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Digital Manufacturing for Smart Small Satellites Systems

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Abstract

The term Industry 4.0 – manufacturing with exploitation of digital technologies – comprises several challenging topics, among others intuitive machine programming, advanced maintenance-enabling technologies as well as flexible logistics. This paper gives an overview on recent research and development of our institute (Zentrum für Telematik, ZfT) in this field, the results of which are combined in an Industry 4.0 demonstration factory for the assembly of small satellites systems. We present a total of six tools to be used in such advanced manufacturing systems and their individual advantages. Based on our experience with industrial project partners, customers and visitors of our demonstration factory as well as on the evaluations of the jurors of several awards, we give a qualitative estimate of the effort required to port the individual tools to new production environments. Finally, utilizing our in-house expertise in the New-Space and Industry-4.0 sectors, we give an insight into the benefits achievable using digital manufacturing for small satellite assembly.

Keywords: digital manufacturing; demonstrator factory; new space; augmented reality user interfaces; human-robot collaboration; predictive maintenance; telemaintenance; quality of service; mobile robotics; intelligent material flow

1. Introduction

While all satellites are highly complex systems, there is currently an upcoming trend to build them in series. This is especially true for small nano satellites, for which mega constellations of over 1000 satellites are planned. Despite having a common modular satellite bus architecture easing mass production a lot, such satellites often differ regarding

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their payload and infrastructure, giving them a broader range of options to fulfill complex missions. For example, they may be used for earth or space observation, to build virtual telescopes or antennas, to offer satellite-based internet access or to enable specific scientific experiments, each requiring individual adaptions of the satellite's architecture. The ZfT developed several tools which accelerate the strongly needed transformation from manual-built satellites to a modern factory which is based on Industry-4.0 ideas – allowing efficient mass production while still maintaining the required option to allow for quick, individual adaption of the production processes to also handle small batch sizes.

2. Overview

This publication has three main parts. Section 3 presents six innovative tools for adaptive production. These tools have been developed together with industry partners and are being employed in practical use at different companies.

We divide our toolset into two different categories, where the first is concerned with classical, collaborative and mobile robotics. Here, we aim at alleviating the programming of complex production machinery, especially industrial robots. A projection-based Augmented Reality (AR) interface for programming of (Sec. 3.1) and collaboration with (Sec. 3.2) industrial robots was created to allow quick adaption of production programs as well as joint close collaboration, sharing a common work environment. In the field of Mobile Robotics and logistics, a highly dynamic Industry 4.0 production environment requires effective and flexible material flow. Innovative concepts of free navigation were developed to allow automatic adaptation of driverless transport systems to changing production conditions and to substitute rigid track-guided transport systems (Sec. 3.3).

The second category is concerned with aspects of connectivity and data analytics. For telemaintenance (Sec. 3.4), the AMS - Adaptive Management and Security System was developed. It integrates Quality of Service of regulated telemaintenance services between different facility locations. Intelligent bandwidth utilization control between the individual services ensures optimal performance and meets highest security requirements. Based on the same framework we present a tool for offline analysis and optimization of production steps that integrates machinery signals with video feedback (Sec. 3.5). Regarding predictive maintenance, predictive control approaches for interactive telemaintenance of machinery are being employed for Industry 4.0-compliant production and testing of miniature satellites (Sec. 3.6).

Sec. 4 discusses the efforts needed to port the developed tools to distinct working environments, while Sec. 5 shows benefits of combining different adaptive production tools in the context of our *New Space*-compliant small-satellite factory.

3. Six tools for Adaptive Production

3.1. Intuitive robot programming

In modern day production there is currently a trend away from fixed production lines outputting a mass of uniform products towards production of individualized products in small batch sizes. Whereas production lines need to be setup only once, there is now demand for flexible and reconfigurable adaptive production systems [1]. This provides a special challenge when employing complex production machinery like industrial robots: their (re-)programming requires expert knowledge and is a time-consuming process. With this in mind, an Augmented-Reality (AR) interface was developed to facilitate the modification of industrial robot work programs, allowing for the robot to be used rather as an easily modifiable tool than a fixed repetitive production machinery. Hence, faster and adaptive changes to production can be done even by non-expert personnel.

AR refers to enhancing a user's perception of his environment with additional virtual information that appears naturally embedded within it, allowing for a quick understanding of even complex data by simply seeing it appropriately visualized. Thus, AR relieves the user of mental complexity and enables him to perform his work more efficiently [2], [3]. Different forms of realizing these virtual annotations in the environment exist, from monitor-based or hand-held displays up to wearable AR glasses. Here, a projection-based approach was used (Fig. 1a): a data projector is calibrated intrinsically and with respect to the work environment, allowing for projecting virtual annotations directly onto working surfaces, thus enabling the user of the system to see the information in relation to the real workpieces without having to carry additional hardware for the display of AR data and keeping his hands free [4].

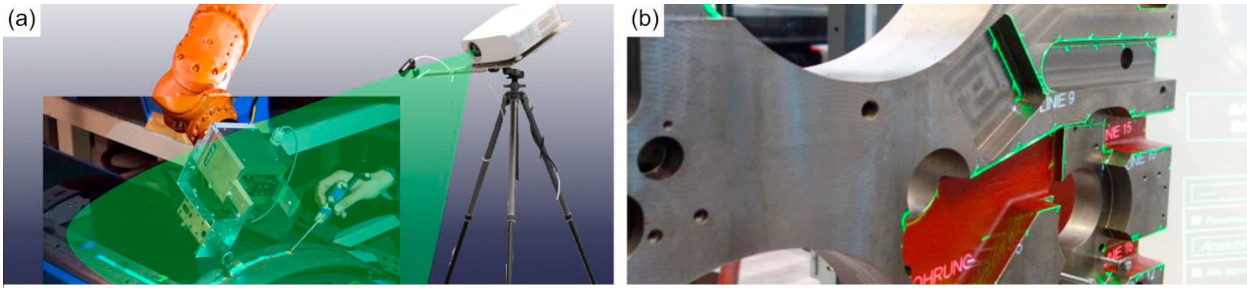

Fig. 1. (a) Intuitive robot programming using projection-based AR

The system developed enables intuitive display of complex robot data like the processing paths of the robot on working surfaces. Examples of such surface-based robot operations are grinding, polishing, welding or drilling. The path is visualized as a series of connected data points that represent the interpolated and linked movements of the robot in contact with the working surface and indicate the currently programmed trajectory of the robot's tool (Fig. 1b). This allows for an easy visual inspection of the processing path: the user can verify whether processing spots are positioned correctly, whether there are deviations from the desired paths, or whether production tolerances of the workpiece are exceeded. Using a six-dimensionally tracked input device, an operator can easily modify or create new working trajectories if required. Using this input device like a 3D drawing pen, users can intuitively draw or drag and drop processing paths on the surface while immediately seeing the resulting trajectory. Color-coding of processing speed, tool currents or applied forces allow the intuitive display of even more data via AR, always in reference to the real underlying work object. The system, described in detail in Ref. [4], allows the modification of complex work programs of industrial robots by orders of magnitude faster than conventional programming interfaces. The intuitive operation with a drawing pen similar to a mouse pointer as a point-and-click device enables even untrained personnel to program complex robots, as the modified working trajectories are automatically translated back to generate functional robot code.

3.2. Human-Robot Collaboration

Another important Industry-4.0 topic is human-robot collaboration (HRC): humans and robots working closely together, sharing a common workspace or even processing the same workpiece at the same time. HRC aims at combining the individual strengths of both partners: accuracy, speed and repeatability of the robot together with the better comprehension of context and production processes of the human, as well as his great adaptability to new situations. HRC has thus the potential to allow for realizing adaptive, fast and easily reconfigurable production systems without requiring specialized personnel, relieving workload from the human collaborator while simultaneously increasing productivity.

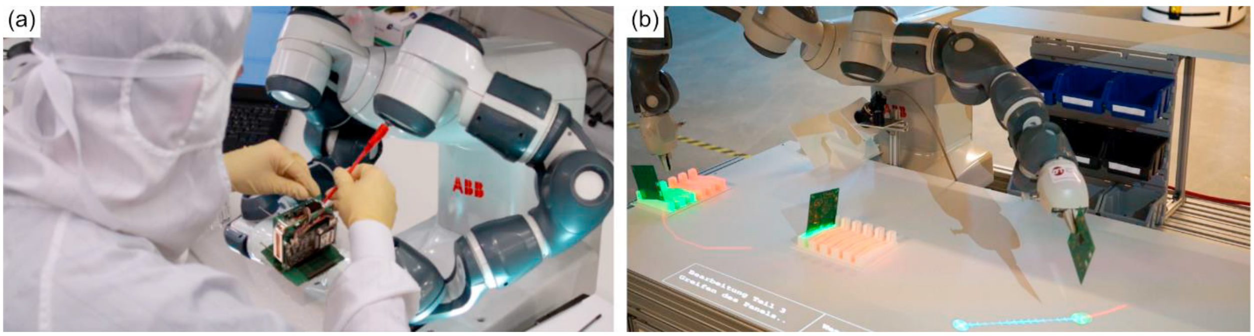

Fig. 2. (a): Collaborative robotics; (b) HRC system at ZfT

In order to realize successful HRC systems, several points have to be addressed. The two most important ones are ensuring the safety of humans in close proximity to robots, and making production steps and the actions of the robot easily understandable to the human to allow for a more comfortable and efficient collaboration.

These points can be addressed with the AR-interface presented in the previous section: enabling projection-based display of data directly in the work surroundings allows for an easy to grasp display of relevant system data: current processing status, inspection and analysis results, sensor data and production steps and actions , as well as text or visual instructions of what the human co-worker is expected to do can be made intuitively visible to the human collaborator, greatly alleviating his understanding of the current production steps and the current and next actions of the robot, while the possible display of complex three-dimensional data like the robot's working trajectory as well as safety sensor or zone data increases the system's safeness while sharing a common workspace. This makes working together with the robot easy even for untrained personnel. Furthermore, the fact that knowledge of production steps is integrated into the HRC system means that it can easily be adapted when changes to the production are required, allowing quick and easy transfer of the system to different working areas and applications.

Besides the AR-interface, while HRC systems can be deployed together with standard industrial robots, additional special safety measures must be taken when employing this type of robot ([5], [6], [7], [8]).The safety aspect of close HRC is also actively addressed by the development of light-weight robots: besides inherently reducing risks by limiting mass, speed and applicable forces, these robots feature integrated force-sensing capabilities and often additional sensors like integrated cameras, making them aware of their surroundings. Thus, they are ideally suited for close collaboration with humans.

At the ZfT, a two-armed ABB Yumi robot was deployed together with the developed AR projection display at a specifically designed HRC workspace. Additionally, the workspace features specific work structures, 3D-printed workpiece holding equipment and robotic grippers as well as a station for vision-based analysis and inspection of workpieces (Fig. 2). This HRC environment was used to develop, test and perform joint small satellite production for ZfT's proprietary small satellite systems.

3.3. Driverless Transport Systems with Autonomous Navigation

Modern adaptive digital production demands an agile production environment: Manufacturing, assembly, integration and test (MAIT) procedures have to be interconnected in a flexible manner. Therefore, material handling – the intralogistics – plays a central role in state-of-the-art production plants. In the past, demands on effectiveness and efficiency led to a huge variety of automated transport systems especially for batch transports. Such systems are usually track guided and use precalculated routes, therefore lacking the dynamic and adaptive features required in Industry-4.0 type production.

Thus, we have developed a software solution for arbitrary types of transport systems, which allows for free, non-track-guided navigation in industrial plants (Fig. 3a). Such a flexible solution requires research and development in the fields of localization, constraint trajectory planning, environment recognition and control. For localization and

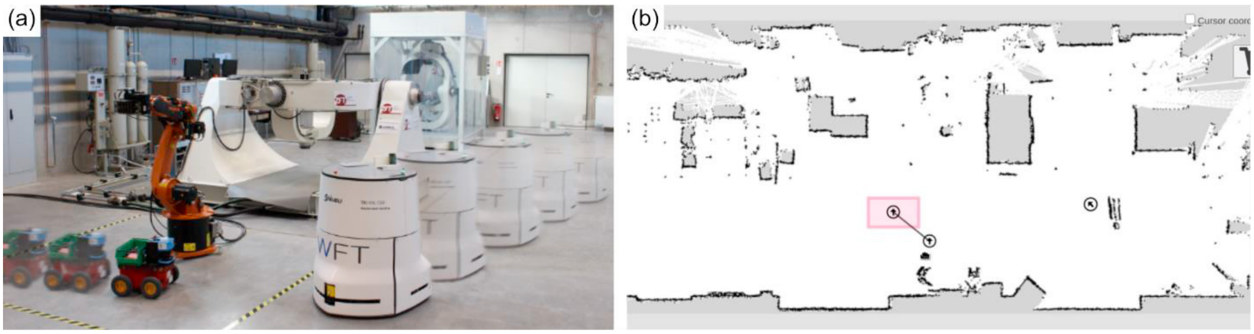

Fig. 3. (a) Flexible material flow in a highly variable production environment; (b) Sensor view of robots.

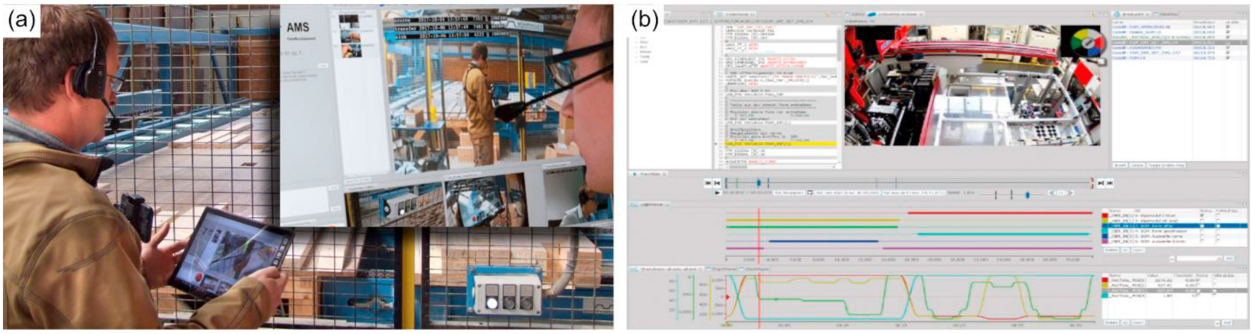

Fig. 4. (a) Robust telemaintenance; (b) Tele-process optimization

environment recognition, typically available sensors such as safety laser range finders (Fig. 3b) and internal odometry are used in combination with adapted state-of-the-art Monte-Carlo- and SLAM-algorithms [9]. Dynamic trajectory planning for mobile systems with kinematic (Ackermann, differential drive) and environmental constraints such as velocity limits, orientation constraints or one-way areas is one of the most complex problems in mobile robotics, as typically no closed-form solution exists. Hence, we developed probabilistic algorithms [10], [11], [12] based on rapidly exploring random trees to overcome the problem for arbitrary robot types.

The developed navigation solution runs locally on each individual robot. Based on current onboard sensor data [13], global environmental information and target poses (position and orientation), a trajectory is calculated which is obstacle free, respects given constraints and is optimized towards user-specified arbitrary criteria, such as energy consumption, path length or operation time. Since the calculated solution is based on up-to-date information and a new plan is calculated for each task, the navigation solution offers an adaptive and dynamic reaction to changes in the environment or task updates.

Mobile platforms equipped with this navigation system are able to map the environment and detect changes. This environmental information is then shared with a central control station, which on the one hand is responsible for receiving and distributing such always up-to-date information among all active mobile transport systems, and on the other hand uses it for situation-aware task deduction, allocation and scheduling. Furthermore, the control station also acts as a link between transport systems and additional production machinery or storage solutions, to allow for flexible interconnection if required.

3.4. Robust Telemaintenance

In a global economy, companies require networked production and add-on services for their products in the field. Developments take place in a control center and are transferred from there to the production sites. To stay competitive, implementation of agile production networks with partners is required. Companies want to participate in the digital economy and rely on add-on services for products in the field as a business model. Appropriate connectivity is based on complex and specific service bundles that have to be transmitted robustly, i.e., securely and in real-time [14].

In the field of remote maintenance, we have many years of experience through market observation and neutral product comparison, and in recent years we have developed our own remote maintenance solution, the "Adaptive Management & Security System" (AMS) [15]. During development, common problems and technical issues have been specifically researched and addressed, such as robustness against bandwidth fluctuations of the transmission path [16], integrated security and a multi-camera system for safe interaction with machines and humans. The tool enables an expert in a telemaintenance center (see inset of Fig. 4a) to safely guide a technician on site through diagnostics and repair tasks (Fig. 4a) while having live access into the machinery’s control system [17]. Moreover, the tool guarantees real-time transmission of the service bundle in less than one second [18], even in intercontinental use while relying exclusively on worldwide available standard hardware (mobile devices, smartphones, tablets, webcams, laptops, virtual servers).

3.5. Tele Process Optimization

Complex production plants are heterogeneously structured and the subsystems are provided by globally distributed suppliers. To optimize such plants and production processes, it is necessary to include this distributed expertise with a specific tool [19]. Due to high rates and data volumes, the machine and sensor data are recorded on the plant itself with access to control systems, field buses and software. Furthermore, additional data, in particular audio-video streams, are recorded for context information. The collected data is synchronized, which is challenging because of different time domains and multi-rate systems. Finally, a comprehensive and consistent data set e.g. of a production cycle is obtained, which can be distributed to experts spread around the world. With the help of this "multi-track industrial data player", which can be considered as an extended, context-aware software debugger, the experts can carry out an in-depth analysis. This takes place asynchronously, in the individual time zones and with possible inclusion of other company resources. Based on this common tool base and preparation phase, the optimization of the process takes place in an efficient tele-collaboration of the experts. The result is then assembled back into the system and can be tested online by means of the telemaintenance tool.

3.6. Predictive Maintenance

Through the use of predictive maintenance, companies expect to avoid unplanned downtime or achieve better planning of their service assignments. There is a hierarchical information situation: In extreme cases, a critical component that needs to be monitored is characterized by the fact that it is expensive and therefore no replacement should be kept in stock. Furthermore, a replacement delivery is not possible at short notice, but the component can fail at any time during its typical lifetime. The replacement of components is also costly, may only be carried out with external specialists and, above all, is associated with a significant production downtime.

This critical component is built into a heterogeneous and complex system, while the entire plant in turn is set up in a production environment and with specific production parameters such as current order situation or ambient temperature.

In order to implement model-based predictive maintenance for such a system, we have developed a Predictive Maintenance System [20]. Its architecture is shown in Fig. 5 and described in detail in Ref. [20] and comprises a transferable process model developed for the industrial partner P&G on the basis of a complex real task. We carry out a bottom-up approach, which tries to integrate as much relevant expert knowledge as possible into the model-based predictions. Investigations of a data analysis without exploitation of previous knowledge were undertaken independently [21].

The first stage of the Predictive Maintenance System is establishing the connection to machine and sensor data like controls, software, field buses, additional hardware and time synchronization, as already described in Sec. 3.5. In the second stage, data quality is ensured while in the third stage, suitable analysis methods such as signal models, physical models, state machines or vibration analysis are applied to the data. For each method (M_1 - M_N in Fig. 5) the characterization of the nominal state is done as so-called *fingerprints*. Health indicators derived from the methods create comparability of several plants and thus enlarge the sample. In the last stage of the Predictive Maintenance

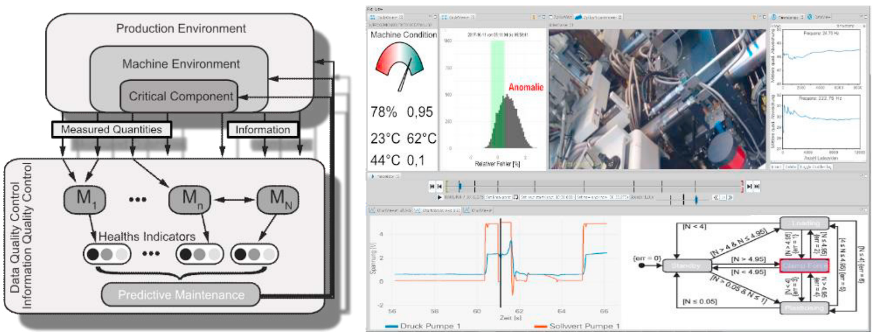

Fig. 5. Predictive maintenance system architecture and dashboard

System, the health indicators are summarized and their development over time is monitored for the best possible prediction horizon.

4. Tool Portability

After presenting the individual tools, this section aims at giving an indication of how much effort is needed to port them to specific working applications. Companies have a need for Industry 4.0 innovations to be rapidly and pragmatically transformed into commercially viable solutions [22]. While the tools themselves are of course already fully functional, they always need to be adapted when employing them in practical applications at different companies for specific tasks. These modifications should be possible with as little effort as possible; however, the effort will inherently depend on the specific application.

The assessment of the porting effort, as summarized in Table 1, is based on four sources: Project partners, client orders, delegations of industry visiting the ZFT-I4.0 Test Center and awards, where an evaluation of contribution and transferability to industry was part of the juror's decision. The individual assessments are explained in more detail in the following subsections. Please note, that these assessments are based solely on our own experience within more than a decade of research in the field. Due to the heteronomy of the individual tools, the specific tasks and target environment for which each tool is ported to and used in as well as the companies' individual sector and culture, only a qualitative assessment is possible.

4.1. Intuitive Robot Programming

Regarding the AR support system for industrial robot programming, the core display system remains unchanged for different applications and requires only initial calibration. However, specific working constraints always require modifications: For example, different tools used by industrial robots in their processing tasks typically include individual constraints like angle of contact which need to be considered when the transfer between displayed AR path to robot instructions is made. Also, the workspace envelope, obstacles or specific AR visualizations for different processing tasks always need to be adapted for the final implementation, resulting in a medium to high portability effort for this tool.

Regarding robot interfaces, solutions for Reis Robotics, KUKA, ABB and Fanuc have been developed so that the system can be used with a broad range of robotic hardware. Modifications can first be tested to ensure functionality, adapted as needed and then be executed by the robot. This type of fast robot program modification allows adapting complex robot work programs quickly and easily and always with respect to the real work pieces. It thus presents a

Table 1. Qualitative evaluation of the porting effort

Tool	Porting effort	Evaluation/Assessment Sources			
		Project partners	Costumer orders	Industry delegations	Awards
Intuitive robot programming	**medium**	Reis Robotics, KUKA, Koenig & Bauer	Schumann Holz	Yes	Telematik Award 2020
Human-robot collaboration	**medium**	OHB System, Von Hoerner & Sulger, Telespazio VEGA	Heraeus	Yes	Airbus Defense & Space Challenge 2017
DTS with autonomous navigation	**medium**	WFT, Wellhöfer	port automator (confidential)	Yes	Innovationspreis IT 2014 & 2015
Robust telemaintenance	**low**	Reis Robotics, KUKA, P&G, Brose, Möhringer	Brose, Bosch-Rexroth, Göpfert	Yes	Telematik Award 2018
Tele process optimization	**medium**	Reis Robotics, KUKA, P&G		Yes	Industriepreis 2015 (best of)
Predictive maintenance	**high**	Reis Robotics, KUKA, P&G		Yes	Industriepreis 2015 (best of)

solution to using complex production machinery like industrial robots as easily reconfigurable and adaptive production tools. Practical implementations have been evaluated in the past with industry partners such as Reis Robotics, KUKA and Koenig & Bauer.

4.2. Human-Robot Collaboration

Similarly, the fundamental AR display system remains unchanged in HRI/HRC applications to allow for intuitive display of work instructions and robot actions. Individual visualizations always need to be developed or at least adapted for each new deployment scenario, however. Also, the workspace requires adaptation to individual applications such that it ideally fits to the task to be performed: This includes for example the geometry of workspace setup as well as design and 3D-printing of individual workpiece holders/grippers. As such, while general AR display options are readily available, some specific visualizations might be required for more complex processing steps, resulting in medium customization efforts for the tools in this category.

An implementation example for common assembly of satellite subsystem boards or solar panel assembly is given in [23], demonstrating the potential of using intuitive system data and instruction display even directly on workpieces held by the robot and the flexible reconfiguration of the work environment using specifically designed 3D-printed assembly equipment. Another use case of the presented AR-display was made in the field of (remote) maintenance [24], [25], [26], [27].

4.3. Driverless Transport Systems with Autonomous Navigation

The algorithms for autonomous navigation are mainly independent from the target platform, which means they can easily be adapted for various vehicle types. Necessary interfaces to sensor systems and actuators are usually manufacturer dependent and require a higher effort when porting the navigation solution. If special optimization goals for the planning are required, further adaptations to the algorithm have to be made. Since the navigation software is designed to run on standard PC-hardware, porting the solution to another system requires furthermore the integration of an industrial PC, which is able to receive sensor data (measurements of security laser scanners, velocity and orientation) from the target platform and can command the drive units (or an external driving steering unit).

The control station (Fig. 3b) has been developed for various domains and can be utilized for industrial applications as well as for surveillance [28] and emergency services. Due to the modular design and flexible interfaces novel functions required by new application domains can easily be integrated and coupled with the standard features of the control station, such as the definition of environmental constraints, goal poses and layered maps.

Therefore, the overall effort for porting the navigation solution is estimated to be medium and highly depends on available interfaces and sensors provided by the target system. Even though the developed solution is very flexible, it cannot work out of the box for arbitrary mobile platforms. Currently the navigation solution is implemented for systems of the company Stäubli WFT GmbH, Pioneer Robots (Fig. 3a), the outdoor rover MERLIN™ and a DJI drone system.

Within the context of the proposed satellite production, different mobile platform classes ranging from heavy duty systems to small robots for small component transport cooperate and collaborate within the whole production environment to enable an efficient, safe and flexible interconnection of the different production steps.

4.4. Robust Telemaintenance

The telemaintenance tool can be easily adopted to almost every environment. The core services have no need for modifications to be used in different plant environments as long as expert, technician and machinery (Fig. 4a) can communicate with each other over a single UDP connection. The system can be used with almost all commercial off-the-shelf hardware and camera models that provide a real-time video stream. For encapsulating scenario-specific traffic, some standard connections are already defined and can be used with ease. Overall, the porting effort is very low.

By allowing for a deep integration of our remote maintenance solution into existing IT services of companies [29] we maintain their absolute data sovereignty. This only requires supplying a connectivity service such as local wireless networks that coexist with existing networks, and the execution of tests, like the emulation of transmission paths in terms of possible interferences and available bandwidths. These aspects represent the largest porting efforts of the whole system. In addition, consulting on systems tailored to the application with regard to energy consumption, mobility, connectivity, range of functions or sensor integration is needed. The system is currently used by customers in the automotive, printing and woodworking industries and in our own satellite factory. Our system has won the *Telematik Award* in the category *Networked Production* of the trade journal *Telematik-Markt.de* in 2018.

In the future we expect that the ubiquitous wireless connectivity of the new communication standard *5G* will greatly simplify the efforts currently required to integrate the system into local wireless networks. Moreover, we expect telemaintenance solutions in general to benefit from the announced real-time capabilities of *5G*.

4.5. Tele Process Optimization

Tele process optimization needs to be adjusted to the specific plant in terms of getting the data. Because of the modularity of the system, only the connector module needs to be modified or exchanged. There are already modules available to connect to RSV(I) robots, S7 PLCs, OPC/UA compliant systems and a universal data acquisition board. Additionally, this system can be used from single data sources up to complex plants with need for multiple cameras and data sources. Hence, in most cases a medium porting effort is expected.

The tele-process-optimization tool has already been implemented with the partners KUKA formerly REIS Robotics and P&G. In that case, porting was quite demanding due to the integration of a proprietary communication protocol. Nevertheless, the potential of the solution was demonstrated for a 24/7 production process, where a cycle time reduction of 5% was achieved without increasing system wear. The developments have been awarded with the title *Industriepreis Best of 2015* from the *Huber Verlag für Neue Medien GmbH.*

4.6. Predictive Maintenance

Predictive Maintenance needs to be transferred to both the plant and the process fairly accurately. It is more of a universal toolbox. The modeling part needs to be done for every specific plant, but usage of this domain specific information is one key advantage of this approach. For multiple plants with similar setup, the model can be reused, which can also help to find unexpected differences between the plants. The fingerprinting approach can be used on many plants without tedious implementation. However, some time for data collection is needed to create the fingerprints in the start-up phase. The overall porting effort is thus quite high.

The system was integrated into a working plant, monitoring it continuously over 1.5 years and deriving concrete instructions for action from the various analysis modules to reduce wear and tear of the critical component, i.e., a hydraulic pump. Proof of the concrete prediction horizon could not be provided due to the lack of a break-down event of the component. The Predictive Maintenance System requires a high integration effort to absorb the expert knowledge, but due to its model-based character, it offers the advantage of a direct understanding of failure causes and the influence for a long-term improvement of processes (prescriptive maintenance). When machine-learning models come to use in the methods module (see Fig. 5) the porting efforts may be reduced, however, at the price of reduced traceability. And even for such approaches, personnel have to be equipped with skills that cannot be transferred in short time [30]. Moreover, machine-learning approaches are driven by data, the existence of which is even in 2020 not a matter of course but the introduction of 5G in relation to the *Internet of Things* may give a further boost to data availability.

5. Sat-Factory Benefits

At the ZfT, a modular satellite bus architecture was developed, allowing for flexible integration and production of up to lot size one. During the often scientifically driven production of a mission specific number of small satellites, the tools presented in the previous sections show their full potential and contribute to our Industry 4.0 based satellite factory [23]. We present our satellite production as an example for the productive use of our toolset.

The AR-enabled intuitive programming and collaboration with robots are very well suited for an efficient and flexible satellite system integration. Even an unskilled human collaborator is able to collaborate with the robot quickly, which is particularly valuable in the start-up phase. Later, the system also allows to easily adapt and optimize steps performed by the robot during the ongoing satellite production. This combination of versatility of human workers and the reliability of using a robotic system to avoid production errors by automating production and testing steps supplement each other perfectly during the production of small satellites with their task-specific small deviations in design due to their size limitations. Production steps themselves can also be improved, for example by using the robot as a flexible and intelligent third or fourth hand, while the human worker is able to adapt the current work steps according to the visual guidance of the AR-system.

Autonomous driverless transport systems enable an easily modifiable and adaptable flow of production parts of the satellites through all individually necessary production and test steps. This also works in fast and frequently changing production environments without manual reteaching thus enabling easy setup, re-location and integration of new production stations into the production workflow as required.

Telemaintenance can be used to get immediate support when working on satellite components and complex machines. Additionally, it can be used by the machine manufacturer to update machinery, enabling just-in-time optimizations, especially on very novel or prototype machines used in the context of satellite building. It is reasonable to assume that augmented reality is able to further improve an efficient remote-maintenance session and projector-based AR was rated to be most valuable as compared to handheld and head-mounted displays especially in terms of usability [27] and performance [31]. This holds true in a static setup but in real-life scenarios the combination of still pictures augmented with real-time annotations offers the best balance between flexibility and the need to discuss technical issues in detail.

The optimization tool is used to optimize novel production steps when necessary. Since it does not require a permanent data connection, it can also be used in harsh environments, like thermal vacuum chambers, or during emission tests. Moreover, processes can be analyzed and optimized while production continues. The discussed telemaintenance tool and the optimization tool are based on the same software framework, but are designed for different purposes. While the telemaintenance tool is intended for online use, the optimization tool is designed for offline use. The alternate use of both tools promises a significant gain in information and accelerates the solution of problems.

The predictive maintenance system is monitoring critical equipment on larger timescales, ensuring machines to run permanently at peak performance while lowering the risk of unforeseen downtimes. Moreover, all collected data contribute to the digital shadow of the satellites themselves and help to optimize the overall MAIT process. In the event of predicted damage, physical models easily allow production steps to be adjusted to avoid failure at mission-critical times.

6. Conclusion

This paper reviews our research on six tools for digital manufacturing that collectively support joint human-machine cooperation and facilitate complex production and maintenance processes. An assessment of their transferability to new application areas was presented, showcasing the potential gain in adaptivity of production processes with these digital manufacturing techniques. The successful combination of several tools in an innovative *New Space* environment was demonstrated in an Industry 4.0 based small satellite production system.

All presented tools can be used as standalone applications in different industry scenarios, provided the willingness to put in the necessary porting effort. However, the latter often poses a problem with companies having to balance between keeping track of future trends while still managing their daily business. Projects that are started under pressure to keep up with current trends are often doomed to fail if the business benefits cannot be clearly specified from the beginning [32]. This experience gained from the introduction of Industry 4.0 techniques into companies presented here will be helpful and necessary to be considered when comparable megatrends such as artificial intelligence and autonomous vehicle-based logistics will be introduced into future manufacturing systems.

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