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Distributed sensors array for composite materials manufacturing quality assurance

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***Abstract*- The paper describes a cyber-physical approach to resolve the automation of quality and reliability enforcement in a manufacturing environment. The approach is based on an architecture of distributed sensors array connected to a local minicomputer, which further communicates using a secured internet connection with an industry 4.0 facilitator hub. The proposed architecture creates an extensible framework to support multi-domain requirements. The effectiveness of the approach is demonstrated in the case of a composite materials manufacturing installation.**

***Keywords*: Cyber-physical systems, Distributed networks, Industry 4.0, Nanosciences and nanotechnologies, Materials.**

I. INTRODUCTION

Composite materials are fundamental for today's industrial environment, providing special characteristics that are unobtainable using raw natural materials. There are only three main types of composite materials (dispersed, fiber-reinforced and stratified), but the manufacturing techniques are evolving continuously, taking advantage of the progress in computers, electronics and sensors engineering [1]. The approach considered state of the art in the composite materials manufacturing field is Vacuum Assisted Resin Transfer Molding (VARTM) [2].

The sensors technology and availability has improved considerably during the last years, with the advance of micro size sensors integrated into mobile phones and internet of things (IoT) devices. They are now used in various applications, such as monitoring the indoor environment, as described in a US patent request [3]. In a manufacturing environment, particulate matter (PM) sensors play a very important role. A calibration and evaluation report of various sensors concludes that low cost particle sensors nowadays provide good data linearity and quality [4].

Distributed sensors arrays are successfully used in various scopes such as partial discharge detection and localization in substation [5], internal thermal monitoring in low voltage random wound coils [6], or cooperating acoustic sensors [7].

In this paper, the authors show how a cyber-physical system can be effectively applied to the manufacturing process of composite materials in order to enforce quality and reliability.

The rest of this paper is organized as follows: Section II presents the composite materials manufacturing domain in order to establish the most important characteristics to be monitored, Section III describes the sensors options available for the required installation, while section IV presents the network requirements for interconnectivity and security considerations. The experimental implementation and results are presented in Section V, followed by the final conclusions in Section VI.

II. COMPOSITE MATERIALS INSTALLATION

According to their internal architecture, composite materials can be classified as follows (Fig.1):

- dispersed composite materials;
- fiber-reinforced composite materials;
- stratified composite materials.

There are several techniques for composite materials manufacturing, including: hand lay-up, vacuum assisted lay-up, resin infusion, spray-up, resin transfer molding (RTM), vacuum added resin transfer molding (VARTM). The hand lay-up method is a simple yet efficient way that requires little capital investment to produce composite materials. The method can be improved by using vacuum assisted technologies to improve the final resin / material ratio. The spray-up method uses a gun to simultaneously spray the reinforced fibers and resin over the mold leading to cheap but poor quality products. The resin injection methods lead to the best quality products, achieving the requirements of the aero-space industry with a very good structural resistance and low resin ratio, obtained in a repeatable, quality controlled, process. The VARTM process, presented in Fig. 2, also ensures that the potentially harmful substances used are contained in the vacuum bag.

This proposed approach is tested on the manufacturing of multifunctional sandwich panels made from fiber reinforced composites as building materials for application in

Fig. 1. Composite material types, from left to right: dispersed, fiber-reinforced, stratified

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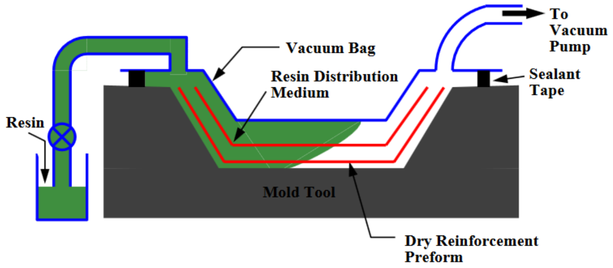


Fig. 2. Vacuum Added Resin Transfer Molding (VARTM) process schema [2]

construction sector. These panels are utilizable as partition wall elements, offering acceptable or even improved levels of sound and thermal insulation compared to conventional wall elements but also additional functions such as energy storage capabilities. Use of green composites (natural fibers, environment friendly resins, etc.) is foreseen for the outer (load carrying) layers of the structure. The targeted panels aim to address an increasing need in the construction industry for structures with low weight, good insulation properties and improved durability, and offer an innovative solution for energy storage that can facilitate emerging energy management technologies.

One of the objectives of the manufacturing installation is to develop a multifunctional sandwich structure that can support mechanical loads, like any other honeycomb or foam cored sandwich panel, combining the capability to store electrical energy. To accomplish that, appropriate energy storage layers (electrodes and solid electrolyte) will be embedded into the panel structure. More specifically, the structural panel will comprise:

- two face sheets, consisting of natural fiber reinforced composites that will provide the required structural properties. These composites may incorporate various modifications based on nanotechnology solutions (e.g. fire retardancy, sound insulation additives, functional nanoparticles etc.);
- a multifunctional core: a layered structure comprising at least three layers of electrochemical energy storage materials (active materials like carbon fiber layers for anode, cathode and ion conducting separator).

The design of such panels will aim to satisfy mass, sound and thermal insulation requirements and safety standards as well as energy storage performance. Reduction of structural weight and volume and enhancement of flame retardant properties are crucial to designing efficient panels for space partitioning applications.

The main drawbacks of natural fibers will be improved by proper chemical treatments. To enhance fire resistance of natural fiber composites, coatings and additives can be used, since they have been found to be very promising fire barrier treatments. One suggestion could be the addition of expandable graphite (EG) and ammonium polyphosphate (APP) as a source of flame retardancy (FR).

For exterior building applications, the development of novel mortars pastes and paints is envisaged. In addition to the currently used photocatalytic agents that promote the self-cleaning capability, special formulations utilizing ceramic based nano-filters and nano-clays will be developed. These additives can control surface roughness and porosity and result in enduring high emissivity.

In order to address all the requirements, the manufacturing process has to be strictly monitored. To achieve the level of control required we propose a system based on distributed sensors, communicating with a central hub responsible for data aggregation, data interpretation and data driven decisions.

III. SENSORS

There are patent applications that cover only some of the objectives set for this project, including the one that is closest to the concept, which is presented in Fig. 3. The system proposed in the patent application [3] aims to integrate sensors and actuators in tiles for false ceilings or floors, supervised by a master system, all mainly aimed at the comfort of the rooms.

What is already thought of is possible from a functional point of view. However, implementations require specific technological solutions made to measure for the occasion and poorly integrated with each other. To overcome these limitations, this paper proposes to create a modular system, scalable and easily interfaced with third-party industry 4.0 systems and managed by users and operators not necessarily equipped with a highly specific technological skill.

Among the situations and events that the system will be expected to manage, there are environmental temperature, temperature of the objects, relative humidity, pressure, proximity of objects, possible touch or touch by a user. These situations and events can be detected in a distributed way over the entire surface of the manufacturing area, or only from the master node. The type of variable to be measured or the type of event to be detected influences the positioning of the related sensors and detection systems. For example, the reading at the master node for the ambient temperature,

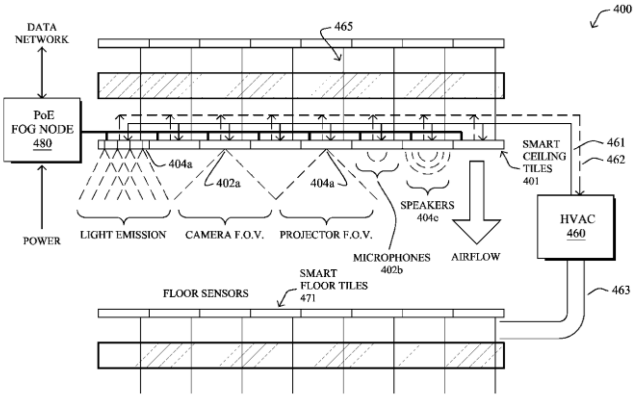


Fig. 3. Overview of the system presented in US2018313558A1 [3]

relative humidity and atmospheric pressure will be sufficient, thus avoiding the redundant installation of the relative sensors throughout the area. On the contrary, the proximity, touch or temperature sensors for objects, depending on the architecture chosen, can be present on at several locations of the building and machineries.

The ability to detect the presence or proximity is one of the main functionalities of the system. There are several possible technical solutions for the implementation of these features, each with its own peculiarities and requirements:

- optical proximity sensors: they generally use the reflection of a beam of infrared light on the obstacle in order to determine its presence within the range of action. This type of sensors is not able to distinguish between inanimate objects and living beings, they are only able to detect the degree of reflectivity of a surface. There are different models and packaging and their detection capacity can be pushed up to distances of about 150 centimeters. They feel the presence of particularly intense light sources placed in their field of vision that could limit their functioning to make them practically "blind". Another factor to consider is the number of sensors installed per surface unit: an excessive density could cause the target object to over-illuminate making it invisible. Moreover, this family of sensors, regardless of their shape and size, require direct exposure to the area to be monitored, making them easily identifiable on the surface of the tiles;
- proximity sensors and capacitive tactile devices: they are based on the principle of the detection of the electrical capacity of a capacitor. The sensor sensitive side constitutes a conductive plate, the presence in the immediate vicinity of a conducting object, realizes the other conductive plate of the capacitor. Thus, the presence of an object creates a capacity that the internal circuits detect, generating the sensor output signal. Depending on the detection range required, there are "within-content" models that can perform their detection function in the short range without the need for external physical extensions. The models which require greater sensitivity and a greater field of action, require an electrode of a larger size, which, however, cannot reach more than a few centimeters.
- resistive tactile sensors: ideal for the detection of touch only, as they offer more advanced interaction possibilities between system and user, they require the installation of special films on the surface of the tiles. Usually they are overlapping films and coated with resistive material, subjected to currents that cross them with lines perpendicular to each other. In case of touch, the point of contact between the films creates a variation of tension on the axes that allows to determine the coordinates with extreme precision. For this reason, the films must cover the entire surface to be monitored, which must have a sufficiently regular shape.
- ultrasonic proximity sensors: they work on the Sonar principle, that is, they emit ultrasound pulses and detect a possible return echo generated by the presence of an object within the nominal flow that can even reach the measurement of several meters. However, some attention must be paid to the size and orientation of the surface of the object that addresses the sensor - in fact, a surface that is too small or badly oriented (not orthogonal to the sensor reading direction) may not ensure the generation of an echo detectable. Furthermore, the presence in the same environment of several sensors of this type can lead to the detection of false positives or to the incorrect measurement of the obstacle distance.

Considering the different options available and their characteristics, the infrared proximity sensor is the best match for our purpose.

The detection of environmental temperature, barometric pressure and environmental humidity can be performed by a separate and independent unit, connected on the same bus common of the whole system. Considering the nature and variability of these measurements over time, the module would operate exclusively in slave mode and could be interrogated more or less at even intervals.

During the last years, great attention has been paid to compact particle sensors used to monitor air quality. In an industrial manufacturing setup these sensors offer an invaluable insight and early alert indicators when something is not operated correctly. Various low cost and compact airborne particle sensors are available, measuring particle concentration of various sizes, such as 2.5 µm (PM2.5) or 10 µm (PM10). There are several techniques used for particle sensing:

- light-scattering techniques: A narrow beam of light is focused on air flowing through a chamber, with a detector placed at angle (perhaps 90°) from the beam such that it is shielded from the light. When particles are present in the air sample, the light hitting the particles will be scattered and some will enter the detector.
- non-dispersive infrared (NDIR): leverages the fact that CO2 molecules have a characteristic resonance mode which corresponds to 4.26 µm mid-infrared light. When the molecules resonate, they absorb energy at that wavelength. Internally, an NDIR sensor is typically arranged as a small tube with a broad-spectrum IR emitter at one end, and an IR detector with a 4.26 µm bandpass filter at the other end.
- photoacoustic spectroscopy (PAS): based on an interesting discovery made by Alexander Graham Bell in the 1880’s that strobed sunlight could produce an audible sound on certain materials. To measure CO2 concentration using PAS, a sealed

chamber would be filled with CO2, one side of the chamber has an IR-transmissive window, another side has a microphone attached to it. As noted earlier, CO2 resonates at 4.26 µm, generating heat and increasing the gas volume. The temporary thermal expansion and contraction generates vibrations which are picked up by the microphone.

An interesting possibility to increase the degree of certainty about the environment in which it is installed, could be to use one or more temperature sensors characterized by a certain directionality. In this way, the system could react not only to the presence and approach of an object, but also to the chromatic feedback related to the detected temperature, as presented in Fig. 4. The ultimate mechanical properties of composite materials are strongly dependent upon the rheological events occurring during the cure cycle. In particular, full-field measurement of the temperature during the curing phase (e.g. distribution of temperature in the autoclave environment) of the composite panels can give important information about their mechanical behavior [8].

IV. Network Considerations

Each node should be able to communicate bidirectionally with a master node as well as to detect the presence of other nodes on its perimeter. The communication bus is decisive for the project because this will depend on the adoptable protocol and therefore the implementable features.

In order to interconnect all the component modules with each other, it is required to choose a bidirectional communication bus able to support a dynamic number of components without distinction that their role is either a master or a slave.

Fieldbus is an industrial communication network for distributed control in real time, which operates at the base level of the automation pyramid to coordinate and connect the field devices (sensor actuator drives) and interacts with the higher levels of the system. The fieldbus architecture is a multi-point architecture in which each device or node involved in the exchange of data is connected to a single line of communication (physical or logical) that is the means of the distribution and collection of information. The communication takes place in digital serial form and at high speed to serve all the nodes involved in the required times.

The connection between two or more nodes of the network can occur through different means of transmission. Each of them presents certain peculiarities that make it preferable in certain environments rather than in others. In the industrial field, the most used are physical connections made by cables or optical fiber. Depending on the type of electrical signal to be conveyed and the required performance, various configurations can be used, for example:

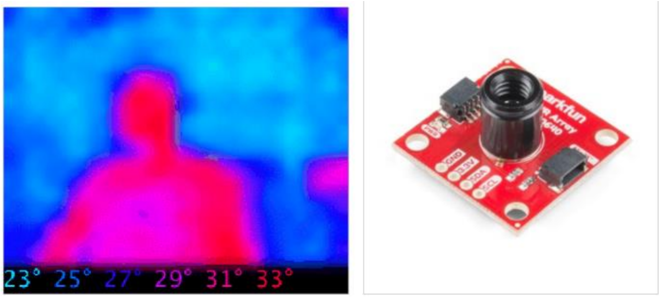


Fig. 4. Temperature array sensor

- copper twisted pair: typical configuration realized with a pair of usually twisted conductors in order to reduce the sensitivity to external interferences. In a typical cable, it is also possible to find several pairs of braided and shielded cables separately. Such configurations are taken to increase the available bandwidth and noise immunity.
- coaxial cable: consisting of a conductor core surrounded by a screen made of conductive material, it allows transmission over long distances even of relatively weak signals. The main disadvantages are mechanical, as they are not negligible in size.
- optical fiber: consisting of a very pure glass core immersed in a reflective shell, which is the ideal support for high bandwidth transmissions in electrically noisy environments as the signals are transmitted through coherent light pulses.

Considering the transmission means listed above and the requirements of simplicity of implementation and immunity to external disturbances, the characteristics of expandability, speed and maximum reachable distance, the EIA RS-485 serial bus is one that meets the requirements. Extremely common in industrial automation, EIA RS-485 is used in industrial networks, including Modbus, Profibus DP, ARCNET, BitBus, WorldFip, LON, Interbus and many other non-standard networks.

A communication protocol is a set of rules and behaviors that two distinct devices must respect to exchange information between them. The exchange of information is generally an operation involving several intermediate phases (levels), each of which is regulated by its own protocol. The International Standard Organization (ISO) has standardized a reference model for the development of protocols oriented to the interconnection of open systems called International Standard Organization Model - Open System Interconnection (ISO-OSI).

Controller Area Network (CAN bus) is a serial communication protocol that supports real-time distributed control and multiplexing for use in road vehicles and other control applications.

The MODBUS protocol defines the format and the mode of communication between a "master" that manages the system and one or more "slaves" that respond to the queries of the master. The protocol defines how the master and the slaves establish and interrupt the communication, as the transmitter and the receiver must be identified, as the messages must be exchanged and the errors detected.

Considering the protocols presented above and the requirements for composite materials manufacturing we implemented a custom communication protocol based on the MODBUS rules and message formats.

V. CASE STUDY

A test setup architecture was designed and developed taking into account the observations made in the previous sections and the target test scenario of manufacturing composite material panels. The setup depicted in Fig. 5 is built around a Raspberry Pi single board computer with integrated flash memory required to temporarily store and process data, as well as a backup storage while the internet connection is not working. The ethernet port available on the single board computer is used in order to connect to the industry 4.0 hub over the internet and enforce data authenticity and security.

By default, the single board computer has two Universal Serial Bus (USB) ports, but these can be easily extended with commercially available USB hub extension boards made specifically for Raspberry Pi. The USB ports are used to connect sensor hubs build using an Arduino board which provided real time operation and input output ports for analog and digital sensors.

In the particular case of composite materials manufacturing, the sensors used in the array are: environmental temperature, environmental pressure, environmental humidity, environmental particle density for several types of particles and temperature array for monitoring each composite panel as it is produced. These sensors provide a good overview of the entire manufacturing facility and the quality of the manufactured product.

The most popular protocols for global communications are the ones from the Transmission Control Protocol/Internet Protocol (TCP/IP) stack. They are used to connect computers, servers and devices to the internet. In the particular case of quality assurance for composite materials manufacturing, the local sensors and devices are linked together using serial line communication, and connected to a single board computer hub that acts as a bridge between the local serial network and the global internet network. This single board computer stores and analyses the data before sending the useful information to the cloud using the application programming interface (API) provided by a main system coordinating the entire industry 4.0 environment.

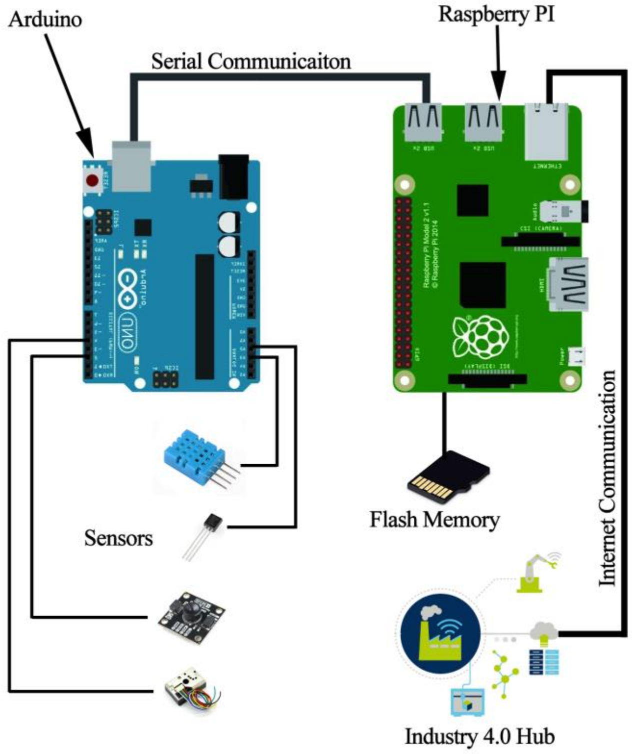


Fig. 5. Case study setup: system architecture diagram

In order to take advantage of the information provided by the array of distributed sensors, the Raspberry single board computer was connected to an industry 4.0 facilitator hub using a special API developed for this task. The required endpoints are presented below.

To authenticate the single board computers connecting to the main hub, each of them has a unique token generated by the system. Each API endpoint expects a JSON Web Token provided in the jwt property of the request body. As described by the standard RFC 7519, JSON Web Token (JWT) is a compact, URL-safe means of representing claims to be transferred between two parties. The claims in a JWT are encoded as a JSON object that is used as the payload of a JSON Web Signature (JWS) structure or as the plaintext of a JSON Web Encryption (JWE) structure. Before deployment, each single board computer is loaded with an operating system image, and a JWT generated for it. This JWT is then used to uniquely identify and authenticate the device when it connects to the system over the internet. It is important to understand that the purpose of using JWT is not to hide or obscure data in any way. The reason why JWT are used is to prove that the sent data was actually created by an authentic source. For security reasons, the API endpoints enforce the usage of the Hypertext Transfer Protocol Secure (HTTPS) protocol, which helps to prevent unauthorized users from stealing the sent JWT by making it so that the communication between the servers and the client cannot be intercepted and decrypted.

The endpoint for sensor data transmission expects a JSON data payload in the following format:

```
{

      "jwt":"eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJzdWIiOiIxMjM0
      NTY3ODkwIiwibmFtZSI6IkpvaG4gRG9lIiwiaWF0IjoxNTQ2MjU5N
      TYyfQ.GQGyPDQpoVqc68NMzI3Eghk7qpUl8UHG1xTNonfTnt4",
 "sensors": {
   {
    id: 1,
    type: "temperature",
    value: 22.78,
    accuracy: 0.98,
    readTime: "1546259471"
   },
   {
    id: 2,
    type: "pressure",
    value: 0.55,
    accuracy: 0.92,
    readTime: "1546259471"
   },
   {
    id: 3,
    type: "humidity",
```

```
   value: 0.68,
   accuracy: 0.97,
   readTime: "1546259471"
  },
  {
   id: 4,
   type: "particle_pm25",
   value: 11.64,
   accuracy: 0.98,
   readTime: "1546259471"
  },
  {
   id: 5,
   type: "temperature_array",
   value:
     [29.72,28.85,29.75,27.84,27.59,28.06,27.13,28.87,28.77,29.23,28.58,28
     .62,28.22,28.04,27.25,29.90,28.98,28.55,28.53,…],
   accuracy: 0.96,
   readTime: "1546259453"
  },
 },
 "sentTime":1546259562
}
```

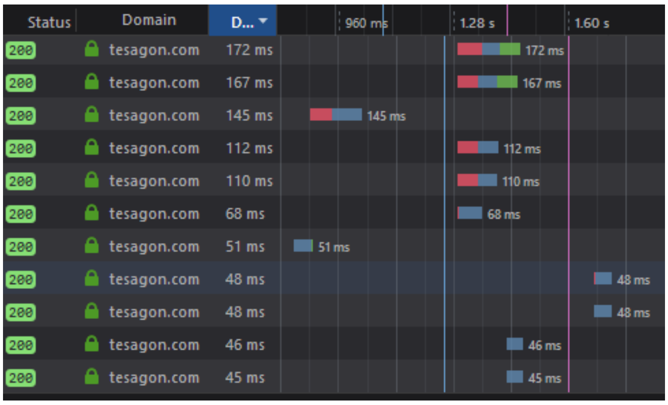
The response is also a JSON indicating the status of the data transmission request. Two examples are presented below.

```
{
 "response": {
  "code": 200,
  "type": "Success",
  "description": "OK data received"
 }
}

{
 "response": {
  "code": 403,
  "type": "Forbidden",
  "description": "Failed authentication"
 }
}
```

In order to assess the maximum load potentially handled by the system, the sensors were read in a continuous loop and data was sent to the main hub. Fig. 6 shows the response time in a scenario with 2 Arduino boards reading 3 sensors each. The communication duration is greater for the first packages because they include domain name server (DNS) resolution. Subsequent API calls are processed on average in 50 ms, at a 300 ms interval. The bottleneck was the read time on some sensors, while the communication took relatively shorter time.

In normal operation, the implemented system was effective in reading all the sensors at a one minute interval and delivering the data in less than 200 ms over the encrypted communication channels to the industry 4.0 facilitator hub, where the data was stored for further use in the user presentation layer and data analysis.



Status	Domain	D...
200	tesagon.com	172 ms
200	tesagon.com	167 ms
200	tesagon.com	145 ms
200	tesagon.com	112 ms
200	tesagon.com	110 ms
200	tesagon.com	68 ms
200	tesagon.com	51 ms
200	tesagon.com	48 ms
200	tesagon.com	48 ms
200	tesagon.com	46 ms
200	tesagon.com	45 ms

Fig. 6. Response time for API calls, sorted by duration

VI. CONCLUSIONS

We conclude that an extensible system incorporating a custom sensors array, control hubs, single board computers and an industry 4.0 hub can be effectively used to monitor in real time the manufacturing process of composite materials, and to enforce quality and reliability standards to the manufacturing process.

The cyber-physical system described in this paper represents a framework that can be adapted to create an extensible monitoring array for various sensors as needs arise. Using the available technologies, it is possible to implement secure communication at industry standards without sacrificing application requirements, such as data throughput or response time.

By integrating a sensors array with an industry 4.0 hub, data was made available to the operators in a familiar environment, facilitating data driven decisions.

Lastly, this approach can be further developed to cover the actual data storage, big data processing and automated learning (e.g. by implementing neural network methodology) based on the sensor values recorded over a longer period of time by the central industrial processing hub.

ACKNOWLEDGMENT

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