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A Modular Smart Vision System for Industrial Inspection and Control of Conformity

Marwan El Helou,¹ Khaled Benfriha,² Abdulrahman M. Al-Ahmari,³ Peter Wardle,⁴ Esma Talhi,⁵ Stéphane Loubère,⁶ Chawki El Zant,² and Quentin Charrier²

Reference

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ABSTRACT

In manufacturing systems, there are several essential tasks to perform before and after the production process. In traditional systems, these tasks were done manually, which can lead to more resource consumption and the risk of human error; however, advanced manufacturing systems and Industry 4.0 tend toward a more autonomous manner. To ensure the compliance of the machining process and the safety of the personnel as well as the machines at the shop floor, the inspection of the overall factory prior to any machining process and the control of conformity of the manufactured parts are necessary in order to know the status of the manufacturing line. This paper proposes a novel modular smart vision system for machine inspection and conformity control of machined parts. Our system uses smart vision technologies embedded in industrial robots and enhanced with image processing and analysis capabilities. The solution also integrates a user interface for human-machine interactions that has been developed with a modular approach, and is designed, launched, and controlled by the manufacturing execution system, allowing agile and customized configuration. By this new approach, the robot inspects all the machines in the factory to check the status before launching the production plan. After the machining process, the system interprets the in situ dimensional analysis for the machined parts and makes decisions about whether the parts are acceptable or require additional machining.

Keywords

Industry 4.0, smart vision system, industrial robots, machine inspection, control of conformity, digital transformation, modularity, manufacturing execution system

¹ Arts & Métiers Institute of Technology, Product Design and Innovation Laboratory, HESAM University, 151 Bd de l'Hôpital, 75013 Paris, France
(Corresponding author),
e-mail: marwan.el_helou@ensam.eu, <https://orcid.org/0000-0002-0019-7371>

² Arts & Métiers Institute of Technology, Product Design and Innovation Laboratory, HESAM University, 151 Bd de l'Hôpital, 75013 Paris, France

³ Raytheon Chair for Systems Engineering, King Saud University, King Khalid Rd., Riyadh 12372, Saudi Arabia

⁴ University of Wolverhampton, Wulfruna St., Wolverhampton WV1 1LY, United Kingdom

⁵ EIGSI, Engineering School, 26 Rue François de Vaux de Foletier, 17041, La Rochelle, France

⁶ Price waterhouse Coopers France \Strategy &, 63 Rue de Villiers, 92208 Neuilly-sur-Seine, France

Introduction

The traditional philosophy of the current automated manufacturing system is to use robots and automated machines to perform repetitive and specific tasks that were performed by humans. This philosophy has massively increased the production rates of goods and services with good quality and has reduced labor and raw material costs. However, today's industry is facing a great deal of constraints and economic challenges, such as decreased availability of natural resources, rising energy prices, and adaptation to constantly changing market demands. The fourth industrial revolution, also known as Industry 4.0, is presented to overcome these constraints and restrictions by combining embedded production system technologies, such as advanced robotics, with intelligent production processes to pave the way for a new technological age that will fundamentally transform industry value chains, production value chains, and business models.¹

Advanced robotic systems are playing a major role in enabling Industry 4.0 implementation, in which the integration of robots in a smart network as well as with humans through virtual reality, augmented reality, and mixed reality have great added value.² Nowadays, advanced robotic systems can communicate directly with the manufacturing execution system (MES), which improves the flexibility of the production process and therefore the mass customization aspect.³ In addition, sensing devices together with artificial intelligence (AI) can be added to a modern robotic system to form a system in which the communication between the machines is achieved autonomously and in a decentralized way. This can extend the decentralization aspect. This challenge concerns a new generation of interactive robots known as cyber-physical systems (CPS).⁴ CPS consists of computational components connected with the surrounding physical components, working together to implement a real-time process.⁵ CPS collect and manage vast amounts of diverse data generated by sensors in real-world environments, including autonomous vehicles, automated production technologies, and machine vision systems.⁶ These data can be managed locally or in a cloud-based manner.⁷

Smart vision systems provide innovative solutions in the direction of industrial autonomy and improve productivity as well as quality management. Originally, a smart vision system was composed of a main processor, image procession hardware, a camera, and an illumination.^{8,9} Now, because of advanced technologies, all the components are combined in one smart camera integrated with detection software. Machine vision systems employ machine learning algorithms and neural networks for object detection, classification, and recognition and utilize imaging solutions such as cameras to identify and label information based on pretrained image models. A machine vision system in CPS can improve the reliability and robustness of the system.¹⁰

To increase the intelligence and autonomy in the shop floor, some industrial tasks were identified as cost and time consuming and require frequent human interventions. First is the task of checking the status, availability, compliance, and readiness of the production lines prior to the start of production, which is commonly known as the industrial inspection process.¹¹ Second is an in situ dimensional analysis task that uses smart cameras to improve the control of conformity of the process control.¹² In the presented approach, smart cameras are considered to give industrial robots the capability of performing machine inspection and in situ parts dimensional analysis. It is important to note that the proposed modular smart vision system is not just achieved by adding smart vision technology to the industrial robots but also by reaching a certain level of modularity and decentralization on the control and the plant operation level of the shop floor to create a modular smart vision system that is designed and launched by the MES in a modular way.

The rest of the paper is organized as follows: the section "Related Work" presents the related research work. It is essential to indicate that modular smart vision systems could not be found in the literature review; hence, smart vision systems that are dedicated to do a specific task are presented in "Related Work." "Proposed Modular Smart Vision System" explains the proposed smart vision system. "Implementation of the Proposed System" presents the experimentation of the proposed system, and "Results" and "Discussion" show the results and discussion. Finally, "Conclusions" concludes the research.

Related Work

The proposed smart vision system for control of conformity and industrial inspection is achieved by reaching a certain level of modularity on the control level. Thus, works related to the modularity in the context of Industry 4.0 will be presented first, and then a literature review for the applications of the industrial control of conformity and inspections by the use of smart vision system will be investigated.

MODULARITY IN THE CONTEXT OF INDUSTRY 4.0

Modularity, which is a design principle of Industry 4.0, can be defined as the capability of system components and processes to be separated and combined easily and quickly in order to reach new functionalities that respond to different industrial requirements.¹³ Modules can be added, rearranged, or relocated in the production line based on manufacturing requirements. Hence, based on the plug-and-play principle, manufacturing systems will become loosely coupled and reconfigurable.¹⁴

Looking back to the literature review, various research and development contributions have been made and published in the context of modular production systems. The study that most closely relates to the smart vision system proposed by this paper is the design methodology presented by El Zant et al.¹⁵ They proposed a modular process methodology with the objective of replacing a rigid production process with a more agile one, by creating functional modules out of standardized machining and transfer operations, and also by transferring the control to the planning layer (MES), thus allowing the orchestration of production plans by the production manager of its human-machine interface (HMI). According to Perzylo et al.,¹⁶ rather than mass-producing similar products, firms must respond to market demand for customized or even individualized products in order to reach clients' satisfaction. As a result, their production lines can have many different variations of products and services, which can only be produced in small batch sizes. In the same context, Gorecky et al.¹⁷ explore the requirements for a modular system architecture such as modular process components, modular supply infrastructure, integrated product tracking, and modular information technology interface in order to be able to react appropriately to current and future challenges. Um et al.¹⁸ designed a real-time virtual reality system of a modular factory by a loosely coupled architecture. The proposed system shows the technological enablers of the synchronization of the physical production module to the virtual environment. Closed-loop adaptive machining based on functional blocks has been proposed by Fan et al.¹⁹ for adaptive process planning and execution. Low-level controllers are implemented to handle low-level tasks, such as motion control and data acquisition. On the other hand, Schioenning Larsen et al.²⁰ explore the challenges, based on development steps, in developing modular services in manufacturing companies. According to them, in order to shift from manufacturing products to offering a product-service system, the key challenges are establishing relationships between products and services, making the business case for implementing service modularity, service communication, and managing new service variants.

In this paper, the proposed smart vision system uses modularity at the MES level in order to launch a flexible inspection plan and react based on the result of the control of conformity system. To the best of our knowledge, the integration of modularity with smart vision systems was not found in the literature review.

SMART VISION SYSTEM FOR THE CONTROL OF CONFORMITY AND INDUSTRIAL INSPECTION

There are many computer vision systems that are used for control of conformity and dimensional analysis in a wide variety of applications. These applications are mainly quality control, measurement, surface and depth inspection, thermal inspection, parts tracing, anomaly detection, and robot vision.²¹ The agriculture sector has captured the attention of researchers for the last decade. Devi, Neelamegam, and Sudha²² designed a machine vision system to inspect the size and quality of rice grains. The proposed system uses canny edge detection to obtain the contours of the rice grains, then develops a region of interest around the contours. The features extracted using this system are area, length, width, and diagonal, which were used to classify rice types with 90 % accuracy. In the context of advanced manufacturing systems, a smart vision system is used for dimensional

analysis of manufactured parts and quality control of welding rods. Huang et al.²³ introduce a visual inspection system for empty bottle quality detection, which mainly includes the precise localization and monitoring of detection zones in addition to defect detection. In the process, many algorithms were used, such as edge points double classification, least squares fitting, and Fourier transform, in order to improve the speed and accuracy of the system. In the same concept, Akundi and Reyna²⁴ designed an automated quality control system based on machine vision for product dimensional analysis. The proposed system offers a simple setup capable of identifying defects of various shapes such as cubes, cylinders, and sinusoidal objects. In addition, the vision system was able to identify millimeter-sized defects, making it practical to use. In the construction field, Kazemian et al.²⁵ present a computer vision system for real-time monitoring of extrusion quality. The developed system is reliable and accurate and uses 2-D videos that are easy to capture and analyze. In the same field, Wójcik and Żarski²⁶ introduce an Red Green Blue-Depth camera for the measurements of surface defect area for bridge inspection. By this solution, infrastructure inspections and maintenance processes are improved in terms of precision, speed, safety, and data exchange between different parties. Moru and Borro²⁷ explore the quality control of gears production by using a special optical lens and a comprehensive standard software for machine vision (Halcon). In this approach, gears are inspected by a smart fixed camera. Li et al.²⁸ proposed a novel cognitive vision anomaly detection method that mimics human cognition ability and focuses not only on normal data but also particular vision properties of abnormal data. The results of their experimentations show that the proposed method exhibits higher accuracy and is more concrete in terms of anomaly detection.

It is obvious from the literature review and according to the best of the authors' knowledge that a modular smart vision system that can be considered as a module in the production line and can be deployed to perform many tasks for different machines and products, guided by the MES in a modular way, based on the industrial need, does not exist, which is the main contribution of this paper. In addition, the dimensional analysis is done in situ without the need to remove the machined parts from the machine, which is a secondary contribution of the proposed system.

Proposed Modular Smart Vision System

The developed smart vision system is divided into two subsystems: (i) industrial inspection of the shop floor machines and (ii) control of conformity that ensure the sizes of the machined pieces.

Industrial inspections are frequently performed in industries. They are intended to check the shop floor for irregularities, alarms, warnings, and machine status and availability before starting a production process. These tasks can be relatively time consuming, and the operator could still miss some information. The proposed modular smart vision system presents how these tasks could be incorporated in a flexible environment, hence fixing both limitations mentioned previously. This system increases the performance of the production line and make the control systems inside the shop floor more autonomous. The collected information during the machines' inspection is communicated with the MES and displayed on its HMI. Thereby, the MES offers the capability to design and configure an inspection plan from the predefined functional modules. The MES customizes, with its own HMI, the different areas to be audited and then launches the inspection plan remotely in a modular and focused aspect. In order to design the modularization of the industrial inspection through the MES, two criteria should be taken into consideration: first, the industrial needs behind the inspection that define the consistency of the controls, such as repetitiveness, dangerousness, complexity and so on, and second, the critical machines and areas inside the shop floor that should be inspected as well as the sequence of operation of the industrial inspection that defines the elementary modules for inspection, such as movements, controls, and interpretation of controls.

In the same context, the smart vision system for control of conformity has the objective to give robots the ability to effectuate, autonomously, an in situ dimensional analysis that traditionally required manual intervention. First, on the MES, the dimensional analysis job is designed and launched, taking into consideration the machine that will be inspected, the diameter of the machined piece, and the accepted tolerance. After the

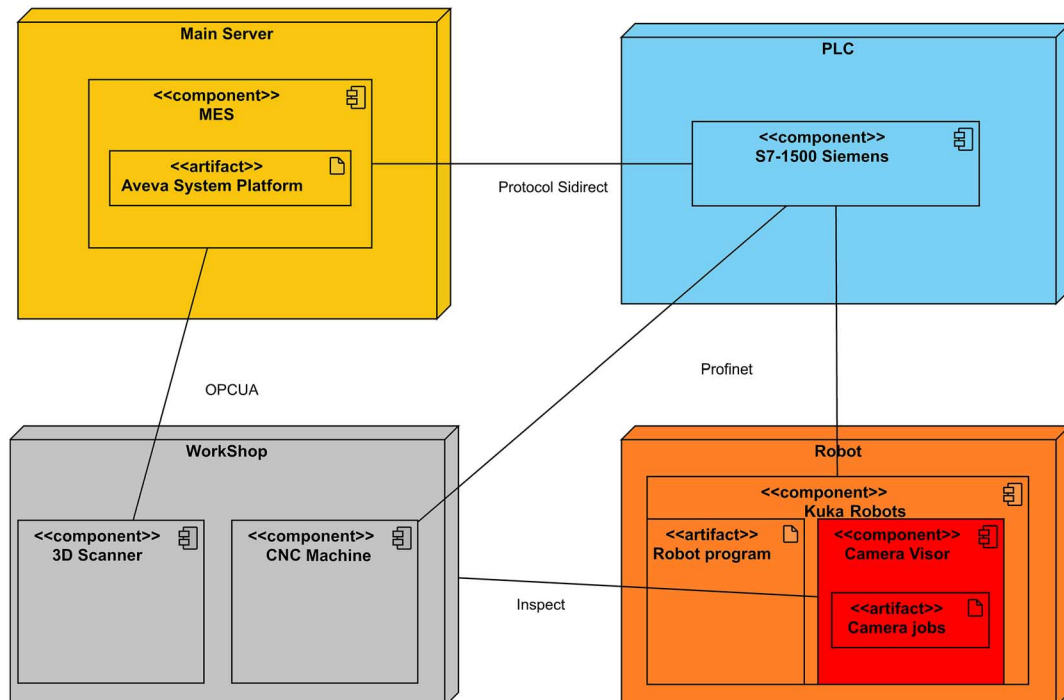
manufacturing of a part is completed, the machine sends information to the MES that the job is done, which in turn sends a command to the smart vision system to perform an in situ dimensional analysis to the manufactured part. The robot detects its environment by using sensors and cameras, takes pictures and analyzes them by the use of intelligent cameras, and communicates the results with the MES. The objective of the proposed conformity control system is to check the dimensional conformity of the manufactured parts while they are still mounted inside the machine in order to limit the defects and save time. In many cases, a deviation from the desired dimension may exist because of tool wear or positioning inaccuracies, which may require additional machining processes to achieve the desired dimension by shifting the cutting tool. The proposed in situ control of conformity is crucial when dealing with continuous production in order to increase production quality and to save time that can be used more efficiently.

Looking at the smart vision system, smart cameras have been integrated with industrial robots by installing the cameras on the side of the robots' tool flanges to obtain the necessary movement for them to reach all affected areas. The smart camera is calibrated to measure the specified dimensions and to check the status of machines. It is considered as a single entity with the robot and thus allows for the autonomy of the tasks. The cameras could then collect images from the shop floor and carry out a set of image processing algorithms, such as pattern identification, brightness and contrast detection, and tool wear detection.

The architecture of the proposed smart vision system, shown in **figure 1**, consists of four layers:

- The MES layer plays the role of an orchestrator that the production engineer uses to design and launch the smart vision system to perform a customized industrial inspection and control of conformity. The MES layer is the layer that add the modularity and flexibility aspects to the proposed system by the possibility to design, in a customized manner, the system based the industrial requirements. After designing the system, the MES sends all "Activation Trajectory Inspection (ATI)" Booleans (Bool) to the Programmable Logic Controller (PLC) via PROFINET, which is an open Industrial Ethernet solution based on international

FIG. 1 Layers of the proposed framework, including the different components and communication protocols. OPCUA = Open Platform Communications United Architecture.



standards. As a result, the PLC sends back to the MES three variables (one Boolean [Bool] and two integers) that indicate the position of the robots and detect and count the anomalies.

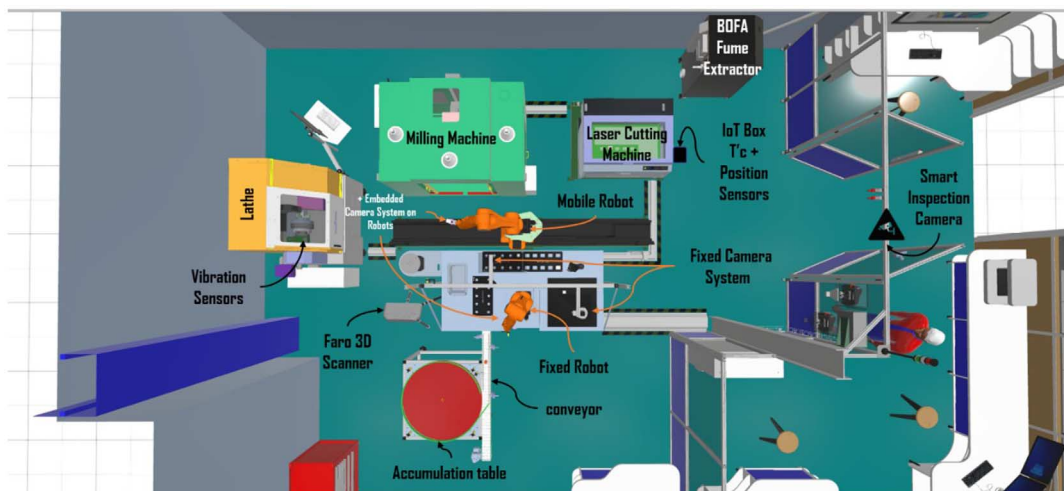
- The PLC layer plays the role of a moderator that arranges and distributes the variables between the MES and the smart vision system in a standardized way. In addition, the PLC is connected to the smart vision system via PROFINET and to the input/output of all machines on the shop floor by using a local network (Ethernet cables).
- The smart vision system layer is the inspection system composed of two smart cameras mounted on one fixed robot and one mobile robot. The smart cameras take photos and analyze them with their associated software and then communicate the analysis with the robots via Transmission Control Protocol/Internet Protocol communication protocol. Robots with smart cameras are combined together to form one component because of the full integration of the smart cameras with the robot software. Hence, the camera does the detection job and communicates the result only with the robot, which in turn exchanges information with the PLC and the MES.
- The shop floor layer is connected to the PLC and consists of all machines and stores on the shop floor.

Implementation of the Proposed System

The smart vision system was carried out and experienced in Platform 4.0 at the Product Design and Innovation Laboratory, Arts & Métiers Institute of Technology. This platform, presented in [figure 2](#), consists of three computer numerical control (CNC) machines: a two-axis lathe (Tormach), a three-axis milling machine (Tormach), and a laser cutting machine (Universal Laser System). In addition, there was a 3-D scanner (FARO) for quality control and two six-axis robots (KUKA) that allow part movements between these different areas.

The fixed robot only has access to the two storage areas and the conveyor, whereas the mobile robot can attend all machines, the table of the 3-D scanner, and the transition store area. Two embedded intelligent cameras (Sensopart VISOR Allround V20) were mounted on the robots, forming the smart vision system and enabling the industrial inspection and in situ control of conformity of the machined pieces. The camera communicates with the robot using PROFINET protocol. There is no direct communication between the camera and the PLC (Siemens S7-1500).

FIG. 2 ENSAM Industrial Platform 4.0 (3-D model). IoT = Internet of Things; T°C = Temperature.



SMART VISION SYSTEM EMBEDDED IN INDUSTRIAL ROBOTS FOR SHOP FLOOR MACHINE INSPECTION

The production engineer designs an inspection plan from functional modules by using the HMI of the MES (AVEVA System Platform). Each location that can contain parts is considered as an inspection module or inspection area, for instance, lathe machine or initial store (Init_Store). **Table 1** summarizes the list of all modules for the two robots with the corresponding cycle codes. Each module is predefined on the MES as well as on the robots in the form of a cycle. Once the MES communicates the corresponding cycle code to the robot, the inspection will be launched.

For better understanding of inspection modules, they are composed of a sequence of preconfigured and standardized operations and robot trajectories. **Table 2** shows a breakdown list of operations of lathe machine inspection module (Cycle Code 223 of **Table 1**). For instance, Robot Transfer is a robot trajectory that moves the robot from one place to another, camera triggering operations are used to start a detection program on the smart camera, and machine door handling is used to open and close machine doors. For the parameters, *S* refers to the robot's speed, *P_i* refers to the next position of the robot, and JobID is the program number from the smart camera software. Camera recognition programs are called jobs, and in the configuration shown, the robot is responsible for sending the JobID to be performed. Therefore, the results of the visual calculations are collected by the robots and sent to the MES together with the robot's current position.

Figure 3 presents the sequence diagram of the proposed system, showing the different executed tasks during the system operation.

The production engineer can arrange the sequence of the inspection by priority in the MES's HMI. The Inspection Modules box contains all the inspection trajectories currently available, and the operator drags

TABLE 1

List of machines' inspection modules

Functional Module	Robot	Cycle Code
Initial store inspection	Fixed robot	121
Transfer store inspection	Fixed robot	122
Conveyor inspection	Fixed robot	123
Laser cutting machine inspection	Mobile robot	221
Milling machine Inspection	Mobile robot	222
Lathe machine inspection	Mobile robot	223
Scanner 3-D inspection	Mobile robot	224

TABLE 2

List of operations of the lathe machine inspection module

Operation ID	Operation Description	Parameters
1	Robot transfer	(S, P1)
2	Trigger lathe panel inspection job	(JobID)
3	Open lathe door	(...)
4	Robot transfer	(S, P2)
5	Trigger tool identification job	(JobID)
6	Trigger tool wear detection job	(JobID)
7	Robot transfer	(S, P3)
8	Trigger part detection job	(JobID)
9	Robot transfer	(S, P4)
10	Trigger unidentified part job	(JobID)
11	Robot transfer	(S, P0)
12	Close lathe door	(...)

FIG. 3 Sequence diagram for shop floor machine inspection.

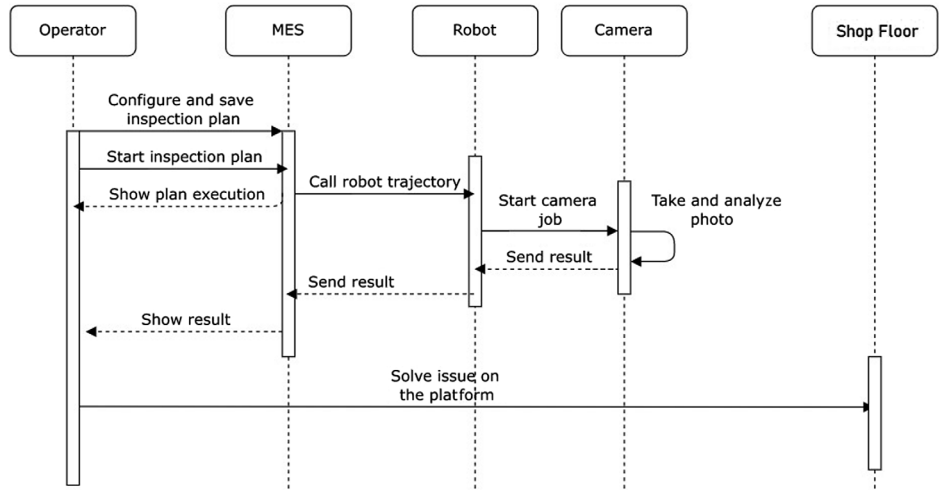
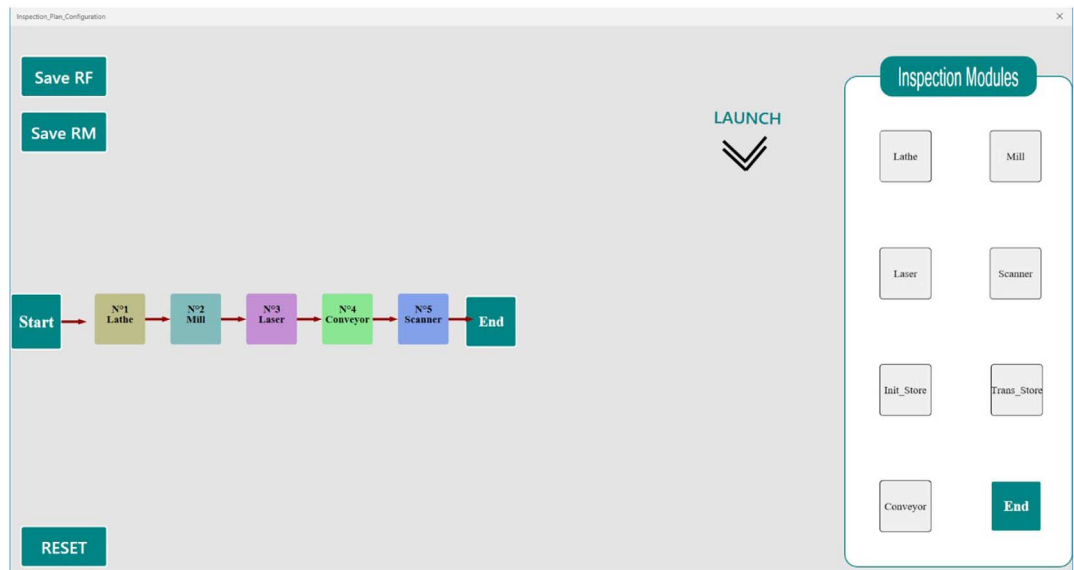


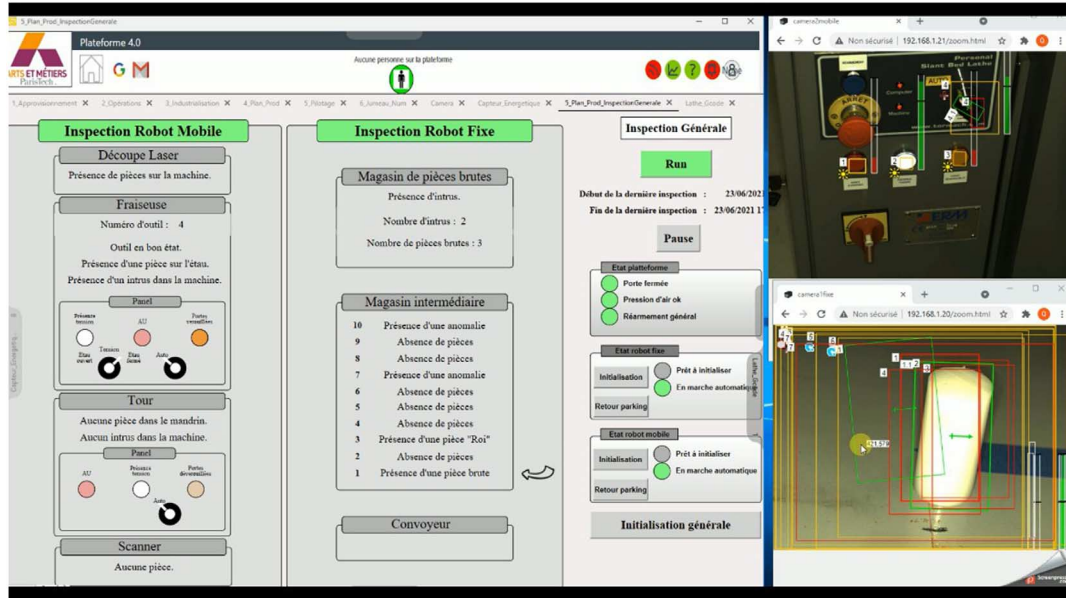
FIG. 4 Inspection plan configuration on the MES's HMI for Fixed Robot (RF) and Mobile Robot (RM).



and drops the trajectories after the START to create an inspection plan that is executed from left to right. Once finished, the operator adds the END block and can then SAVE the plan for each of the robots. **Figure 4** shows an example of the designed functional modules for fixed and mobile robots to perform industrial inspections. To start the inspection, the operator clicks on the LAUNCH button, which opens the **figure 5** interface. This interface allows the operator to get the robots ready for external usage and start the plan by pressing the RUN button. The two inspection boxes showcase the result of the camera in real time.

The detected parameters by this industrial inspection are the presence of parts inside the machines, type of parts, tool identification, and tool wear detection. In addition, the machine's electrical panels are inspected in

FIG. 5 Inspection's result on the HMI monitoring screen and the acquired images by the cameras.



order to verify the position of the keys and check the light-emitting diode lights to identify the emergency stop of the machine and the door status if it is locked or not. If any anomaly is detected, the MES will send an error message for an operator to fix the issue. The output of the industrial inspection is visualized on the HMI monitoring screen of the MES, as shown in **figure 5**, where the statuses of all the machines and the stores at the lab are presented. Therefore, the smart vision system is integrated with the HMI of the MES to orchestrate the inspection design and visualize the associated results.

SMART VISION SYSTEM EMBEDDED IN INDUSTRIAL ROBOTS FOR MACHINED PIECES' IN SITU CONTROL OF CONFORMITY

The in situ control of conformity is autonomously performed by using the same smart vision system previously described after the finished operation on CNC machines. Right after the lathe machine completes the execution of

FIG. 6 Camera installation on the robot and robot inspecting a machined part inside the lathe machine. (A) The camera mounted at the end of the robot, behind the gripper. (B) The robot entering the lathe machine to take a photo. (C) Close-up of (B) showing inside the machine.

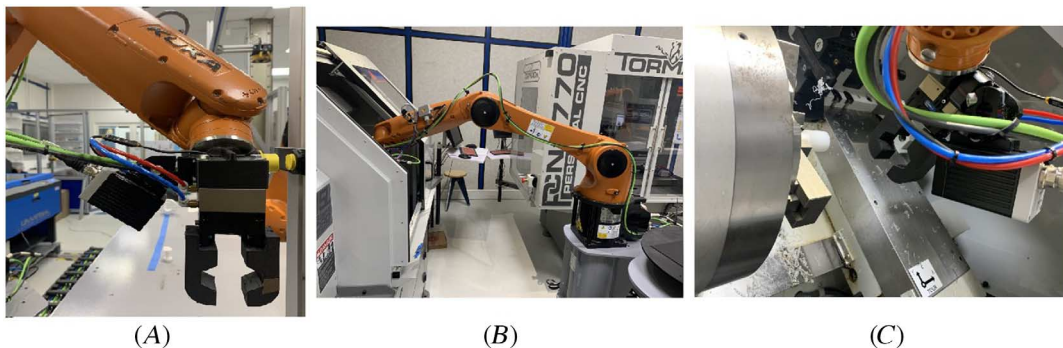
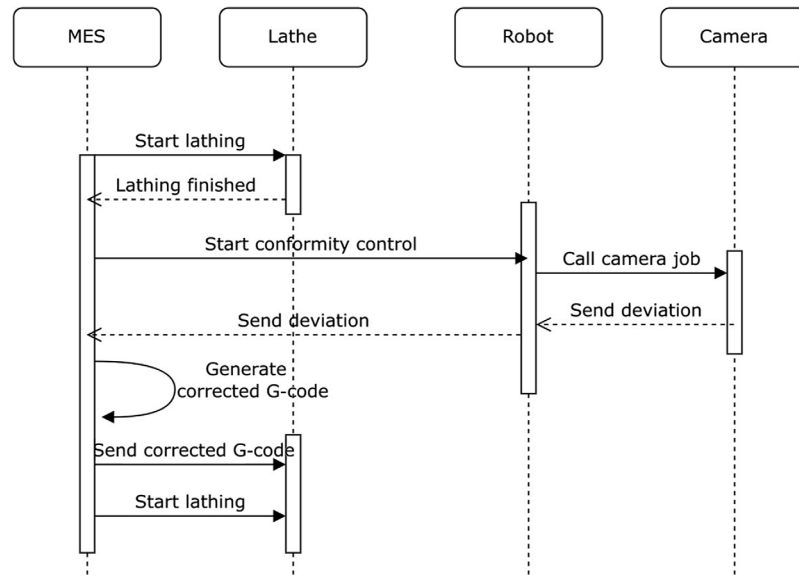


FIG. 7

Sequence diagram of the smart vision system for control of conformity.



the G-code, the machine sends to the MES that the machining is done, so the MES commands the mobile robot to move inside the machine to take images of the manufactured part and analyze it (fig. 6). Several dimensions of a machined part are inspected, and the deviation is measured. In the experiment, the diameter of machined parts is checked inside the lathe machine. The measurement obtained by the smart camera is compared with a reference dimension, and then the deviation between them is identified. The decision of the dimensional analysis is made based on the error value, and the robot communicates the dimension result to the MES.

The proposed approach is applied to a simple cylindrical part in which the original diameter is 30.00 mm and the desired diameter is 25.000 mm with an accepted tolerance of ± 0.05 mm. After performing a dimensional analysis of the part, the diameter is 25.680 mm, which is not acceptable and needs to be rectified. A new G-code is generated by the MES and sent to the lathe for execution to rectify this error. The new diameter is rechecked, and it is equal to 25.036 mm, which is acceptable. Figure 7 presents the sequence diagram of the in situ control of the conformity system in order to better explain the concept.

Results

To validate the usefulness of the proposed solution, the time it takes for an operator to manually realize the operation is compared with the time the robot with a camera takes.

For the first application (in the section “Smart Vision System Embedded in Industrial Robots for Shop Floor Machine Inspection”), an operator needs 3 min to inspect the entire platform, and the robots take 3 min 25 s. At first glance, the operator seems faster; however, human error is more likely to occur, especially because operators can forget to inspect some machines or validate this step without doing it carefully. Secondly, the platform is a simple production line with a small area; however, a factory can have huge number of machines to inspect, distributed in a huge space. In that case, the operator will take much more time than a robot. Finally, it is important to note that during the robot inspection, the operator is free to do other industrial tasks that will be more efficient for the production.

For the control of conformity application (the section “Smart Vision System Embedded in Industrial Robots for Machined Pieces’ In Situ Control of Conformity”), other means to attain it are either by an operator directly measuring the feature on the part or using a quality control machine, such as a 3-D scanner. The results are as

follows: 29 s for the robot, 54 s for the operator, and 4 min for the scanner. The scanner takes much longer because measuring a part with the camera or manually with a caliber takes a few seconds, whereas scanning is a long process. However, scanning gives better and more complex results than a simple dimension. The operator takes almost double the time compared with the robot. In addition, the operator has to enter the platform, which requires completely stopping the production for security. The other problem with quality control solutions is that they often require removing the part from the CNC, which decreases the precision.

The experiments show that the proposed solution leads to reducing the time required to perform dimensional analysis of products and is a promising solution for industrial inspection, especially in large-scale factories in terms of time, accuracy, and autonomy of the process.

Discussion

In industries, control of conformity and industrial inspections are critical tasks that are identified as cost and time consuming and require frequent human intervention. The proposed system in this paper uses smart vision technologies embedded in industrial robots to perform industrial inspection of all machines in a factory before launching the production plan and control of conformity through an in situ dimensional analysis of the manufactured parts after the machining process in an autonomous and flexible manner. This modular smart vision system shows flexibility, high efficiency, and time-reducing results, as previously explained.

On large production lines, the proposed industrial inspection and control of conformity system saves cost and time, not to mention its congeniality with mass customization production aspects in an evolving shop floor 4.0. Furthermore, the proposed system is in line with Industry 5.0 of the European Commission²⁹ because it complies with a more sustainable industry thanks to the gains in terms of safety and saving raw materials. In the experiments, a simple part was machined for demonstration. However, in more advanced factories with a huge number of machines and therefore more complex manufactured parts and a more dangerous environment,³⁰ the manual inspection and control of conformity of machined parts become more challenging. Hence, by using the proposed system, inspection time and cost as well as production quality could be improved dramatically.

Conclusions

In manufacturing systems, there are several essential tasks to be performed before and after the production process. In traditional systems, these tasks are done manually, which can lead to more resource consumption and the risk of human error; however, advanced manufacturing systems or Industry 4.0 tend toward a more autonomous manner. This study has presented a modular industrial inspection and control of conformity, combined into a single system, that uses a smart vision system embedded in industrial robots. This system, compared with the manual execution of the inspection and parts measurement tasks, shows high efficiency, high level of shop floor visualization, and time-reducing results.

Finally, the proposed system remains rigid and depends on various restrictions, such as the uncertain conditions of the workshop. Thus, as future research will show, the use of AI will enhance the system to detect disturbances and adjust measures according to them. In addition, it is important to utilize the collected data from this system in order to train a predictive maintenance model and to integrate the results into a numerical digital twin that can generate recommendations, such as changing cutting tools. Finally, a novel idea is under development at the platform 4.0 of LCPI, which is the installation of smart vision cameras inside the machines in order to continuously control the conformity of the parts during the machining process and to implement a corrective action in real time.

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