user group would receive specific virtual information to assist in daily operations and to monitor the production process. Integrated cameras within the glasses could also be used as sensory input to enhance SCADA applications and thereby increase the virtual reality experience of the SCADA system.

Besides the hardware, there are other challenges to tackle when mobile devices are in play. Most of them are related to computer vision techniques such as markerless based recognition of the environment, dynamic registration and real-time processing. To the best of our knowledge, no killer application exists at this time that is able to handle these restrictions. This does not bring down the potential benefits of MR, but it shows that much work remains. Companies will also need highly integrated IT networks to exchange data through all layers of the company and to maintain databases of CAD models up to date.

As technology and research advances, new developments will be tested on the set-up in the future. Besides experimenting with new hardware and software possibilities, a strong focus will be set on the identification of the beneficial information flows between SCADA/Manufacturing Execution Systems (MES) and the operator and the integration of this information through the hardware.

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