Postprint. Original Publication: Schmitt, Sarah S.; Mohanram, Praveen; Padovani, Roberto; König, Niels; Jung, Sven; Schmitt, Robert H.: Meeting the Requirements of Industrial Production with a Versatile Multi-Sensor Platform Based on 5G Communication: 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications. Piscataway, NJ: IEEE 2020. DOI: https://doi.org/10.1109/PIMRC48278.2020.9217230

Meeting the Requirements of Industrial Production with a Versatile Multi-Sensor Platform Based on 5G Communication

Sarah S. Schmitt
Production Metrology
Fraunhofer Institute for Production Technology (IPT)
Aachen, Germany
https://orcid.org/0000-0001-6593-4152

Praveen Mohanram
Production Metrology
Fraunhofer Institute for Production Technology (IPT)
Aachen, Germany
https://orcid.org/0000-0001-5772-5705

Roberto Padovani
R&D Measuring Systems
MARPOSS S.p.A.
Bentivoglio, Italy
https://orcid.org/0000-0002-5985-6992

Niels König
Production Metrology
Fraunhofer Institute for Production Technology (IPT)
Aachen, Germany
https://orcid.org/0000-0001-9163-8306

Sven Jung
Production Metrology
Fraunhofer Institute for Production Technology (IPT)
Aachen, Germany
sven.jung@ipt.fraunhofer.de

Prof. Robert H. Schmitt
Production Quality and Metrology
Fraunhofer Institute for Production Technology (IPT)
Laboratory for Machine Tools and Production Engineergin WZL
RWTH Aachen University
Aachen, Germany
https://orcid.org/0000-0002-0011-5962

Abstract— **To face the requirements of current and future industry and to push the digitalization of factories, an international consortium in the project 5G-SMART develops a versatile multi-sensor platform communicating via 5G. To achieve an adaptable and flexible system, the embedded device is designed in a modular approach, consisting of a local processing core, integrable field sensors and a 5G modem. This paper covers the concept and design of the elaborated versatile multi-sensor platform and therewith presents a system that overcomes the limitations of current sensor systems and enables an interconnected real-time monitoring for production industry.**

Keywords— sensor systems, process monitoring, 5G communication, edge cloud, digital twin

I. INTRODUCTION

A. Current and future industry

Today the manufacturing sector is undergoing a digital transformation addressing the challenge of mastering more and more demanding processes and increasing efficiency. A fourth industrial revolution has started with the objective of making the vision of highly efficient, connected and flexible Factories-of-the-Future a tangible reality. To further improve efficiency in production and to be able to adapt production to small lot sizes and individualized products, production lines need to be highly integrated and flexible to incorporate dynamic configuration changes without compromising on safety and quality. The need for an all-embracing documentation of the production as a shop floors digital twin comes up stronger than ever [1]. In order to meet such demands, future manufacturing systems will require the extensive implementation of versatile and scalable real-time monitoring of production and processes - a perfect match between sensors, communication and computation modules.

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B. *State of the art*

Sensor systems for industrial processes are already today commonly used to monitor and control manufacturing processes. They are mostly connected using Ethernet or fieldbus protocols over wired connections. Traditional wired solutions often result in limited flexibility, sometimes they are even impractical, with high costs of deployment due to the need of thoughtful planning [1]. Wireless solutions do exist (e.g. Wireless IO-Link™ and WirelessHART®), also in the form of a multi-sensor platform [2], but they need to be optimized for future manufacturing industry concerning their flexibility and sensor diversity. Current multi-sensor platforms focus on certain applications and have limited real-time capability. The authors are unaware of any available platform that is dedicated for industrial purpose concerning sensor-sensitivity, robustness and ingress protection. Actual sensors are usually separated stand-alone systems, where different parts of the process are not interconnected causing additional efforts to route data to centralized computation services, e.g. edge-cloud systems. Besides, such island solutions restrict interoperability between machines, which is needed to coordinate the complete production process chains and to get an extensive documentation for optimization purposes. Point-to-point connections inhibit flexibility and a simple management. Furthermore, in many cases the existing infrastructure is even unable to support the demanded network density and data volumes that arise when such interconnectivity applies to a lot of machines [1]. Finally, well-known wireless standards such as Wi-Fi® or Bluetooth® do not meet reliability requirements, especially not in connection with reproducible latency.

C. *Objective*

A modular design is needed that can be customized for each process and handle diverse types of information and heterogeneous data sources [3]. On top of that, the real-time requirements must still be met. Furthermore, industry will benefit from the ubiquitous availability of a wireless connection, having the potential for universal connectivity without changing transmission media. A sensor system with data analytics and processing in the edge or cloud improves the flexibility and scalability of industrial solutions. It also simplifies maintenance such as software upgrades since software components are not distributed across the factory but rather deployed in a more centralized way. In addition, this will facilitate remote software supervision. Finally, centralized device management and deployment of configuration to the sensor platforms allows for easily assigning measurement parameters to numerous sensors and thus creating sensor networks.

II. CONCEPT OF THE 5G ENABLED VERSATILE MULTI-SENSOR PLATFORM

The wireless 5G versatile multi-sensor platform (MSP) aims to address and solve the aforementioned limitations of current sensor-systems. We envision a fine-grained system of widespread sensors and transducers, whose heterogeneous data is collected, transferred via 5G and aggregated in a local cloud close to the shop-floor, that we call the Factory Cloud.

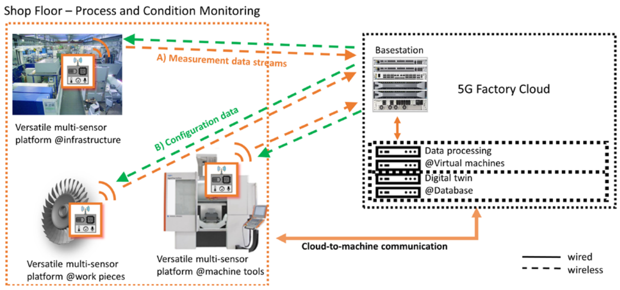

Fig. 1. General concept of the implementation of the versatile mutli-sensor platform

The general concept can be seen in figure 1: on the shop floor, multiple machines and workpieces as well as the infrastructure, are equipped with MSPs and are connected via 5G to the Factory Cloud, where measurement data can be processed and stored. Extracted information can then be fed back as process parameter adjustment or control to the machines. Sensors are tuned and orchestrated in form of configuration data. Many diverse physical quantities can be measured or sensed across a factory, relating to machines, workpieces, and the

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infrastructure as well. Each of those may have different requirements, especially regarding reliability and latency that can potentially be rather challenging. Critical process parameters in machining are for example accelerations or forces, which are an indicator of unforeseen behavior of the workpiece to be machined. Chatter marks or tool deflection may be the result, leading to insufficient quality of final product. In order to instantly react on such incidents, a latency less than 10 ms may be required to adopt the machining parameters. This requirement is typically associated with the URLLC (Ultra Reliable and Low Latency Communication) [4] feature of 5G.

A. Pervasive data sources

For the digital factory to be effective, it has to cover the many different variables affecting the production: machine processes are the most prominent and well-known by the field of machine condition monitoring, but also workpiece of significant value could be equipped with a dedicated multi-sensor unit. Besides that, the factory environment might provide useful insight and be sensorized as well [5]. As a result, these information sources are widespread across the shop floor, generating huge amount of data traffic to the Factory Cloud. One challenge is to integrate all of them for efficient processing and into a digital twin, where the heterogeneous data is fused for analysis [6]. Only 5G can provide the required reliable and scalable network with high device density and the high bandwidth that derives from it.

B. Time synchronization

Since each system generates data based on its own local time reference, data fusion creates another challenge regarding the synchronization of data streams. A coherent timing is mandatory for meaningful analysis of the fused data: 5G is again the game-changer, with specific features being included in the most recent 3GPP Rel-16. [7]

C. Real-time capable platform

Very high link reliability and low latency are mandatory for the safety of the operations and the effectiveness of the monitoring, with the purpose of the highest quality with minimal wastage of resources. A feedback has to be directly provided to the control system of the application for a quick reaction in the milliseconds range, which is needed in order to respond within the cycle time of the machine's numerical control (NC), hence the URLLC [4] features of 5G are the foundations of the solution. To reach ultra-reliable and real-time capable data transmission the whole communication architecture including protocols, interfaces and local edge cloud servers have to be optimized for real time control. For such high requirements it is necessary to already have a real-time capable sensor platform with 5G-backbone structure. Therefore, the platform makes use of embedded systems like microcontrollers or FPGAs in order to achieve a high capacity for signal processing and synchronized data flow across the platform.

D. Centralized device mangement system

In typical dedicated solution, the operating configurations are defined before or at deployment. However, those configurations may need to be updated depending upon the application. Measurement parameters and signal processing algorithms can be tuned, operation such as enabling or disabling sensors, and security patches can be applied. These kinds of changes can be carried out on single devices or even on groups of devices. Centralized management of remote devices - including reconfiguration and software or firmware updates - is enabled by the IP-connectivity of 5G devices, and together they allow for true flexibility and mobility of the sensors.

III. IMPLEMENTATION OF THE PLATFORM

The concept is implemented by a three-step approach: Digitalize, Delegate, Dispatch.

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Digitalize

Each physical quantity of interest is converted into a digital information *as soon as possible*, meaning that only the minimum conditioning and pre-processing has to be performed close, or within, the sensors. Examples of such pre-processing are filtering or FFT of raw data into index values that bring the information of interest in fewer bytes. On one side, the transmission of raw data allows for flexible processing in the Factory Cloud, but it increases the energy consumption due to the large amount of transmitted data; on the other side, local pre-processing may improve such energy figure, but it may also affect the total latency. These trade-offs are heavily dependent on the specific sensors and application and they should be left as a tunable configuration.

Delegate

The data stream is delivered to the Factory Cloud, delegating as much processing as possible to this local computing capacity, thereby exploiting the full flexibility and scalability of software services. The Factory Cloud must be close enough to the data sources, so that the latency requirements can be met, for example by means of non-public network feature of 5G-NR [8, 9], as well as network slicing [10].

Dispatch

The Factory Cloud is not an end-point of the information flow, but a cross section from which feedback is generated to the shop floor, aside the digital twin. This return path combines both hard real-time low-latency signals for the machine, and the control and configuration ones, whose timing requirements are less stringent.

As result from this concept, the multi-sensor platform is a versatile solution that enables the collection of any relevant information by means of three core components, with a modular approach:

1. an industrial-grade embedded device that interfaces to sensors and transducers
2. a 5G link exploiting URLLC features
3. a Factory Cloud

A. Embedded device

The modular approach presented as in figure 2 is followed also in the hardware of the embedded device, which is designed to be re-used in the many different implementations that are required by the physical (acceleration, torque, temperature, etc.) or non-physical (trigger, events, etc.) quantities of interest.

The same local processing core and 5G modem are utilized for every specific implementation, so that a significant hardware and firmware design effort can be re-used. The local processing core is intended to be updated and configured for operation from the Factory Cloud, based on the actual sensors that are connected to it. Suitable sensors are for example IEPE vibration sensor KS95C100 from MMF with a conditioning module or K Type Thermocouple with RTD converter (MAX31865).

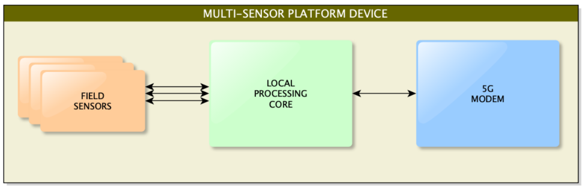

Fig. 2. Modular architecture of the MSP device

The implementation can be either a single, compact, and fully integrated device including the sensors, or a mechanically modular device. A rugged external connection can be provided for the sensors, both for installation needs and for economic or management opportunity, and even for the 5G modem. The RG500Q Module from Queltec or a 5G router from WNC are 5G modems that are expected to be commercially available soon.

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B. *Mechanical design*

Each unit is a rugged water-proof device that can be confidently operated in a workshop environment, potentially in presence of chips from the metal cutting, as well as the chemicals of the lubricants. For robustness and compactness of the unit an integrated antenna is preferred; the challenge is then the electromagnetic shielding of a metal box: a careful design with tempered glass or technical plastics is adopted in this case.

C. *Local processing core*

In order to satisfy the requirements of compactness and low energy consumption, while being powerful and versatile enough to support a wide range of sensors and configurations, the local processing core has to be a high-performance embedded microcontroller. Integrated communication peripherals are mandatory, including serial interface buses (e.g. SPI or I2C) for the sensors, and USB or Ethernet for connecting to the 5G modem. A modern Cortex-M class ARM core is a good choice balancing the processing capabilities with energy saving operating modes.

D. *Field sensors interface*

In the 3-Ds approach the sensors have to be digital sub-blocks, therefore they are either digital transducers (e.g. counters, triggers) or they are based on digital integrated semiconductors (e.g. MEMS accelerometers with integrated analog to digital conversion). They may also integrate both an analog signal chain and the analog to digital conversion.

The modularity of the field sensors is then obtained by using for each of them the same interface for data, power and control paths. The bus will be shared by all the sensors, whose coordination is in charge of the local processing core firmware. The firmware and the sensors are designed to provide an auto-discovery functionality, so that the embedded device is capable of exposing itself and its capabilities to the platform. In any implementation of this design a combination of internal and external sensors can be mixed. The versatility of the multi-sensor platform supports a deep level of diagnostics, therefore environmental sensors could be advantageously integrated in the embedded device: an internal temperature and humidity sensors can detect or prevent failures like overheating or leakage and intrusion of liquids as well as anomalies like drifts in the measured values. Battery monitoring will also enable predictive maintenance of the platform itself.

E. *Power supply*

The power supply of such embedded device is a critical design challenge, because of many competing constraints, like the compactness of the unit and the energy requirements of both the sensors and the 5G link. However, a third constraint is related to the type and convenience of the energy source. A lithium battery is the standard choice due to its superior energy density per volume, but the method and frequency of recharging (or swapping, in case of primary batteries) has an impact on the customers' acceptance. The platform has to be convenient in every aspect, including its periodic maintenance.

There is not a single correct choice between primary or secondary batteries. A primary battery poses a further mechanical design challenge in order to provide an opening for the user to swap the depleted batteries, while guaranteeing to be consistently water-proof in spite of repeated openings. It also has to last long enough so that its replacement will not be perceived as a relevant time-consuming burden on the operators. It is therefore only suitable to low power and low data rate sensors. A secondary battery does not need to be removed, but it must be periodically charged. From a mechanical design point of view, a power connection is required, either a traditional contact connection, or a wireless power one. The first one is simpler, but subject to wear and need for IP-grade connectors. The second one is long-lasting, but it requires another electromagnetic opening made of technical plastic or glass. From a product design perspective, both variants of the embedded device would coexist, with either disposable or rechargeable batteries, each one being suitable for different specific applications.

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F. 5G modem

The 5G modem is expected to be integrated in the embedded device in most cases. Nevertheless, the design is open to an external connection for it as well (see Fig. 2). This might be needed in conditions that are incompatible with electromagnetic propagation or antenna operation requirements. High speed digital communication buses like a USB or Ethernet are used to link 5G modem and local processing core. The 5G modem will also provide the required time synchronization [5] across the whole multi-sensor platform. Not every sensor requires an absolute time information and may or may not need to be tightly synchronized with other sensors or the machine, but the platform has to support this feature, so that the information streams can be correlated during the processing in the Factory Cloud by time-stamping [11].

G. 5G link

The 5G link is the enabler of the multi-sensor platform and it is fundamental to its versatility. In contrast to commonly used standard or proprietary industrial wireless protocols, 5G is a cellular communication system which offers different deployment options ranging from completely public networks that requires no on premise installation at all, up to non-public, isolated network deployments requiring a complete, self-sufficient infrastructure. In particular, a major advantage of a 5G link is that it uniformly integrates into a wide area network and does not rely on point-to-point connections like e.g. Bluetooth®. The customer benefits of both a simpler and faster initial deployment, and a reduced maintenance effort.

5G URLLC features overcome the previous cellular technologies limitations in terms of reliability and latency [4], which were the main drivers for the implementation of proprietary and short-range wireless links. Only 5G can meet the end-to-end latency requirements in the order of a few milliseconds, with reliability of 99.999% [5]. Additionally, it offers capability of connecting a larger number of devices compared to existing technologies.

The 5G link is bi-directional, therefore the versatility is two-fold. On one hand, by aggregating the information coming from any source in the manufacturing plant, newer and deeper processing can be performed to optimize the productivity from many points of view like quality of produced parts, efficiency of machinery, prediction of machine condition, material and stock management, and many more. On the other hand, from a central coordinating position each sensor can be reached, in order to tune or adapt its configuration to the ever-changing production conditions. This will reduce the need of production engineering personnel to go around a factory in order to implement improvements at the single workpiece or single machine level.

H. Factory Cloud

The MSP reaches its versatility by shifting tasks from the embedded devices towards high performance processing servers, which are located close to the shop floor so that the latency requirements can be met. Concerning data processing, there is a trade-off between energy consumption on the MSP and task overload in the Factory Cloud. The sensor modules are required to be as small as possible with very low energy consumption, therefore data processing should be limited. This would also improve the battery runtime of the MSP. On the other side, offloading too much of the computation to the Factory Cloud could overload the servers. By including efficient pre-processing, a limited amount of data needs to be transmitted and processed. The Factory Cloud then fills the gap of resources for efficient and scalable data analysis at production site level. In particular, a low latency and high reliability return path is enabled by its privileged location within the factory premises, allowing for a direct interaction and control of the machines. In addition, this delegation strategy reduces the energy consumption of the devices. In combination with the fast track between sensors and machines, the Factory Cloud processing realizes the ideas of a truly digital factory, being the central hub for digital twins, securing high-performance data storage and predictive maintenance.

IV. SUMMARY

The versatile multi-sensor platform (MSP) is a powerful tool for high performance process and workpiece monitoring, allowing resilience for a flexible production environment. It overcomes the limitations of current sensor systems by providing connectivity of different sources in the production equipment and it facilitates the routing of data to computation services. With its modular design it can be customized for each process and handles diverse types of information and heterogeneous data sources. Besides handling pervasive data sources, the MSP features the time synchronization of data and a centralized management system with industrial-grade performances as real-time and reliability. The embedded device has a modular design to achieve an adaptable and flexible system, consisting of a local processing core, interchangeable field sensors and a 5G modem. The MSP treats data in a three-step approach: digitalization, delegation and dispatch: the measured quantities are digitalized close to the sources and delivered to the Factory Cloud, where the processing is delegated to feed the Digital Factory and to dispatch control information back to the shop floor. It is a solution that combines the embedded devices on the shop floor, communication via 5G to profit from the URLLC features, and the local computation capabilities in form of a Factory Cloud. The MSP platform can cover and connect a large number of machines across the shop floor and even whole production sites, allowing for a real digital twin and extensive process monitoring.

ACKNOWLEDGMENT

“This work has been performed in the framework of the H2020 project 5G-SMART co-funded by the EU. The authors would like to acknowledge the contributions of their colleagues. This information reflects the consortium’s view, but the consortium is not liable for any use that may be made of the information contained therein.” Parts of the concepts have been derived from the project "5GSensPRO - 5G-based sensor technology for monitoring in production", funded by the European Regional Development Fund (ERDF) 2014-2020 (funding code: ERDF 0801636).

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