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Robotized assembly and inspection of composite fuselage panels: the LABOR project approach

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Abstract. The aerospace manufacturing is looking at ways to change their production processes in order to improve costs, flexibility and efficiency. The LABOR project, acronym for *Lean robotized AssemBly and cOntrol of composite aeRostructures*, aims at introducing robotic solutions for the assembly line of fuselage panels adopting medium size robots equipped with smart tools, Human Robot collaboration approach and a distributed software architecture. The system consists of a jig that holds the panel to be assembled, two 6-axis robots mounted on moving platforms in order to reach the whole panel and real time measurements to perform the quality control of the assembled components. The cell automatically performs the referencing of the robot working area on the basis of the recognition of geometric features of the parts to be coupled (edges, holes, etc.) through the use of 3D smart inspection tools. After the "one shot" drilling and countersinking operations, the hole is processed to guarantee a high standard of the process. Installation and sealing of the fastener complete the working cycle. Furthermore, an advanced multimodal perception system monitors the collaborative workspace in real time for safe human-robot collaboration (HRC) tasks. The project started in March 2018 as part of the European Clean Sky 2 research program. Three partners - LOCCIONI, UNICAMPANIA and UNISA – are developing the prototype cell in collaboration with LEONARDO S.P.A. that is the Topic Manager.

1. Introduction
One of the main challenges in aerospace manufacturing is to increase the level of automation to improve quality standards, production and efficiency rates and flexibility. These objectives have been reached by means of a lean and flexible automated solution in replacement of manual assembly or complex ad-hoc machine constructions and/or high-payload robots.

1.1. The LABOR project
Aeronautical robotic applications adopt quite heavy and big robots equipped with large, usually multi-functional end effectors (see Section 1.3). LABOR [1] proposes the uses of an assembly jig

to hold the panel and two medium size 6-axis robots, namely the internal and the external robot with respect to the curvature of the panel, mounted on linear axes to reach the full length of the panel. A smart inspection tool allows real time measurements and robot self-adaptation to the environment in which they move and to the performed operations. Self-adaptive processing tools for composite structures perform an automatic drilling and fastener insertion, guaranteeing high accuracy. LABOR significantly lowers costs and makes maintenance and programming easy through a distributed intelligence architecture.

1.2. The LABOR requirements
The full demonstrator is compliant with a Technology Readiness Level (TRL) 7 and assemblies a section of fuselage composed of 6 panels containing both windows and doors and divided in a AFT and FWD sides. The assembly cycle starts by referencing the robot working area on the basis of the recognition of geometric features of some parts to be coupled (edges, holes, etc.). Then, a "one shot" drilling and countersinking operation is performed before applying sealant on the proper fastener and complete the automatic cycle by installing it on the panel. These operations are executed on skin shear ties, stringers, intercostal and stringer splices. These components are assembly in three steps: firstly, they are drilled and countersunk by the robots and, then, they are manually removed by human workers for further manual operations. Finally, the workers reinstall the parts on the skin panel and the LABOR cell completes the sealing and riveting operations. The target cycle time is 30 s per hole (excluding fastener inspection) on a CFRP and thermoplastic compound panel with 9 mm grip fasteners. The assembly panel material is a stack CFRP + CFRP or CFRP + Aluminum, with 10 mm maximum thickness. The positioning tolerance is ± 0.2 mm and the normal precision is less than $0.5°$. The system allows co-working activities when human operatiors enter the workcell to insert and remove temporary connecting part, to apply sealant by interposition and to remove metal burrs on the edge of the holes. HRC module is compliant with the current standards as ISO 10218-1/2 [2] [3] and ISO/TS 15066 [4].

1.3. Related works
According to the Global Market Forecast 2018-2037 [5], there is a strong need to increase productivity in the aviation industry to reduce the production costs and increase their efficiency rate. Use of automatic or robotic solutions is very limited especially for regional aircraft manufacturing lines: the high required positioning accuracy can be guaranteed only by using external expensive metrology systems. Existing solutions for fuselage assembly are Airbus A320 [6], Bombardier CSeries Aircraft [7] and FAUB [8] which adopt large robots, heavy end effectors and expensive measurement systems to compensate the unavoidable calibration errors and the limited absolute accuracy, making it impossible to realize HRC activities. On the contrary, in 2017, the VALERI project [9] proposes a mobile manipulator with tactile sensors for supporting human operators. The use of collaborative robots and physical-contact detection systems are unsuitable for industrial purposes because they introduce unsafe solutions and unnecessary production-time loss and low efficiency. Concerning the smart tools, one of the most multi-functional end effectors for composite aerostructure assemby is the MFEE by Kuka Systems Aerospace [10] which possesses functionalities compliant with LABOR but, due to its weight and dimensions, it requires a robot payload higher than 210 kg, as well as, it reaches a positioning accuracy limited to ± 0.5 mm.

2. Workcell Design
The LABOR workcell is shown in Figure 1 and mainly consists of an assembly jig and two 6-axis robots. The former holds the fuselage panel and is equipped with two motors which rotate

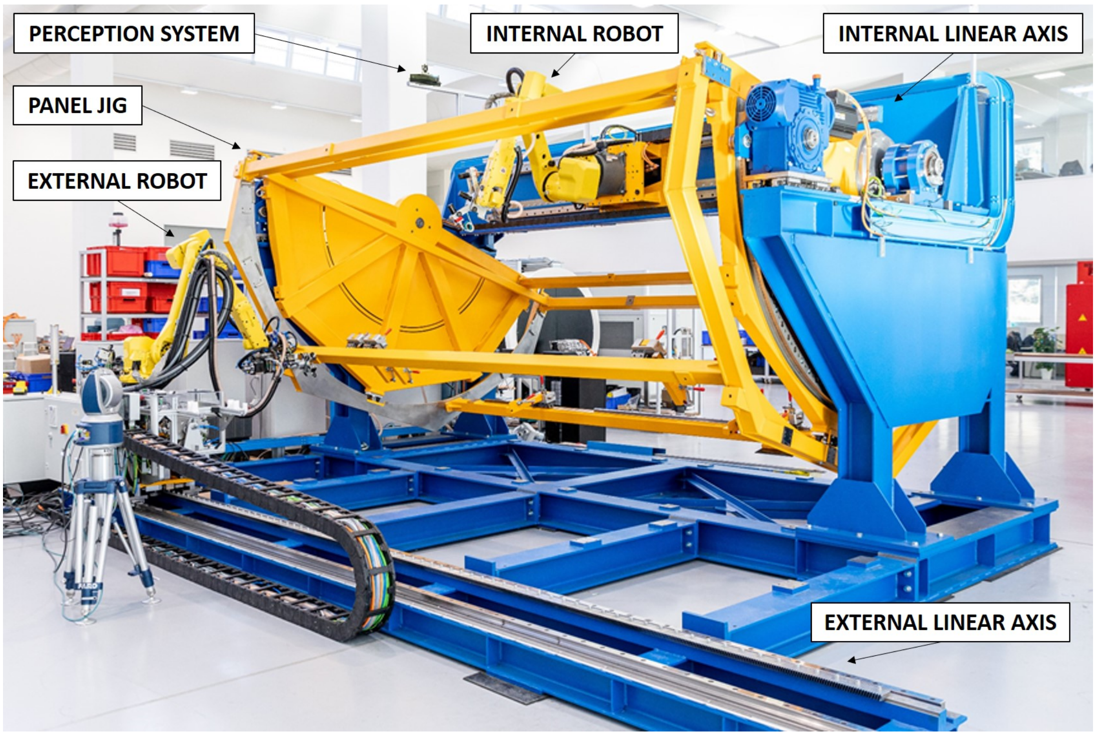


Figure 1: Final workcell design.

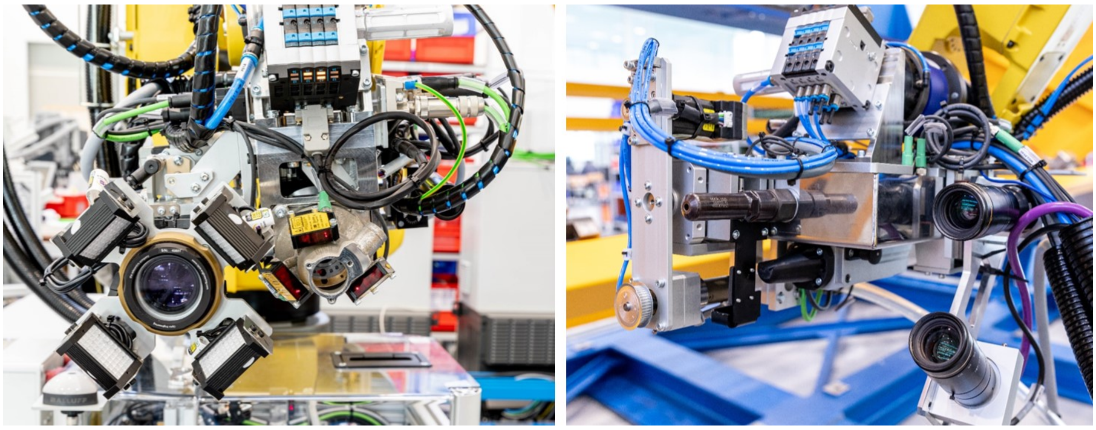
the panel during the assembly process, while the robots are mounted on the two sides of the panel and are mounted on linear axes. The cell is supplied with an advanced perception system to monitor the collaborative workspace (see Section 3). There is a *Fastener warehouse* which handles up to 8 different fasteners (with variable diameters and lengths), a *Drilling tip warehouse* which is a carousel of 15 positions, and a dedicated *HRC workstation*. Safety fences are installed to guarantee the operator accessibility. Four dedicated smart tools have been developed.

The external robot handles two different tools (see Figure 2a) that can be exchanged through a quick tool change system placed on the robot basement:

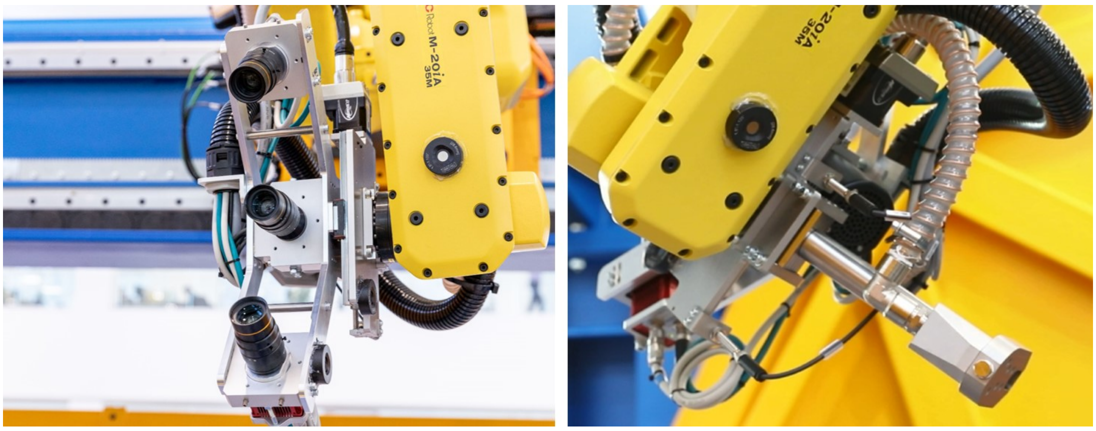
- *Drilling and 2D Inspection Tool*: the robot approaches the drill point and performs an orthogonal alignment with the panel skin through the 3 laser sensors installed around the drilling nose. An automatic electrospindle is mounted on a linear axis to control the advancing motion during the drilling task. A vacuum pipe removes powder and chips, while a force sensor controls the robot during the panel stack clamping. A lubrication system and two telecentric lens on two 2D cameras have been integrated to perform the hole and countersink inspection, i.e. fastener flushness, locking ring, stem height, hole and countersink diameter measurements and absence of burrs check;
- *Fastening and sealing tool*: the pneumatic gripper has been conceived to hold the fastener end. The fastener is automatically selected from the *Fastener Warehouse* and is brought to the gripper tip through a pneumatic transmission system. The fastener is rotated to execute the sealing application through a pneumatic rotary actuator. The sealant gun has been housed into the tool mechanical structure, and connected to the electrical motor that controls the sealant dispensing. Finally, a structured LED light pattern projector and the 2D camera have been integrated to execute the fastener flushness measurement.

The internal robot handles only one tool that is fixed on the robot flange (see Figure 2b). The tool is composed of two parts: the counterthrust tool and the 3D internal inspection tool:

- *Counterthrust tool*: the main component is the counterthrust rod that has been connected through to the suction pipe with the cell aspirator;
- *3D inspection tool*: the structured LED light pattern projector and the three cameras composing the tool have been installed on a screw-nut mechanism actuated by the electric motor. The tool executes the referencing of internal robot with respect to internal panel features and the installed fastener measurements, i.e. delamination and fastener sleeve height and diameter measurements.



(a) External robot tools: *Drilling and 2d Inspection Tool* (left) and *Fastening and Sealing Tool* (right).



(b) Internal robot tools: *3D Inspection Tool* (left) and *Counterthrust Tool* (right).

Figure 2: External and internal robot self-adaptive tools.

From a software point of view, the main concept of the LABOR architecture is the development and the integration of different intelligent modules. Each module is an independent node which manages all the hardware components and it is related to and communicates only with the HMI module, the cell supervisor. Commands and feedbacks are sent from/to the HMI modules through an OPC-UA bus, the communication protocol chosen according to its intrinsic flexibility, adaptability, transparency which have to be fulfilled to satisfy the distributed intelligence approach. The interaction and communication of each module through the network allow to build a more complex system and to achieve the final complete task.

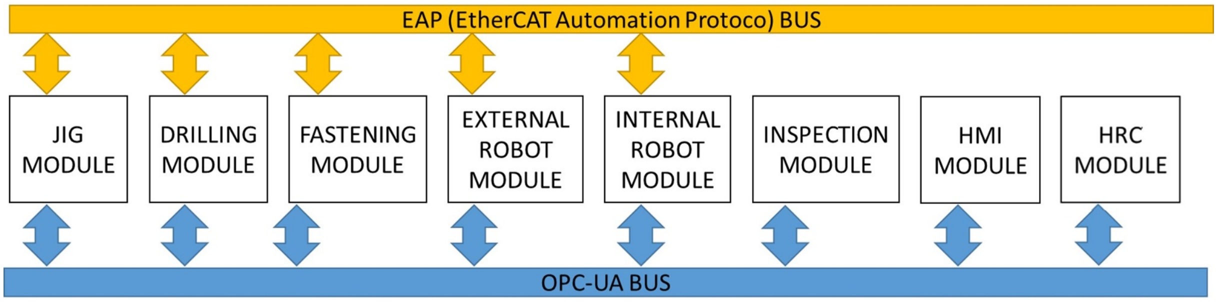


Figure 3: Distributed intelligence architecture.

3. HRC Module

Collaborative robots are typically not used in aerospace manufacturing because of their maximum payload of 35 kg and their limited force-torque safety function. Using conventional industrial robots of medium size for a collaborative cell is possible when integrated them with a safety-rated monitoring system [11]. The LABOR HRC module complies with the robot safety standards ISO 10218-1/2 and TS 15066 by implementing a *Speed and Separation Monitoring* (SSM) scenario. SSM *suggests* to compute the minimum protective distance, S, by considering the maximum robot speed, v_R, as well as the typical human speed, v_H (2000 mm/s):

$$S = \alpha[(v_H T_R + v_H T_S) + (v_R T_R)] + (B) + (C + Z_S + Z_R), \tag{1}$$

where T_R is the time required by the system to identify the operator, T_S is the time required for a complete robot stop, C is the intrusion distance, Z_R and Z_S are the robot and the human position uncertainties and B is the Euclidean distance travelled by the robot while braking.

While the standard equation 1 not foresees α (i.e., $\alpha = 1$), the LABOR approach introduces α representing a scaling factor which evaluates the current risk assessment analysis (see Section 3.2). Moreover, the adopted solution heavily considers the current v_R and v_H.

3.1. Related works

Standard optical protection devices use laser scanner technology to separate humans from the robots [12]. The off-the-shelf devices ([13] and [14]) divide the layout of the shared workspace into three zones associated with pre-defined, constant robot speeds which are selected according to the worker distance from the robot. In literature, motion capture systems are combined with range sensors [15] or artificial vision systems [16] for distance monitoring. This is the most suitable approach for pure coexistence in a collaborative workspace but the current solutions are no robust for industrial applications and produce a high percentage of false positives during the human tracking step, thus producing unnecessary robot stops which get worse production time. On the other hand, a common approach for the robot speed monitoring consists in using a reactive motion planning that modifies the pre-programmed path to generate a new collision free path [17], [18]. Unfortunately, in manufacturing environments it is often required not to modify the robot pre-programmed path because it can involve violation of some constraints. Reliable monitoring of the dangerous zone can make the robot slowing down when necessary, as shown in Section 3.2.

3.2. Reliable human detection and control system solution

The adopted multimodal vision system combines the 3D data, acquired from a depth sensor, with their thermal information, read from a thermal camera. Details about the whole developed pipeline have been originally reported in [19]. By merging depth and thermal data through a

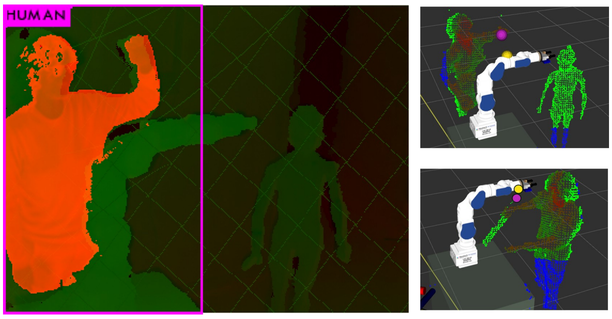


Figure 4: Reliable human detection: the depth-thermal image (left) read by the CNN to distinguish human operator from a plastic mannequin and thermal point cloud (right) showing the purple sphere belonging to the human cluster at minimum distance with respect to the yellow robot sphere.

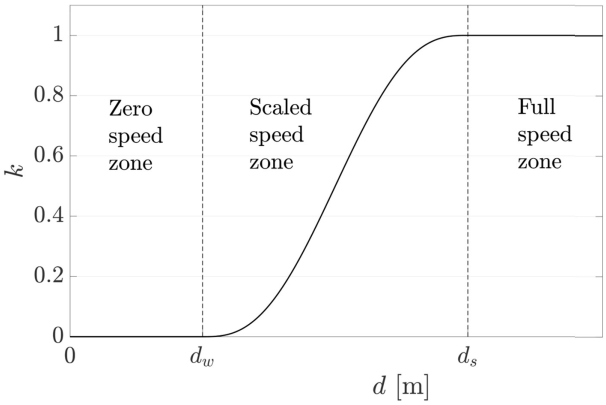


Figure 5: Relation between d and k; S is the minimum separation distance computed in real time as in equation (1)

novel image mapping approach (Figure 4 left), a retrained YOLOv3 [20] convolutional neural network (CNN) executes a reliable detection of human workers. In real time, a thermal point cloud computes the separation distance, d, between the human worker and the robot, thus selects both $\boldsymbol{p_R}$ and $\boldsymbol{p_H}$ (with its own temperature), the point belonging to the robot surface and the one belonging to the worker, respectively (Figure 4 right). From this step, the algorithm extimates v_H and v_R, i.e. the magnitudes of the instantaneous velocities of these points, projected along the direction identified by them. By collecting this data, S is computed as in equation 1, considering the current values of d, v_R, v_H, the temperature of $\boldsymbol{p_H}$, as well as the current risk assessment estimated through a fuzzy logic which computes in real time the α value ([0,1]). By comparing S and d as shown in Figure 5, the control algorithm estimates the scaling factor k ([0%, 100%]) to be directly used as the speed override of all the robot motion instructions. More details are reported in [21].

Table 1: General aircraft panel assembling operations without and with HRC

	WITHOUT HRC		WITH HRC	
OP CODE	HUMAN	ROBOT	HUMAN	ROBOT
OP10	Shear ties, frames and aluminium stringers assembly on SFRP skin	NA	Shear ties, frames and aluminium stringers assembly on SFRP skin	NA
OP20	Panel drilling	NA	NA	Panel drilling
OP30	Panel countersinking	NA	NA	Panel countersinking
OP40	Hole inspection	NA	NA	Hole inspection
OP50	Stringers de-assembling	NA	Stringers de-assembling	NA
OP60	Stringers cleaning	NA	Stringers cleaning	NA
OP70	Stringers deburring	NA	Stringers deburring	NA
OP80	Sealant application	NA	Sealant application	NA
OP90	Stringers re-assembling	NA	Stringers re-assembling	NA
OP100	Panel riveting	NA	NA	Panel riveting

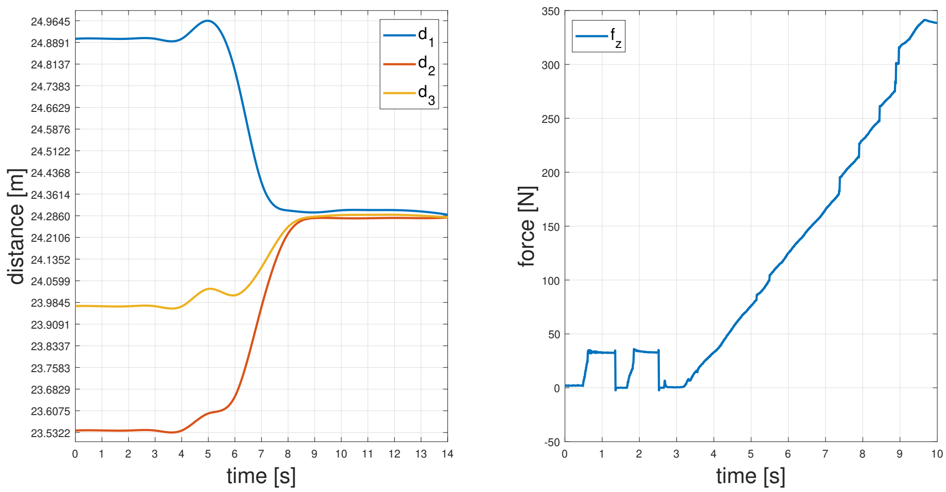


Figure 6: Distances read by the laser sensors during the alignment operation to ensure the drilling axis is orthogonal to the panel skin (left); clamping forces measured during the panel stack clamping operation (right).

3.3. Optimization of the collaborative work cycle

To fully exploit the HRC module functionality, the work cycle of the SIDE FWD panel, which needs the combination of both robot and manual activities, has been redefined with respect to a fully-automated work cycle (Table 1). The main idea is that the human worker and the internal robot can work simultaneously on different panel areas. This approach ensures the human safety by executing the collaborative algorithm described in Section 3.2. Simulated analyses estimate that the time to manually assemble the panel is around 15 h. LABOR reduces the working time of about 40% with a standard fully-automated working cycle, while the percentage rises by using the HRC module (48%).

4. Cooperative control of robots

The application of a clamping force is needed to produce a local stiffening of the panel, in order not to bend or damage it and to avoid burrs in the interface between the different parts of the stack during the *one-shot* drilling operation. This objective has been achieved through the use of cooperative thrusts from both robots, based on force measurements. The external and internal robots coordinate themselves to build up the desired clamping force thus realizing the clamping of stacks of material. Note that the adoption of force sensors allows the monitoring of forces during the entire drilling process.

The open-loop solution is based on the idea that both the drilling tool of the external robot and the counter-thrusting tool of the internal one push the panel until a force threshold is reached. The operation is divided into three thrusts, as shown in Figure 6 (right): the external robot approaches the panel and applies 30N along the drilling axis in 1.5s, then the internal robot approaches the panel in the opposite direction by applying 30N in 1.5s and, finally, the external robot completes the pre-load application till 340N. Note that sensor readings are zeroed after each thrust to specify only force variations. To guarantee the required hole axis angular tolerance of ± 2 deg, before the clamping force operation, the drilling axis of the external robot is aligned to ensure normality to the panel surface. The alignment operation rotates the robot tip around the drilling point by reading the values of the three laser sensors mounted on the drilling tool till the three distances are inside the required tolerances, as shown in Figure 6 (left).

5. Conclusions

The paper describes the main requirements of the LABOR project, the main components of the cell and the operations to be performed, i.e. drilling, sealing, fastening, inspection, HRC by summarizing the main proposed approaches. Based on these requirements, the developed drilling, fastening, sealing, clamping, referencing and inspection tools are presented paying attention to the dimensions of the tools and the number of tool changes required in order to meet the objectives of the project, i.e. to adopt the concept of lean automation involving the use of small/medium size robots. Moreover, ergonomics, flexibility and reduced costs of the overall structure has been described, as well as an overview of the developed human-machine collaboration system architecture. A video showing the main functionalities of the LABOR cell is available at `https://images.loccioni.com/Share/142d68f4-49f9-4b46-bb96-621e3440042b`.

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