Multifunctional Cell for Complex Aerostructures Assembly and Aircraft Maintenance Assisted by Neural Network

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The main objective of the project is to develop and validate a robust multifunctional assembly cell, able to assist manual activities like the installation of typical fuselage systems and flight equipment, including the cabling throughout the cabin structures or the application of sealant. This cell will guide the worker thanks to Mixed and Augmented Reality during the assembly and inspection processes. The worker will be assisted by a Co-Robot, while Artificial Intelligence algorithm based on Neural Networks will continuously check the quality of operations. The system will improve the methods for assembling and inspecting aircraft and aerostructures, with significant cost reduction and improved competitiveness. The system will be validated at Pomigliano D'Arco Plant (ITALY), within the EU funded Research Project CleanSky2, in particular for the future Regional Aircraft Fuselage demonstrator assembly.

The future of aircraft manufacturing factories is oriented to more flexible and adaptable manufacturing systems, with new processes that enable shorter manufacturing cycles, higher environmental friendliness, and better energy efficiency and integration. In addition, new challenges come from the highly customized production that is aimed at manufacturing new aircraft under request, and from new materials that are making aircraft lighter and, therefore, more environmentally friendly. Such challenges are driving further changes in manufacturing new aircraft. In this way, future manufacturing industries also must be reactive, so that the time to market is reduced radically, and the quality level is kept high. Of course, companies also need to be cost effective to remain competitive in current globalized markets.
Aircraft manufacturers are constantly improving their products, ensuring that they are more cost-efficient and more environmentally friendly. One way to achieve these objectives is by reducing the weight of the aircraft, which results in lower fuel consumption. This has led to increase the use of composite materials within structures of aircraft. Carbon fiber reinforced polymer (CFRP) composite is used in industries whose products must feature high strength and rigidity in relation to weight. On the other hand the CFRP makes complex the assembly process and the inspection of aereostructures. To improve their competitiveness, aerostructures manufacturers are focusing their efforts on new designs of complex aerostructural components and on optimization and automation of processes. Among all the processes, the assembly operations of an aircraft accounts for more than 40% of the work in its manufacture. These operations have a considerable impact on the final quality of the aircraft, on its cost and on its manufacturing cycle.

Aircraft assembly demands the highest possible quality standards. The procedures are therefore complex especially when dealing with new materials, where the accumulated experience is shorter. The systems have complex configurations in an environment whose design and training cycle times are also getting shorter and shorter. The high complexity of procedures leads to errors, loss of time and increased costs due to wasted materials and rework. This results in loss of productivity and competitiveness.
Assembly of aircraft, including typical fuselage systems and equipment installation, cabling through the cabin structures, sealing/paste dispensing is still mainly done manually. Many of these activities are today in non-ergonomic conditions due to difficulties of access. Negative effects associated to manual work are:

- longer time for task execution;
- low accuracy and repeatability;
- limited presence of process information;
- reduced ability to detect failures in the process, which causes reworks;
- wrong and unsafe installations, due to errors or Foreign Object Damage (FOD).

The traditional manual approach to aircraft assembly seems to be insufficient, as it does not take both the maximum of the worker's skills and capabilities and it neither benefits from the new automation and support technologies.
In today's workplace, the increasing use of new technologies such as Artificial Neural Networks (ANN) in Artificial Intelligence (AI), Mixed and Augmented Reality (MR/AR) and Collaborative Robotic (Co-Robot) is helping to improve the productivity of many industries. Therefore, a future aircraft factory would be incomplete if essential technologies

were not considered. It is therefore necessary to innovate the assembly and quality control processes of aerostructures, taking advantage of the new support of these new technologies. This will help to achieve higher efficiency and quality in aircraft production and to reduce to zero the risk of failures due to manual activities.

OBJECTIVE AND CELL STRUCTURE

The proposed solution takes into consideration the driver factors needed for industrialization: increased structural integration, reduced total costs and structural weight, enhanced multifunctional materials, reduced environmental impact and extended duration of aircraft life.
The scope of the project is to develop and validate a multifunctional assembly cell, able to assist manual activities as the typical fuselage systems and equipment installation, including cabling throughout the cabin structures. These activities are complex because of: high number of similar part, path and accessibility, aircraft customization, etc. Manual operations may bring to wrong and unsafe installations, such as Foreign Object Damage (FOD) and reworks.
The multifunctional assembly cell is a platform based on state-of-art technologies such as neural network software, mixed reality, augmented reality and collaborative robots. These technologies will reduce to zero the risks mentioned above, by means of guiding information, model holograms overlapping the real state of installation, image analysis and various sensors.
The cell to develop and validate will be focused on an Artificial Intelligence software with neural network and will consist of the following main hardware:

- Co-robot for assembly, automatic sealing/paste dispensing and quality checks;
- Helmet for mixed reality application;
- Glasses for augmented reality application;
- PC, HD Cameras and sensors to implement applications and AI software.

The demonstrator for multifunctional assembly cell will be a fuselage barrel already designed to test the Pax Cabin features. It will include on-board systems and advanced solutions for increasing passenger comfort and safety, such as: FAS, Galley, Lavatory, EC Seat, T/A Insulation, Lining, Service Area, Stowage Bin, Lighting & Cabin Layout, E-ECS and systems.

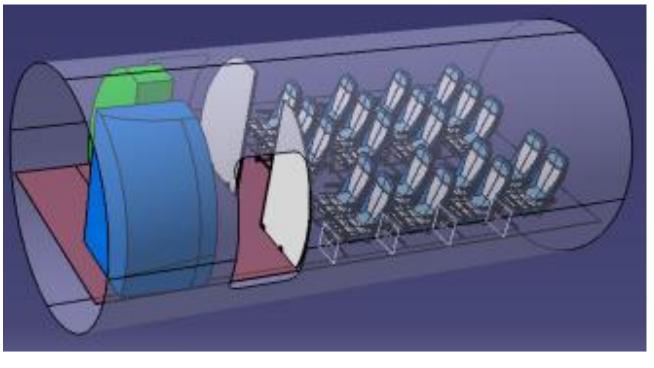

Figure 1 - Cabin demonstrator layout

Such demonstrator has been also considered as suitable demonstrator for the project and its tasks. The cell focuses on the development and validation of a multifunctional cell equipped with state-of-art technologies such as ANNs, MR/AR, and co-robots.
This cell will be applied to three use cases (Figure 2) that represent different manufacturing activities: structure installation (US1), wiring (US2), and robotic collaboration in structure installation, wiring and sealing (US3). These use cases will demonstrate, test and validate the developed technologies.

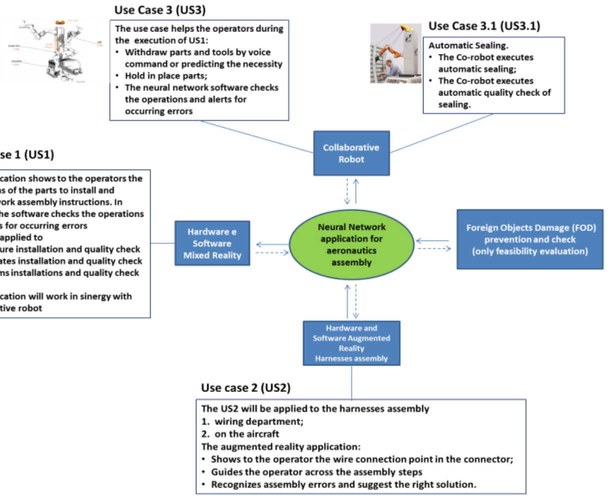

Figure 2 - Use case architecture to demonstrate the technologies

The application of these technologies in real working environments in the aircraft industry is challenging. Despite the proposed technologies have been already used independently in industry, they have been seldom combined to generate a complete support and verification tool. The project proposes the following specific objectives:

- SO1: To achieve aircraft quality targets higher than the traditional assembly process. The use of artificial intelligence for automatic quality control in the assembly line will reduce the number of discards, waste, failures and rework. It is estimated it will reduce by 80% the number of reworks, approaching to zero the risk of failures due to manual activities and by 80% the inspection time.
- SO2: To obtain designs with more restrictive targets in terms of weight and performance. The cell will be equipped with tools to assist the worker in the assembly process. Mixed and Augmented systems will guide the workers, and collaborative robots will assist them in carrying out certain tasks, while completing other tasks autonomously.
- SO3: Significant reduction of production cost, in terms of reduction of times/flows, in particular for complex manual activities. By 20% reduction in assembly direct time due to the automation and human-robot collaboration is expected and up to 25% cost saving due to less staff involvement (efficiency of the personnel cost).
- SO4: Innovative methodology to obtain manufacturing instructions from engineering models. The approach will use geometric reasoning algorithms to infer information from the geometrical description of a

product. This information will include the geometry of components, the logical structure of the assembly process (i.e. which components need to be assembled first due to its geometric constraints), the path of the sealant, etc.

- SO5: A paperless approach. The worker will access technical data and instructions during the manufacturing phases from mixed and augmented reality systems.
- SO6: Direct implementation of “as built” configuration and design changes management. The assembly cell will be provided with cameras to capture information of the actual process providing a mean for capturing the “as built” configuration and manage design changes.
- SO7: A feasibility evaluation will be done to study the use of artificial intelligence for Automatic FOD recognition and control.

To achieve that, the project has established the following operative objectives:

- OO1: To develop quality-checking systems using neural networks.
- OO2: To develop neural networks to identify assembly errors.
- OO3: To integrate a collaborative robot for improved aeronautics assembly.
- OO4: A mixed/augmented reality to assist and guide operators in assembly process.
- OO5: Automatize the extraction of manufacturing instruction from engineering models.
- OO6: A cost-benefit analysis of the multifunctional cell
- OO7: To implement four Use Cases to validate the cell performance.
- OO8: To develop FOD (Foreign Object Damage) recognition algorithms based in neural networks.

Thanks to all above, this project will lead to an increase in the assembly process performance. The project will consider artificial intelligence in order to create a platform that enables the completion of different assembly processes with higher quality standards. As a result, a zero risk of failures assembly process will be able to be a fact in the near future.

CONCEPT AND APPROACH

Project Concept and Approach

The development of cell will follow a V engineering model, where each step is represented by a work package (WP).

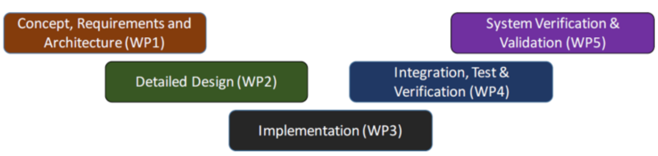

Figure 3 - Math of a V engineering model to the work package structure of cell

The first process is the conceptualization of the manufacturing activities defined by the use cases, and the definition of the requirements and of the architecture. This activity will be performed in WP1 “Cell architecture and Trade-off Analysis”. This is a critical activity in which will be analysed the current activities and how the cell will support the operator and automate some of the elements (using the co-robot or ANN based quality control).

In parallel to the specification of the cell, a trade-off analysis will be performed, taking into account different alternative architectures of the cell and how effective they would be when applied to the proposed use cases. This analysis will provide a first approximation to the expected improvements obtained by applying the support technologies to the processes studied in the use cases. KPIs linked to the project objective will be defined and an estimation of the benefits possible with the cell will be defined. Once the initial phase is complete, the project will move to the detailed design phase. This phase will be completed in WP2 “Engineering and manufacturing requirement definition”. This process will define the engineering models of the cell for each specific use case. To optimize project time and costs, where applicable the engineering models will include several use cases within the same model. This process will also generate guidelines for the development of the cell, including the usage of AI, MR/AR and Co-robots. Finally, the manufacturing requirements will be generated for each of the process included in the use cases when performed by the cell.

The development of the AI assisted cell will take place under WP3 “AI Assisted Cell Development”. The process will begin with a detailed design of the cell, including all its elements hardware and software. This process is intimately related to the specifics of the use cases of the cell, whose development will take place during the integration, test and verification phase that will take place in WP4 “Use Case Development”. WP4 will carry out a feasibility analysis about preventing and the checking the presence of Foreign Object Damage based on the capabilities of the defined cell. Foreign material comes in many shapes and forms. It may present itself as a hand tool, dust, grime, oil, metal shavings, loose nuts, bolts, cotter pins, lock wire remnants, pencil, pen, packing material, etc. (SO7).

One of the main challenges in the development of the cell is the integration of all its components and of the system with the industrial environment in which it will operate. For example, the cell needs to be flexible enough to handle changes in the specifications of the tasks to be performed, without requiring extensive rewrite of any of the software components (robot control software, MR/AR support tools, ANNs, etc.).

Typically, during the modification of a process (for example a new path for sealing) these changes are first defined by using computer aided tools for the geometry, modifying the manufacturing guidelines, etc. For this reason, it is necessary to develop a methodology that enables to transfer information from the digital definition of the process itself to the behaviour of the cell. This is a critical aspect for all the technologies involved, for example:

- artificial intelligence algorithms need to know the structure of a product to identify if elements are correctly assembled (US1, US2 and US3) or if the sealant is applied in the correct area (US3.1);
- assistance tools based on MR/AR need the structure of a task (i.e. the steps that need to be followed to complete it, what are the relevant holograms to present, etc.) to present the operator with the correct and

relevant information in US1 and US2;

- collaborative robots need to know what path they have to follow to apply sealant or where components are located (US 3.1).

Positioning of the project

The project will consist of innovation activities oriented to achieve a system prototype demonstration in operational environment (TRL 7) of technologies which are currently in an applied research level. Nowadays, technologies like mixed and augmented reality, robotics and ANNs (WP3) and productivity evaluation (WP5) are well-known in the industry and their use is growing. In manufacturing, many companies run AI-based computer vision algorithms for some of their activities in areas such as defect detection. Therefore, the Technology Readiness Level (TRL) for these technologies, understood in the context of the manufacturing industry sector, is higher than 7 in some applications. Nevertheless, in this project, these technologies will be used to develop an integrated multifunctional cell in which different activities will be carried out: installation of fuselage systems and equipment including cabling through the cabin structures, or sealing application. These activities are complex due to the high number of similar part, path and accessibility issues, aircraft customization, etc. Since the technologies used need to be adapted to these conditions, the starting point for the development of the cell can be considered TRL 5-6.

In the case of collaborative robotics and mixed and augmented reality, they are known and are typically used separately, but not in an integrated, industrial and optimized form. Hence, their TRL is 5. However, as a result of the project, these technologies will be validated and demonstrated in an operational environment, achieving TRL 7.

Therefore, this cell goes a step beyond by integrating all these technologies in a single solution. The project will develop and validate an integrated multifunctional assembly cell able to perform different type of operations guided by ANN software.

Overall Approach And Methodology

The objective of the project is the development of an AI assisted cell capable of assisting in several task required in the construction of aircraft such as:

- quality checking;
- installation of components;
- application of sealant;
- assembly of harnesses;
- assist operators by holding components or withdrawing parts;
- assist operator providing access to technical specifications;
- alert the worker when assembly errors happen.

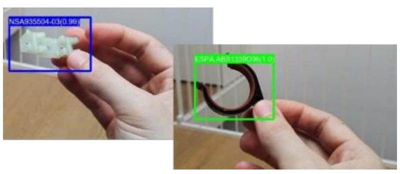

Figure 4 - Parts recognition by ANN software

The cell will be able to assist operators in some of these tasks, while it will be able to complete others autonomously (such as sealing application). The cell will ensure the quality of the results of each task using neural networks. The cell will use several Industry 4.0 technologies such as:

- Artificial Intelligence for inspection, quality control and assembly errors identification;
- collaborative robotics to assist the worker and complete some tasks autonomously;
- Mixed and Augmented Reality to guide the operator and provide a bidirectional communication channel between the operator and the cell and its components.

To achieve this and the project objectives, is proposed the development of a methodology (SO4) to obtain manufacturing instructions from engineering models to capture the relevant data from the engineering description of each task of the three use cases. Geometric analysis of the CAD model will be used to obtain the dependency relationships between the assembly of the different components, i.e. which are the possible orders in which the components can be assembled, and thus which components should be present at a given time. This information will guide the operator along the process and will check the state of the assembly of different components. The CAD information will be also exploited for other activities, such as the generation of motion plans for the collaborative robot or to trace the position of the harness of the plane. All this information will be structured and stored for use by the different elements of the cell. From this, we can see two different types of information will be at work in the cell:

- static information that defines the activities (such as components, assistance information, quality control actions, path to follow for sealant application etc.) that can be obtained from the definition of each task;
- working information used during the actual execution of a task (such as what is the current operation, what is its state, what is the position of the robot, etc.), that will change during the execution of the tasks of each use case.

Considering this distinction it is proposed, as part of its methodology, to obtain manufacturing instructions from engineering models, to define two software modules to handle these sets of information (Figure 5): the manufacturing instructions module and the activity planner.

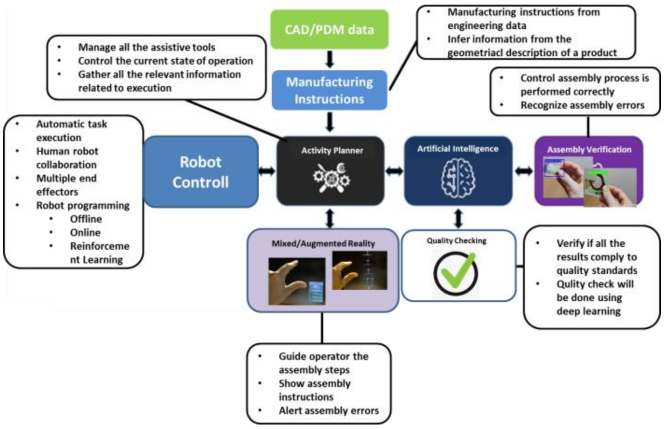

Figure 5 - Cell structure

The Manufacturing Instructions module will handle the static information.

Even if this information does not change for a certain product, this module needs to be able to handle different configurations of a product, changes to these configurations, and modifications to each procedure. This module will employ geometric reasoning algorithms to obtain the relationship of assembly of different components from its CAD product structure either automatically or with the help of a user. The process will also automate the generation of simulation environments for robotics importing data from the engineering models of the use cases into simulation tools such as Gazebo. All this information will be structured and safely stored for its use by the different components of the cell during execution. The information of the assembly process, for example, will be stored in a generic graph structure (such a Petri Net) that enables the generation of alternative procedures.

The Activity Planner will handle the dynamic state of the cell during its operation. It will use the information generated by the Manufacturing Instructions module, data from the sensors installed in the cell and information and instructions provided by the operator as input to define the current state of the task and provide the relevant information to all other hardware and software modules composing the task. Once the cell is running, it will use the manufacturing instructions to orchestrate the actions of the different agents that can potentially act to complete a task: the operator, the ANNs checking for quality control, the collaborative robot and the assistance software based on mixed or augmented reality depending on the specific use case. This planner is a software agent that oversees the actions of all other participants in the completion of a task and will plan the course of actions using a structured decision-making approach. It will, for example:

- communicate with the worker using mixed or augmented reality application to provide instructions and get input (using a specific interface and/or voice commands);
- Indicate to ANN-based agents in charge of quality control what the current task is and receive feedback from them about the results.
- Transmit to the control software of the collaborative robot control what its current task is, and receive input from the robot about its state and the state of its actions, i.e. is the action complete?

A flexible AI architectures based on ANNs, will be used to handle the quality control processes (SO1). Contrarily to traditional approaches AI based technologies, such as artificial neural networks, they are demonstrating to be very efficient in solving computer vision problems in a flexible way. Neural networks require great amounts of data to train them and being effective. To solve this problem pre-trained neural networks for industrial applications will be used, and using the technique of transfer learning, the final neural networks for quality checking will be generated. In the project will use ANNs for:

- automatic quality control in the assembly line, reduce the number of discards, waste, failures and rework. Is estimated to reduce in 80% the number of reworks, approaching to zero the risk to failures due to manual activities and 80% reduction of inspection time;
- assisting the worker during the assembly process detecting assembly errors, thus helping reduce the risk of failures;
- a feasibility evaluation will be done to study the use of artificial intelligence for Automatic FOD recognition and control (SO7).

Developing a neural network from scratch takes a long time, if possible the cell will base its neural networks on architectures that have already proven their effectiveness in similar problems: R-CNN[1], Fast R-CNN[2], Yolo[3], or RGB-D approaches[4]. This architecture will be modified to handle the quality checks.

To achieve this, the cell will be equipped with different hardware devices. High definition and depth cameras will be placed in the cell. These will be used to identify if all the assembly steps have been completed correctly: all parts have been installed, the parts have been placed in the right position and with the right orientation, the harnesses have been assembled without errors. Other devices such as laser scanners will be used to perform other inspections, for example in the sealing operation US3.

Depending of specifics of the Use Cases, the inspection devices will be guided by a collaborative robot. The co-robot will take two main roles in US3: completing tasks automatically (such as applying sealing US3.1) or assisting operators during manual tasks (i.e. assisting manual tasks of US1 and US2 in US3). The robot must handle different tasks in the assembly process, so it will be equipped with different end effectors: a robot gripper to hold assembly parts, a sealant dispenser and inspection devices for quality checking. The incorporation of co-robots in the workplace provides additional complexity to the planning of manufacturing tasks, since the actions of the robot have to be coordinated with those of the worker. In addition, even if modern co-robots are designed to be safe when working with a worker in the same space (coexistence), the workers need to adapt themselves to the presence of their new mechanical companion, to avoid collisions or injuries.

This issue will be approached from several points of view. First, the manufacturing instructions module will generate information, such as virtual models for the offline programming of the robots. These models will be used in a simulation tool such as Gazebo or a more advanced simulator developed in Unity. Motion planning algorithms in static scenarios will generate predefined trajectories for situations where uncertainty is low, such as the trajectory to follow to apply sealant. During execution, these models will be completed with information from the cell sensors to generate dynamic trajectories in those cases where collisions with unexpected elements, such as the worker, are possible. In this case, the trajectory will be generated either using traditional motion planning or by using reinforcement learning based on ANNs. The robot will also communicate during execution with the Activity Planner to coordinate its actions with the overall state of the task. All the control software of the robot will be integrated with ROS, since it simplifies the integration of devices and algorithm, while allowing a very flexible, responsive and open architecture.

Finally, a critical aspect is the coordination of actions between the robot and the worker. This requires the development of an interface between the two. The mixed or

augmented reality assistance tools will serve this purpose. Thus, the robot will be able to communicate its state and intentions through a virtual interface (visualizing the motion trajectory to complete using a MR device). The operator will be able to also communicate with the robot to define specific task or help the robot in uncertain situations.
The cell will take advantage of these capabilities presenting the worker with information relevant to the current task such as:

- Holograms presenting where a component is missing (US1);
- Assembly instructions integrated in the real environment through a mixed reality headset (US1), or as a list using augmented reality glasses (US2);
- Position of the robot and programmed motion, a hologram will present the action of the robot before its actual execution (US3).

MR helmets and AR glasses usually have additional hardware capabilities that will be exploited, like cameras and microphones. When possible the cameras (both colour and depth cameras) will be used as an additional input for the system. Thus, the system will have a point of view of the worker. This information will be fed to other modules as input to the ANNs in quality control or in the control of the robot.
If possible, taking into account the noise conditions of the factory, voice commands will be used as input by the worker. One of the main advantages of voice interfaces is that they enable a hand-free operation.
On the other hand, the use of MR/AR adds an additional difficulty to the correct planning of the activities of each use case in which they are applied, since it requires the generation of the appropriate contents and the testing of the information provided. This aspect will be handled by using information gathered from the Manufacturing Instructions module described above, to automate the generation of instructions for the worker. In the case of MR, the information from CAD models will be exported to standard formats such as STEP for its presentation as holograms, using a visual engine such as Unity 3D.
Both the use of the co-robot and of the MR/AR assistance tools will help achieve Strategic Objectives SO2 and SO3. Mixed and Augmented assistance tools will guide the workers and collaborative robots will assist them in certain tasks while completing others autonomously. One of the objectives of the cell is to leverage these technologies for a true paper-free approach (SO5) to engineering. Using mixed reality helmets and augmented reality glasses the operators will directly access the information stored by the Manufacturing Instructions through the MR/AR applications. They will be also capable of feeding back information to the system. The same tools, including all the input from the sensors of the cell and the state of the process, will also be used to implement a capture the “as-built” configuration of the product (SO6): images of the final state of the process, validation data of the control quality processes, completed steps, section of applied sealant, etc.

CONCLUSIONS

The development and validation of a multifunctional assembly cell assisting, through Neural Network, complex manual activities such as the installation of typical fuselage systems and flight equipment, will provide a breakthrough step in Aircraft Industrial processes. This cell will guide the workers using Mixed and Augmented Reality during the assembly and inspection processes. The worker will be assisted by a Co-Robot, while Artificial Intelligence algorithm based on Neural Networks will continuously check the quality of operations. The system will improve the method to assembly and inspect aircraft and aerostructures, with significant cost reduction and improved competitiveness.

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