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5G-Based Multi-Sensor Platform for Monitoring of Workpieces and Machines: Prototype Hardware Design and Firmware

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Citation: Mohanram, P.; Passarella, A.; Zattoni, E.; Padovani, R.; König, N.; Schmitt, R.H. 5G-Based Multi-Sensor Platform for Monitoring of Workpieces and Machines: Prototype Hardware Design and Firmware. *Electronics* **2022**, *11*, 1619. https://doi.org/10.3390/electronics11101619

Academic Editor: Antonio J. Marques Cardoso

Received: 14 April 2022
Accepted: 17 May 2022
Published: 19 May 2022

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Abstract: In this paper, we introduce a 5G-based multi-sensor platform for monitoring workpieces and machines. The prototype is realized within the EU-funded 5G-SMART project, which aims to enable smart manufacturing through 5G, demonstrating and validating new generation network technology in industrial processes. There are already state-of-the-art solutions, but with drawbacks such as limited flexibility, brief real-time capability, and sensors aimed at single applications. The 5G-SMART multi-sensor platform is designed to overcome these points and meet the requirements of Industry 4.0. The device is equipped with different sensors to acquire multiple data from workpieces and machines of the shop floor, wirelessly connected by 5G to the factory cloud. A hardware design description of the prototype is provided, focusing on the electronic components and their interaction with the microcontroller. Verification of the correct functioning of the board is given, with a basic library for the main peripherals used as a basis for the final firmware.

Keywords: industrial 5G devices; 5G use cases in smart production; smart manufacturing; smart sensor network; Industry 4.0; multi-sensor platform

1. Introduction

Industrial manufacturing interfaces with the introduction of 5G networks in production. The realization of smart manufacturing is now possible thanks to the unique features of the new-generation network technology: low latency, extremely high reliability, scalability, and predictability. These features allow for real-time control of machinery and devices on factory shop floors. Sensors are directly integrated into them and can send a large amount of data in a short time, achieving the Industry 4.0 objectives. From a telecommunication point of view, great strides have been made in new network technology. The goal is to provide new 5G-enabled sensors that can be used for production purposes.

In state-of-the-art, industrial sensors still have significant limitations. The connections are still based on cables, limiting their flexibility. Wireless solutions are already present, e.g., Wi-Fi® or Bluetooth®, but cannot meet the strict specifications of latency and reliability. The solution proposed in this paper is a multi-sensor platform (MSP). The prototype consists of a modular system for monitoring workpieces and machinery of the shop floor in a factory.

At the industrial production level, there are already sensor platforms, but requirements such as latency, reliability, and versatility are not met. Several papers have been published presenting MSP solutions. In [1], the XDK sensor from Bosch is described; Ref. [2] describes the EU project for MSP for smart building management solutions. A Zigbee-enabled wireless sensor platform is described in [3], which is limited by data rate and range; Ref. [4]

describes the prototype of a wireless hosting sensors device for water monitoring. Other wireless sensor platforms discussed [5,6] use Bluetooth or Wi-Fi to transfer process data from sensors. These wireless standards are limited by latency, range, and throughput, which, for many industrial applications, are of high priority. The new 5G standard meets the requirements of versatility and latency and enables the use of wireless sensors for industrial monitoring applications. "Meeting the Requirements of Industrial Production with a Versatile Multi-Sensor Platform Based on 5G Communication" [7] describes the design of an MSP with 5G to meet the industrial standard. The paper explains the steps to realize an industrial-grade sensor platform and describes the technical architecture in depth. It includes the hardware used, the software to realize the real-time data acquisition and data transmission with the 5G. The proposed MSP integrates various types of sensors, both internal and external, to send data in real time to the factory cloud [8].

The MSP is designed as part of the European Horizon 2020 project 5G-SMART. The project's objective is to demonstrate, evaluate and validate 5G in industrial processes and identify valuable business models. The main applications are robotics, automation production, and smart manufacturing [9]. The three main sites where prototypes and new technologies are tested are: Fraunhofer IPT in Aachen, which represents a shop floor with machining centers; Ericsson Smart Factory in Kista, where the factory of the future is being planned; and the Bosch Semiconductor Factory in Reutlingen, where a real-world semiconductor factory is tested [10].

With this paper, we aim to describe the main activities behind the realization of the MSP prototype. Section 2 reports the materials and methods used. Layout and use cases of the MSP within the Aachen trial site are provided in Section 3. Section 4 describes the hardware design of the MSP, analyzing the elements of the system architecture. From the hardware components, a basic library for the final firmware is presented in Section 5. Section 6 describes the MSP software architecture. Conclusions and future research are given in Section 7.

2. Materials and Methods

The design process was supported by the creation of a basic library of the individual peripherals for the final firmware, realizing a hardware abstraction level. The datasheets of the hardware components were analyzed and reported. Tests for the verification of the board are provided, and the main microprocessor interconnects and I/O interfaces are described. The software architecture is analyzed and described.

The compiled toolchain for hardware component evaluation is the STMicroelectronics™ STM32CubeIDE [11]. This platform provided the code configuration of the STM32 microcontrollers utilized for development and debugging based on C/C++ programming language.

3. Multi-Sensor Platform: Layout and Use Cases

The MSP prototype is shown in Figure 1 [12]. The prototype has dimensions of 100 mm × 100 mm, and the housing is realized in blackened ionized aluminum.

Figure 1. MSP prototype.

The lateral section with three circular connectors for the external sensors interfaces is provided on the left. The top side of the device shows the printed 5G-SMART logo. In the aperture of the housing, the board with the main electronic components is visible. The aperture will be covered with a plastic panel, under which a flat radio antenna is attached to prevent signal disturbances. An accelerometer is mounted on an integrated support to detect and measure device vibrations without distortion. The 6800 mAh lithium-ion battery is placed in the lower part of the board, with dimensions of 90 mm × 60 mm. On the right, the circular connector to the external ancillary communication module is provided.

The MSP use cases tested at the Aachen shop floor trial site are highlighted in Figure 2 [13].

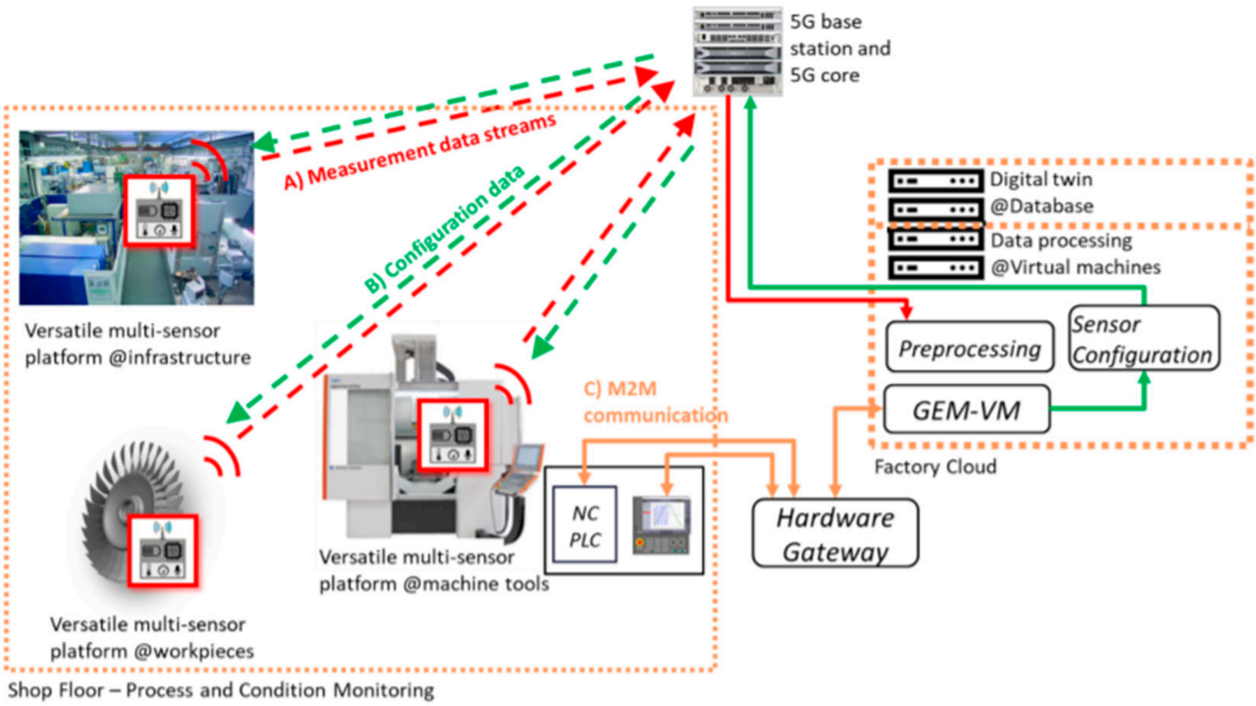

Figure 2. MSP use cases.

The MSP device will be mainly used in the following manufacturing applications:

- Condition monitoring of machine tools used in milling machines, grinding machines, and electro-erosion machines;
- Condition monitoring of workpieces;
- Infrastructure monitoring, such as for heatmap of labs and shop floors.

The measured data are collected by sensors and processed in real time. The measurement data stream (A) is the path through which the information is transferred from the sensors to the network. The information reaches the 5G base station and the 5G core. Once data are processed, they are sent to the factory cloud. Parallel computing and virtualization are the basis for big data processing, enabling virtual machines and digital twins of physical devices. Data processing pipelines are realized through Kubernetes clusters. Sensor data are transferred through the 5G network and processed inside the clusters [13].

The 5G network ensures the interaction between sensors, machines, and workpieces. Configuration data are sent in downlink from the factory cloud via 5G to the MSP sensors (B) for MSP measurement customization for the different applications.

The MARPOSS ARTIS Genior™ modular monitoring system (GEM-VM) [14] is a virtualized monitoring system applied within the communication stream of the MSP. It is mainly applied for predictive maintenance purposes. Data are processed by the software platform and sent to the cloud for data analytics. In the cloud predictive algorithms based on mathematical models identify variations from the optimal values. This reduces latency before a failure happens, saving time and cost to extend machinery lifetime and improve performance. Thanks to sensor monitoring, the MSP applications benefit from the presence of GEM-VM; repairs and replacements are carried out only when strictly necessary.

This technology is based on spectral analysis of the vibration signal. The vibration condition is always present in the machinery; therefore, its monitoring allows for detection of problems in a predictive way, avoiding breakdowns. The GEM-VM receives process signals from machine tools and performs fast Fourier transform (FFT), power spectral density (PSD), and noise spectral density (NSD) analysis. Acceleration, gravity, temperature, and velocity signals are analyzed in time and frequency. Constant vibration and temperature monitoring allows a quick stop signal to be sent within 1 ms of receiving a discordant value in order to prevent damage.

The machine-to-machine (M2M) communication (C) is the wired connection that enables a data stream between the factory cloud and the numerical control unit (NCU) in machinery. This is achieved through a hardware gateway installed in the form of a Genior™ modular central processing unit (CPU) via PROFINET. Feedback control is provided by transferring the information from the factory cloud to the physical machine. Programmable logic controllers (PLCs) and NCUs installed in the machinery can communicate with the gateway to receive the outputs of process and condition monitoring.

4. Hardware Architecture

As described in Section 1, the MSP is based on a modular architecture. Internal sensors and a local processing core are integrated into the mainboard. Three sensors are externally connected. An external ancillary module is provided for 5G communication.

In this section, we define the different core components of the board. The embedded components of the architecture system and the final hardware design of the prototype are highlighted in Figure 3.

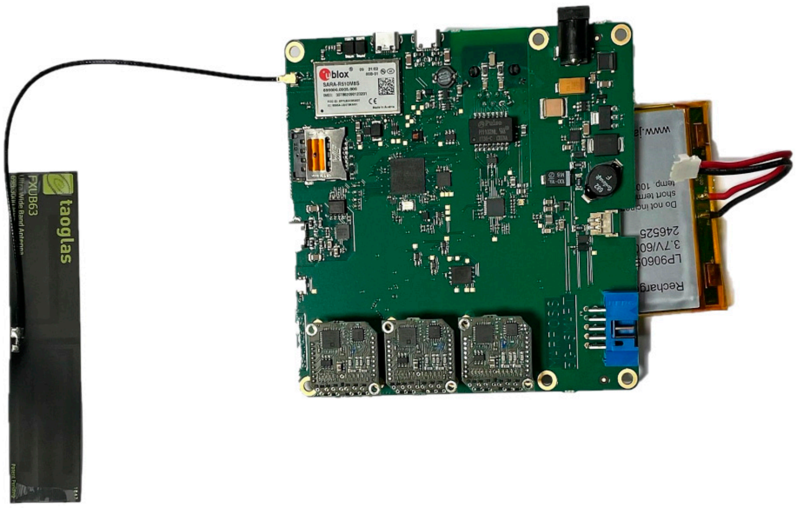

Figure 3. MSP hardware prototype.

4.1. The Microcontroller

The microcontroller is the *STMicroelectronics™ STM32F429IIH* (Geneve, Switzerland), which belongs to the ARM-Cortex™-M family and represents a tradeoff between processing power and power consumption. Therefore, the selection of the core was influenced by the requirements of compactness and low energy consumption and by the adopted peripherals for the sensors' data transmission and reception. It is a 32 bit ARM Cortex™ for microcontroller applications equipped with 176 pins and high-speed memories [15].

Low power of the embedded microprocessor is essential for a wireless device to increase battery lifetime, reduce the device size, and simplify the power supply.

The voltage domain range for the battery is [1.65 V ÷ 3.6 V], whereas the power supply range is [1.7 V ÷ 3.6 V] [16,17].

4.2. 5G Module Interface and Time Synchronization

The connection between the 5G module and the microcontroller is external. Thus, it requires specific design attention concerning water-proof connections needed for machine-integrated applications in connection with coolant. Time synchronization is essential for the MSP, as the ultimate goal is to aggregate data within the trial site in real time. Because the synchronization features of 5G were still under development at the time of the project, the chosen component is the *u-blox*™ *SARA-R5* (Thalwil, Switzerland), a 4G LTE component that is a module for Industrial Internet of Things (IIoT) solutions due to its characteristics such as security, wide coverage, and compatibility with other *u-blox*™ families. Moreover, it has low power consumption, long battery life, and low costs.

The serial communication interfaces of the module are universal asynchronous receiver-transmitter (UART) and USB. A microUSB-B interface is needed to implement the device's diagnostics. A network indicator with a green LED allows for verification of the network status. A micro-SIM connector links the *u-blox*™ *SARA-R5* with the external SIM.

An external DC power supply is required for the radio module. In order to minimize the system power consumption when it is not used, an ultra-low resistance load switch is inserted inside the board [18].

For connectivity to the 5G module, a standard Ethernet interface and USB are provided. The Ethernet is preferred, as it has less IP overhead as compared to the USB. The 5G module used also has an Ethernet interface to transfer data between the controller and the module.

The main elements of the Ethernet interface are Ethernet physical layer transceiver, signal transformer, and circuit protection.

- The Ethernet physical layer transceiver is a *Micrel Inc.*® *KSZ8081RNB* (San Jose, CA, USA). The role of this device is to provide a transceiver for data transfer and reception and to enable the Reduced Media Independent Interface™ (RMII) needed to reduce the number of data interfaces. It has a single power supply of 3.3 V. The connection between the Ethernet physical layer transceiver and the external ancillary module is provided by a connector. A magnetic interface is needed to realize the connection [19].
- The signal transformer is a *Pulse Electronics*® *H1102* (San Diego, CA, USA), which is needed to interface the ancillary module to the Ethernet physical layer transceiver using a magnetic surface port [20].
- The *STMicroelectronics*™ *USBLC64* implements a protection circuit to prevent malfunctions of the device in the case of electrostatic discharges. It is realized by connecting the data transceiver with the ESD suppressor [21].

The main components of the USB interface side are a USB-to-UART bridge controller, a digital isolator, and two micro-USB connectors, which make the microprocessor behave like a host. A step-up converter is needed to generate the 5 V for the microprocessor USB peripheral.

- The USB-to-UART bridge controller is a *SiliconLabs*® *CP2102N* (Austin, TX, USA). The component manages the data exchange between the USB and the UART peripherals and integrates the connection with the microprocessor. The transmission data rate is up to 3 Mbaud, and the average operating current is 9.5 mA [22].
- The digital isolator is a *Texas Instruments*™ *ISO7221C* (Dallas, TX, USA). The dual-channel isolator implements the translation of voltage during data transmission and reception. High voltages are filtered [23].

4.3. Onboard Sensors and Memories

For integrating environmental and process monitoring sensors, three onboard sensors were selected: one accelerometer, one internal temperature and humidity sensor, and one gyroscope.

- The accelerometer is a *STMicroelectronics*™ *LIS2DH12*. The role of this component is to measure the acceleration concerning the orthogonal axes on a scale of 2 g, 4 g, 8 g, or 16 g. The digital motion sensor has an acceleration range of $[1\ \text{Hz} \div 5.3\ \text{kHz}]$ and a supply voltage range of [1.71 V ÷ 3.6 V]. The serial communication interface is the serial peripheral interface (SPI) [24].

- The internal temperature and humidity sensor is a *Texas Instruments™ HDC2022*. The role of this sensor is to monitor the overheating or entry of liquids into the device. This component has a very low power consumption, with an average current consumption of 50 nA. The serial communication interface is the inter-integrated circuit (I2C); the microprocessor behaves as a master, whereas the sensor acts as the slave. When the accelerometer is in one-shot mode, the measurement starts. Then, the default sleep mode is restored. The device has periodical wakeups from the default mode, in which it works in conversion mode. Finally, when a measurement is triggered, the device performs operations in measurement mode. To verify the state of data after measurement conversions, information related to the condition of the sensoris sent to the microprocessor [25].
- The gyroscope is a *STMicroelectronics™ A3G4250D*. The role of this component is to monitor the device's orientation in workpiece monitoring applications to prevent damage. A second-order low-pass filter is utilized to limit noise. Very low power consumption is one of the main characteristics of this device. The serial communication interface is the SPI [26].

The two main memories are EEPROM and FLASH.

- The EEPROM is a 4 kbit memory, used only for basic configurations, such as data type and production settings. It has a low power dissipation, with a typical average current of 5 mA and a maximum clock frequency of 10 MHz. The communication peripheral needed to link the memory with the microprocessor is the SPI.
- The FLASH is a 64 Mbit memory used to store system logs of the microprocessor. It has a low power dissipation, with an average current of 4 mA and a maximum clock frequency of 20 MHz. The communication peripheral needed to link the memory with the microprocessor is the SPI.

4.4. Power Supply

The power supply of the MSP consists of a lithium-ion battery. This is a secondary battery and therefore needs to be recharged. This requires an energy source, as a recharging circuit to be powered is needed. The main components of the recharging circuit are a battery gas gauge, a voltage-level translator, and a battery charger. A step-down converter, also called buck chopper, is needed to regulate voltages: a DC/DC switching converter based on ON/OFF regulation.

- The battery gas gauge is a *Linear Technology® LTC2942* (Milpitas, CA, USA). The component's role consists in measuring board temperature, voltage, and battery charge state. The battery gas gauge is also used to monitor the battery's charge availability. The state of charge (SoC) of the battery is determined by a coulomb counter, which is one of the inner components of the device. This is achieved by measuring the differential potential between the two SENSE pins, which must be lower than 50 mV. An inner analog-to-digital converter is used to measure the temperature, thanks to a temperature sensor on the chip, and to measure the applied voltage [27].
- The voltage-level translator is an *NXP Semiconductors® PCA9517ATP* (Eindhoven, The Netherlands). This component aims to realize a bidirectional voltage-level translation for the serial data (SDA) and serial clock (SCL) signals between the microprocessor and the battery gas gauge. The peripheral for serial communication is the I2C [28].
- The battery charger is an *Analog Devices™ LT3650* (Norwood, MA, USA). The component has a programmable charging current of up to 2 A, which a sense resistor of 20 kΩ can reach. Moreover, it can be directly connected to a machine's electrical cabinet, with an input voltage of 24 V. The device has two internal timers: an end-of-cycle time of 3 h and a precondition time of 22.4 min, which is needed in case of generation of battery faults [29].

4.5. External Sensors Interfaces

Three external digital sensors were selected for implementation of the MSP: a strain gauge sensor to monitor mechanical stress imposed on a workpiece, an accelerometer to measure the vibration of the device, and a temperature sensor for the deformations due to temperature. The external sensors are mounted on the MSP board through interfaces. The connection is realized through the use of six coupled connectors. The electrical components of the interface are standardized and equal for all types of sensors. The main components are an analog-to-digital converter, an instrumentation amplifier, a voltage regulator, and EEPROM memory. These interfaces comprise a power supply and data interfaces, such as SPI and I2C, in a 18 (2×9)-pin configuration, which is needed for the sensor modules.

5. Prototype Validation Firmware

In this section, we describe the architecture of the MSP testing firmware, with the aim of checking hardware blocks at a functional level. This is done to manage potential issues that the system could have. A basic library of the individual peripherals is provided, implementing a kind of abstraction level of the hardware. General-purpose and device-testing commands are programmed. Those building blocks will be the basis for the final operating firmware state machine [30].

5.1. Testing Commands

As described in Section 2, the compiler tool used for debugging is an *STMicroelectronis*™*CubeIDE*. The procedure for block initialization is:

1. START.
2. System Initialization. The microcontroller is programmed to operate at a system clock (SISCLK) of 168 MHz; high-speed external clock (HSE) of 32 kHz and 25 MHz, thanks to the presence of two external oscillators; high-speed internal clock (HSI) of 16 MHz; low-speed internal clock (LSI) of 32 kHz; and low-speed external clock (LSE) of 32.768 kHz.
3. Load data from memory.
4. Initialization of the peripherals: SPI, UART, I2C.
5. Initialization of the general-purpose inputs/outputs (GPIOs). The MSP microprocessor is of the UFBGA type and is equipped with 176 pins. The pinout is organized in eight groups, labeled 'A', 'B', 'C', 'D', 'E', 'F', 'G', and 'H', which are configurable as inputs to read digital signals or outputs to control other hardware blocks.
6. Task Initialization.

A description of the commands is provided in Section 5.1.1 for the general-purpose and Section 5.1.2 for the device-oriented. When executing, it will receive *OK* in the case of correct execution, <*val*> with the command value, *err*<*n*> in case of error, with *0* value for *n* in the case of successful execution, *1* for syntax error, *2* for out-of-range value, and *3* for non-utilization of the command after the task initialization.

5.1.1. General-Purpose Commands

The general function implementation is provided below.

Print Firmware Version

The function

cmdErr_t getFwVersionCmd(cmd_t cmd)*

implements the command to print the firmware version on terminal *'5G TESTING—v 0.3'*.

List of Available Commands

The function

cmdErr_t helpCmd(cmd_t cmd)*

implements the command to list the available tests of the firmware. On the terminal, *help[]* provides the list of available commands, and *help[<cmd>]* gives a description of the <*cmd*> syntax.

Write/Read Bit

The function

cmdErr_t wBitCmd(cmd_t cmd)*

implements the 'Write Bit' command. It is used to set *nPort [A . . . I] ([0 . . . 8])*, thus the labeling and number of the 9 microprocessor ports; *nBit [0 . . . 15]*, thus the number of one of the 16 bits; and *bitState [0,1]*, thus the state is ON/OFF.

The function

cmdErr_t rBitCmd(cmd_t cmd)*

implements the 'Read Bit' command. It is used to set *nPort [A . . . I] ([0 . . . 8])* and *nBit [0 . . . 15]*.

Management of the LED outputs

The function

cmdErr_t wLedCmd(cmd_t cmd)*

is implemented to check the correct blinking of the four LEDs connected to the microprocessor. On the terminal, the execution state is printed: *<led> = 0/off*: all LEDs are OFF; *<led> = 1/r*: Red LED is ON; *<led> = 2/y*: Yellow LED is ON; *<led> = 3/b*: Blue LED is ON; *<led> = 4/g*: Green LED is ON; *<led> = 5/all*: all LEDs are ON.

Show Command Tags

The function

cmdErr_t showCmdTags (cmd_t cmd)*

is implemented to print a list of 'Tags' on the terminal, thus string keys that refer to specific parameters.

Quit Command

The function

cmdErr_t quitCmd(cmd_t cmd)*

is used to reset the whole system.

5.1.2. Device-oriented Commands

Three hardware components of the MSP board were tested and verified with respect to the microprocessor: the *u-blox™ SARA-R5* radio module based on the UART interface, the *Linear Technology® LTC2942* battery gas gauge based on the I2C interface, and the *STMicroelectronics™ LIS2DH12* accelerometer based on the SPI interface.

SARA-R5 Module: Setup/Write

The function

cmdErr_t sRadioSaraCmd(cmd_t cmd)*

is implemented for the radio module 'Setup'. On the terminal, it returns the state of the device: ON/OFF.

The function

cmdErr_t wRadioSaraCmd(cmd_t cmd)*

is implemented for the radio module 'Write'. The *wradio <cmd>* sends the AT command. When correctly executed, an *OK* is received. Otherwise, a general AT command can be used. It returns, for example, the manufacturer, model, and serial number IDs.

Accelerometer: Axes Reading

The function

cmdErr_t rAccCmd(cmd_t cmd)*

provides the Accelerometer "Axes Reading". It is implemented to read the three axes with a decimal number in the sequence X, Y, Z. The acceleration level is specified through the sensitivity end-scale options of 2 g, 4 g, 8 g, and 16 g.

Battery Gas Gauge: Read/Write

The function

cmdErr_t wGaugetCmd(cmd_t cmd)*

provides the battery gas gauge "Write". The battery gas gauge data are stored in internal memory, composed of 16 registers subdivided into: status register ('A'), control register ('B'), accumulated charge register ('C', 'D'), threshold registers ('E', 'F', 'G', 'H', 'K', 'L', 'O', 'P'), and voltage and temperature registers ('I', 'J', 'M', 'N'). When *wGaugeCmd* runs on the terminal, *nreg[0 ... 15]* sets the number of the register to be written; *regvalue[A ... P]* sets the register value.

The function

cmdErr_t rGaugetCmd(cmd_t cmd)*

provides the battery gas gauge "read". On the terminal, *regvalue[A ... P]* sets the register value to be read.

6. Software Architecture of the Multi-Sensor Platform

Sophisticated software was developed to control the hardware and manage the data flow from sensors to the cloud. The software workflow consists of the following phases:

- Setup;
- Application.

6.1. Setup Phase

The core of the sensor platform is the STM32F4 series microcontroller. After powering the platform, the controller first initializes the system with the corresponding system and peripherals clocks, and the system interrupts. The controller is programmed to operate at 168 MHz generated by the internal PLL clock. It also generates 48 MHz for USB and 25 MHz for the Ethernet PHY chip. The microcontroller's peripherals are SPI, I2C, UART ports, Ethernet PHY, and GPIO. Their corresponding DMA channels are initialized. These DMA channels enable data from the sensors to be directly written to the memory without the controller's intervention. This enables the controller to be effectively used for other essential controls. The external and onboard sensors are connected to the microcontroller via the SPI and I2C interfaces. The UART ports enable the communication channel to the SARA-R5 module for setup and receiving the timestamps. In addition, another port is enabled to act as a debug interface.

The SARA-R5 is set up to establish a connection to the base station and enable the *CellTime* feature to receive timestamps. After successful peripheral setup, network configuration occurs, whereby the controller initializes the TCP/IP stack for networking. The controller uses a lightweight TCP/IP stack (LWIP). It initializes the stack and enables the DHCP connection to receive the IP address for the module over the Ethernet. After successful DHCP acknowledgment, the controllers open the socket communication. It opens two ports: one for UDP data transmission and the other port for receiving the reconfiguration over the LWM2M protocol. UDP is used for transmission, as it has a low overhead and is fast compared to other protocols. The LWM2M is used for remote reconfiguration of sensor platform parameters. The Wakaama implementation of the LWM2M stack is customized and scaled down to have a low stack and memory usage while working alongside a non-blocking UDP communication with multiple ports.

6.2. Application Phase

A real-time operating system is integrated to have a concurrency of the application due to the availability of multiple sensors and network interfaces that manage these functionalities as tasks. The open-source *free-RTOS* is integrated to perform this functionality. The following tasks are set up:

- Sensors;
- UDP server;
- Reconfiguration.

6.2.1. Sensor Task

The sensor interface tasks are interrupt-triggered tasks, whereby the external sensor data, after configuration, place their data array on the memory, which triggers the task to gather the data and conditions and sets it up for transmission. The onboard sensor task is time-triggered with periodicity to gather the platform diagnostic data and packs it for transmission.

6.2.2. UDP Server Task

The UDP server task is an event-triggered task to receive data to be sent to the cloud from the sensors. This task sets up a network socket using the LWIP stack to send the data packets as a UDP message. The task first creates two sockets and sends the data to these sockets to achieve data redundancy on the cloud application side. After successful data transmission, it moves to sleep mode and waits for the next trigger for data. A unique data format is considered for each sensor to differentiate sensor data.

The external sensors, for example, vibration sensor *ADCMXL3021*, after configuration, send data array packets directly stored on the RAM of the microcontroller via the DMA channel. After successfully writing data to memory, an interrupt is generated, triggering the sensor task to acquire the data from the RAM cache, preprocess the data, pack it with a timestamp, and notify the UDP server for data packet transmission. The UDP server packs the data as a UDP packet with necessary headers and information and sends it to the destination address in two ports to achieve redundancy.

6.2.3. Reconfiguration Task

The reconfiguration task enables the sensor platform configuration to be dynamically modified using the LWM2M protocol. This unique protocol enables configuration management as objects and resources centrally managed from the cloud. This protocol uses a small portion of the memory (around 50Kb RAM, 150Kb FLASH) and is effectively managed by the RTOS of the MSP. The LWM2M is built over the LWIP TCP/IP stack, using the UDP protocol with CoAP overlay. The Wakaama implementation of the LWM2M stack in the POSIX environment is ported to the sensor platform and scaled-down to use minimum stack and memory while working alongside the LWIP UDP protocol in non-blocking mode to have seamless data traffic between various socket ports. The sensor platform works as a client, registering the configuration parameters and receiving requests for a change of parameters. Parameters such as sensor configuration, data manipulation, enabling/disabling of specific sensors, and battery charge requests are handled by the client, as listed in Table 1

Table 1. LWM2M. Client configuration.

Peripheral	Parameters
Mainboard	Enable/disable sensor Modify destination IP/port Static/DHCP configuration Prioritization of sensor Send raw/processed data Request configuration detail
Vibration sensor/ Microphone sensor	Sampling frequency increase/decrease Optional parameters (FFT, filters, sensitivity)
Strain gauge/torque/force sensor	Sampling frequency increase/decrease Sensitivity configuration Calibration request
Temperature sensor	Sampling frequency Calibration request
SARA-R5 module	Periodicity of synchronization Cell time parameter configuration
Internal sensor	Threshold to trigger an alarm Sampling frequency

The configuration data are stored in the EEPROM. When the controller starts up, the configuration data is first read from the EEPROM and stored in the configuration variables used to set up the sensors. When the LWM2M server requests a configuration update, these variables are updated, triggering the sensor task to send the configuration and save it in the EEPROM for the next startup.

6.3. Smart Device Handling

In addition to the data handling, the software also controls the hardware efficiently via its GPIO controls. Hardware peripherals such as the SARA-R5 module, which consume a lot of power, can be turned off via the GPIO pins to conserve the battery. In case of overcharge or low power detected from the LTC2942 module, an interrupt triggers the software to alert the system for maintenance of the device module. The other onboard sensors periodically check the sensor platform environmental data for water intrusion or overheating. This is significant, as the sensor platform is deployed in a harsh industrial environment and can potentially be destroyed in case of coolant leakage into the box and overheating of the sensor platform. The sensor platform can be switched off remotely over LWM2M to protect the device in case of abnormalities. In addition, this information can be logged and analyzed to enable predictive maintenance of the device. With this software architecture, a powerful smart sensor system is developed to cater to the needs of an Industry 4.0 wireless robust data acquisition system with intelligent control and management.

7. Experimental Setup and Results

To compare the performance of the 5G-enabled MSP with respect to an industrial cabled solution, we describe the use case of workpiece monitoring in a five-axis milling machine. The milling process is complex, and the workpiece needs to be monitored for various parameters that affect quality, namely natural frequency, bending force, temperature of the coolant, etc.

Figure 4 describes the experimental setup used to measure performance. It comprises the sensors integrated into the test workpiece. The MSP is enabled with vibration, strain, and temperature sensors to perform condition monitoring. These sensors are integrated into the workpiece to be monitored. Another set of sensors is integrated into the workpiece and connected to the industrial data acquisition system, which is the GEM sensor module system from Marposs. The software is configured to match the sampling frequency used by the industrial data acquisition system. The strain sensor samples data at 1 KHz, the vibration sensor at 20 KHz, and the temperature and humidity sensor at 100 Hz. The data between the industrial and 5G solution are logged in the monitoring software.

Preliminary results show the latency of the industrial solution and the 5G sensor solution is between 11–12 milliseconds. This is in line with the current 3GPP release 15 of the 5G network. This is significantly lower than other wireless cellular standards. such as 4G, Wi-Fi, and Bluetooth, which have higher latency of data transmission. The latency range is within the acceptable limits in terms of the requirements for data transfer from the sensors, which could be further improved with the upcoming 3 GPP release 16 for 5G.

The major advantage of the setup is the increased mobility of the sensor platform without the need for additional effort, such as wiring, powering up, and external modules for the sensors. It enables rapid deployment of the sensor to gather data and send it to the cloud for real-time data analytics, such as condition monitoring and predictive analytics. With the SARA-R5 module, the timestamp-integrated data packet is useful for creating real-time digital twins to fuse data from the sensors and the machine.

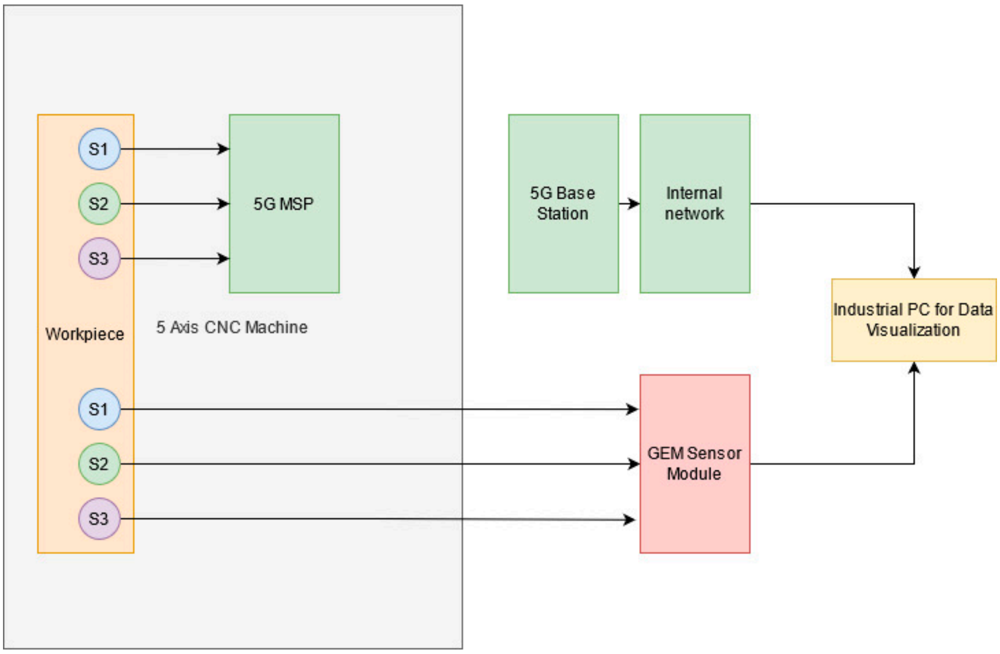

Figure 4. Experimental setup with MSP, wired sensor, and visualization PC.

8. Conclusions

The limitations of state-of-the-art industrial sensors and multi-sensor devices have been presented and discussed. Low-flexibility and real-time control capabilities, wired connections, and high latency limit industrial production. With the advent of 5G technology and its high reliability and low latency characteristics, the possibility of designing 5G devices for smart manufacturing has emerged.

In this paper, we presented an MSP prototype equipped with both internal and external sensors capable of collecting different types of information, i.e., acceleration, humidity and temperature, and vibrations. Its modular architecture and the presence of interfaces for external sensors allow it to be placed on any workpiece, in any machine tool, or the infrastructure present on the shop floor of a factory. The connection with an external ancillary communication module allows for various types of 5G communication modules to become available on the market either now or in the future. The MSP realizes the idea of a 5G device that is, at the same time, flexible, reliable, and modular. Changing of the communication module for a more recent one, e.g., when switching from 3GPP Rel. 15 to Rel. 16, can be achieved without redesigning the whole prototype. This guarantees market-wide flexibility and reliability.

These characteristics were first analyzed from a hardware point of view. The main components were introduced and described. Starting from the hardware components, a hardware abstraction layer was created, the building blocks of which serve as the basis for the final operating firmware. Three device-testing commands were presented and described. Additionally, general-purpose commands were introduced.

As a state-of-the-art project, the device was tested at a prototype level. Future developments consist of actual study at a trial site and verification in real situations for the described application use cases. Several benefits are expected with the use of such prototypes, such as optimization of production processes, increased automation, better control of diagnostic processes, and fault detection, which will be achieved by an improvement in connectivity, flexibility, and applicability.

Author Contributions: Conceptualization, A.P., E.Z. and R.P.; methodology, A.P. and E.Z.; software, P.M. and A.P.; validation, P.M., A.P. and R.P.; investigation, P.M. and A.P.; resources, P.M., A.P. and R.P.; data curation, P.M. and A.P.; writing—original draft preparation, P.M. and A.P.; writing—review and editing, A.P., E.Z., R.P. and N.K.; visualization, N.K.; supervision, E.Z., R.P., N.K. and R.H.S.;

project administration, N.K.; funding acquisition, R.H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was performed under 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 any of the information contained herein. The 5G-SMART project received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 857008.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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