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Research paper

VISTA — Vision-based inspection system for automated testing of aircraft interiors: A panoramic view ☆

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ABSTRACT

Automation is a driving force in manufacturing, enabling quality and scalability during production and assembly. In contrast with the automotive industry, civil aerospace automation has traditionally lagged. However, the adoption rate of methodologies embracing automation for manufacturing, assembly, and testing is now accelerating, with new technologies being tested to enable reliable and safe assembly and inspection steps. This paper introduces a semi-automated system for quality control during the final production steps of single-aisle aircraft, namely after the automated assembly of hatrack and sidewall elements in the passengers' area, but before any seating elements are assembled in the environment. Quality control is performed using color and 3d cameras mounted on a custom holonomic mobile robot. The acquired data is processed for identifying geometrical or surface defects by using machine learning based models and 3D processing-based algorithms. The results are provided to an inspector officer using different on-site and off-site validation modalities. The obtained results enable us to affirm that the proposed solution looks very promising for semi-automatic quality control, and it can serve as a foundational framework for efficient manufacturing in the aerospace industry.

1. Introduction

Automated processes are vital in modern manufacturing. The automotive industry, benefiting from a favorable historical context, has achieved faster economies of scale, driving automation ahead of industries like aerospace. This difference is particularly evident in quality control, where automation lags behind the production and assembly phases.

Several factors make automating quality control in aerospace riskier. Primarily, the civil aircraft market is niche compared to automotive. For instance, jet production was within three digits in the 20th century [1]. Although recent GAMA reports indicate accelerated production [2], these numbers remain minuscule when compared to over 10 million cars produced in the U.S. in 2023 [3], limiting investments in innovation.

Nevertheless, the need and drive for automation should extend beyond economics. Inspectors in aerospace repeatedly perform judgment-based tasks, like assessing geometric and aesthetic features in passenger and cargo areas. These tasks, often done in ergonomically challenging environments, may lead to operator fatigue, impacting measurement accuracy and posing injury risks [4,5].

Automating quality control can enhance safety and productivity by improving the consistency and accuracy of inspections, benefiting both workers and passengers.

Early work recognizing the importance of robotics and computer vision in aircraft inspection includes [6–8]. Initiated in the early '90 s with FAA funding, this research focused on using a mobile robot to inspect aging aircraft, particularly hard-to-reach fuselage areas. The robot, equipped with eddy current sensors and cameras, collected data for human inspectors to analyze in safer environments. These studies highlighted the growing role of vision systems, employing techniques like edge detection and low-pass filtering, while also exploring the potential of neural networks.

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A recent review on visual inspection in the maintenance, repair, and overhaul (MRO) of aging aircraft [9] highlighted that fuselage defect detection remains the most studied issue, driven by the task's regularity and the growing role of long-distance aviation. Impacts with birds and other objects are frequent concerns requiring quick assessment and repair. Additionally, structural deterioration at joints, such as fatigue cracks, loose rivets, and de-bonding [10], is closely examined, along with external components like doors and tires [11].

However, as explicitly noted in the systematic literature review discussed above by Yasuda et al., there is a notable lack of work devoted to aircraft construction and assembly. This still holds to the best of this paper's authors knowledge.

The work described in this document has been carried out while working on Vision-based Inspection Systems for automated Testing of Aircraft interiors (VISTA), a European project financed through the Horizon 2020-Clean Sky 2 initiative, aimed at the development of a more automated system for performing post-assembly inspection of aircraft lining, in which different kind of panels must be inspected, looking to surface defects and considering their respective arrangement, collecting and verifying geometric measurements such as gaps, steps or lack of parallelism.

VISTA, as many research projects developed under the Clean Sky 2 initiative umbrella, addresses some of the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development [12], with a particular focus on SDG 9: Industry, Innovation, and Infrastructure, by promoting automation in the working environment. The VISTA project also addresses SDG 8.8, by avoiding particular situations, typical in manual quality inspection operations in narrow and low environments that endanger worker safety, like the cargo area.

The work reported in this document approaches the quality control task in a semi-automated way, combining robotic and human skills. Indeed, while a properly equipped autonomous robot can collect all the measurements needed to identify geometric and surface defects, human skills and traits are both exploited and aided in the final judging process. Some quality control activities of aircraft lining are related to human taste, like comfort and aesthetics, which are unsuitable for formalized automatic judgment. Human inspection officers still handle the final validation stage, with the system providing ways tailored to specific needs, covering the standard "on-site" working and the increasingly popular remote working ("off-site") situations through different visualization front-ends.

The main contributions made in this work for the scientific community and aerospace industry in implementing a system for inspecting aircraft assembly lining, and in particular the passenger and cargo areas, are:

- Design and implementation of a platform for multi-modal assembly lining quality control, comprising both 3d and color imaging, for detecting geometric and surface defects;
- Design of a unified script-based automation encompassing all stages required for quality control, including robot navigation, robotic manipulation, sensing, data exchange, and processing;
- Introduction of specific XR (AR & VR) presentation modes customized for both on-site and off-site validation scenarios;
- A human-centered semi-automated approach to assembly lining inspection, freeing the operators from repetitive measurement operations without compromising worker's safety, with gains in measurement consistency. The human inspector's know-how is still central in validating the potential defects reported by the system.

Given the wide scope of the VISTA project, the main objective of this paper is to discuss the overall architecture of the devised solution. Indeed, some subsystems and part of this work have already been discussed in the scientific literature. In particular, the methodology behind the assessment of geometric and surface defects can be found in [13–15], while a discussion about the presentation layer has been provided in [16]. This paper is focused on the description of the system as a whole and mentions to previously published results are included only when useful to the overall explanation, with the aim of enhancing the narration.

The rest of the paper is structured as follows. First, overall research project objectives and requirements collected during the inception phase are reported. This is followed by a brief analysis of the choices made working within the overall constraints established by the objectives. The methodology section is meant to introduce the choices made while designing the system, highlighting the importance of opting for the most appropriate sensing technologies and the criteria at its core, with the rest of the system to follow. The general hardware/software architecture is then introduced. Details regarding the various aspects of the quality control solution, including but not limited to data acquisition, navigation and coordination, data processing, and data presentation, are reported. Experiments and results are provided. A discussion section follows them. The paper is wrapped up with conclusions and a brief presentation of topics open for further investigation.

2. Related works

Quality control is essential for surviving and thriving in an expanding global market. It has many forms and is not limited to the production of goods either, with applications and connections in many research areas, including mathematical modeling [17–19].

Traditionally, human operators have performed a visual inspection to check whether the produced goods match or exceed some expected metrics. This is not always possible. The issue cannot be visible superficially, such as when checking the structural integrity of parts that employ nondestructive techniques like thermographic and ultrasonic testing [20–22].

Human visual inspection can be time-consuming, leading to increased investment in quality control automation. However, aircraft manufacturing has yet to fully adopt this shift due to its limited production output and stricter quality standards. Still, insights from the automotive and other industries, which shares similarities with aircraft manufacturing could help adapt automated quality control practices.

Geometric measurements needed to find geometric defects due to the wrong arrangement or alignment of individual pieces are common in the automotive and aircraft industries. Human operators traditionally perform those measurements using a caliper while inspecting manufactured aircraft. While automating these activities, switching from contact-based solutions to contact-free approaches is common, as a recent review of optical metrology in the modern manufacturing industry has shown [23]. In [24], authors propose a custom-designed hand-held system for performing gap and flush measurements. In particular, a smartphone-based solution has been developed for the automotive industry, keeping the human-in-the-loop. The smartphone is connected to a portable laser triangulation measurement system, with a custom-designed application guiding the user in the acquisition process to reduce measurement uncertainty. While a calibration procedure was devised and implemented to keep uncertainties in check, which proved effective in laboratory settings and experiments, more realistic scenarios have shown how operator usage and uncontrolled environmental conditions can increase measurement uncertainties.

This contrasts with the way humans are kept in the loop in the VISTA project. Here, the approach that has been followed strives to automate every repetitive or ergonomically risky task. Human know-how is employed in a supervision role.

As reported in [9], using computer vision after manufacturing, during aircraft construction and assembly, is still rare.

In this context, the papers most related to the work presented here are in [25] and [26]. The work by Zhang et al. [25] is oriented toward large-sized parts, and it is based on a custom-made acquisition system employing two high-resolution cameras, a laser-line projector, and a control system. Using the stereo-vision system, the authors propose an accurate profile measurement system able to reconstruct profiles accurately, provided that boundary reference points are available and that surround the large-sized part to be evaluated. Meanwhile, in [26], a methodology for gap and flush measurements from 3d point clouds is proposed. It is worth noting that the 3d point cloud can be unstructured, and the authors claim robustness to different types of scanner data. However, outliers, high noise areas, and uniform local density are problematic cases which the method, devised around different densities in seams and non-seams areas, is not capable to cope with.

The latter two works are interesting since they cover key topics at the foundation of quality control of aircraft assembly lining, too. However, the work presented here approaches the problem differently for several reasons. Compared to [25], the work here is oriented toward acquiring smaller areas. Although this approach is at the expense of a higher number of acquisitions, the nature of aircraft lining assembly advises against scanning with a wide field of view. While sidewalls almost mimic the curvature of the fuselage, they are mounted inside, meaning that concavities, not convexities, are the scene-stealing main actors. Moreover, other panels, such as the overhead compartments, present a higher curvature when compared to the fuselage. The work presented here also prefers using a-priori knowledge of the parts being inspected via a CAD model instead of using explicit reference points, which might not be present in every shot and panel type. Another key differentiator is that an off-the-shelf 3d area scanning device is preferred, with its more compact form factor better suited for the deployment on the scanning robot, which is part of the system. Indeed, automating the way measurements are taken was another of the key objectives of the project.

Compared to the work in [26], the usage of a specific 3d area scanning device enables to work on structured data, and this characteristic is exploited to solve a 3d problem, like the extraction of contours on which of gaps and other 3d measurements are based, using 2d image processing based on the matrix arranged data from the scanning device. The employed methodology, moreover, is able to identify surface based defects, in addition to strictly geometrical ones.

While designing a solution for aircraft interior post-assembly testing, the complexity of the system became evident due to multiple environments and requirements. This led to decomposing the inspection into smaller tasks. Exploring the Robotic Operating System (ROS) revealed the MoveIt! package [27], specifically MoveIt! Commander scripting, for robotic arm control. Although additional solutions like Robowflex [28] for simplified motion planning have been made available in the meantime, the VISTA project required a broader solution integrating navigation, manipulation, sensing, communication, and processing. As no existing solution fit these needs, we adopted and expanded the MoveIt Commander syntax to script code inspection missions as a list of executable steps.

Last but not least, given the importance of relying on the human-in-the-loop concept, in order to exploit inspection officers know-how, while offloading repetitive and physically demanding tasks to an autonomous robot, additional needs exist on the presentation layer too. In this context, eXtended Reality (XR) has shown an increased role in manufacturing [29]. In the VISTA project, as an additional novelty, virtual and augmented reality solutions are investigated for increasing productivity in specialized off-site and on-site scenarios.

3. VISTA requirements

These work results were obtained during the VISTA (Vision-based Inspection System for automated Testing of Aircraft interiors) project, funded through the European Union's Horizon 2020 research and innovation programme under grant agreement No 785410. The aim of the project, framed within a more extensive research effort for better-automating aircraft production under the ACCLAIM framework umbrella https://www.projectacclaim.eu/ (Accessed: 2024-03-01), is the design and development of a semi-automated testing post-assembly testing of aircraft interior installations in both cabin and cargo areas to ensure quality and reliability of located components.

Fig. 1. Topic Manager facilities for the ACCLAIM framework, including the VISTA project. Stairs and an elevator enable access to different floors. This location has been used for perception system design and testing.

Indeed, the project has been kickstarted as the final step of several research projects, supervised by Fraunhofer IFAM institute running the ACCLAIM framework and hosting a simulacrum of a section of an AIRBUS A320, used as a common test ground, visible in Fig. 1. Using IFAM facilities, several projects have contributed in envisioning innovations on the way to a Future Aircraft Factory, in particular:

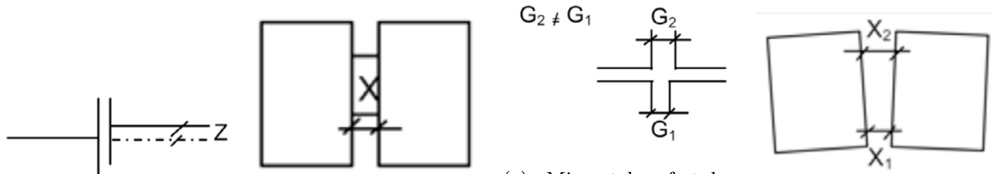
- CALITO redesigned lining panels for faster and more accurate assembling, also by devising a fastening mechanism based on clips in place of bolts and rivets;
- EURECA worked on the automated assembly of panels by designing and building several robots for assembling different panels, such as hatracks, sidewalls and cargo panels;
- SIMFAL simulated and evaluated several assembly scenarios, including planning and optimizing automated assembly tasks of cabin and cargo interior parts, involving human workers and cobots or robots only.

The last goal, automatic quality control post-assembly, is pursued by developing a non-contact solution for automatically inspecting geometrical and surface characteristics of common aircraft parts, such as sidewalls and hatracks (also known as overhead storage). It is worth noting that the quality control of the correct installation of hatracks and sidewalls in the passenger area is executed before additional parts, like passenger seats, are put in place (a decision made by all interested parties).

Another important aspect is that the projects were started in different times. In particular, VISTA was scheduled to start after the other ones were already in progress. On one hand, this choice enabled the project to be built on more mature grounds. On the other hand, it reduced the chances to influence the other projects for even more attractive results due to a tighter integration.

It is also worth pointing out that while post-assembly measurements are achieved with a high degree of automation through the design of a holonomic robot equipped with suitable sensors, the quality control performed by the system is still supervised by inspection officers. Data is presented through several user interfaces, optimized for specific scenarios, and even advanced modalities like augmented reality for on-site decision validation.

Ensuring the absence of geometrical and surface defects is necessary for aircraft manufacturing for different reasons, which involves both



(a) Steps (b) Gaps (c) Mismatch of tolerances (d) Parallelism

Fig. 2. Geometric defects related to panel arrangement, from [15].

the safety of operations and a more "holistic" quality of the passenger's journey. In particular, checking panel arrangements and alignment guarantees the safety of operation. This means overhead compartments can be opened safely, and Unit Load Devices can be stored in the cargo area without issues. In the passenger area, checking and avoiding surface defects such as discoloration, scratches, and so on contributes to passengers' comfort.

Traditionally, all these tasks are performed manually via visual inspection and use of a caliper. This set of relatively simple tasks must be performed hundreds or thousands of times during a typical working day. This exposes the quality check to cognitive fatigue. Moreover, performing such tasks in zones like the cargo area can cause serious concern from an ergonomic perspective, exposing workers to potential injuries, as directly assessed by SIMFAL project partners [30].

For these reasons, performing quality control starting from data acquired manually is insufficient. Automation is required during data acquisition, too. A robotic platform with suitable sensors must autonomously navigate both cabin and cargo environments. This poses several constraints to the platform dimension since it must be able to pass through the doors, including the lower cargo one. At the same time, its sensors must reach very high vantage points to inspect the highest part of the hatracks.

Given all these constraints, a few reasonable assumptions are made about the status of the individual panels. In particular, the mounted individual panels have already passed a Quality Assurance phase in the production factory. Therefore, the defects identified after the installation are either attributable to the installation phase itself, as a by-product of a wrong/imprecise installation, or related to the wear and tear of the mounted panels due to robotic manipulation. Under this assumption, defect types to be detected after installation can be broadly distinguished between geometrical and surface defects. Geometrical defects are mostly related to a wrong positioning or alignment of linings in aircraft interiors. On the other hand, robotic manipulation of the panels can cause wear and tear, changing their surface appearance or creating scratches on them.

These considerations enable us to define defects that need to be checked against, both from a perspective of geometric arrangement and a surface one.

Geometric defects to detect, as shown in Fig. 2, include:

- Steps occur when two adjacent panels, intended to remain at the same height, manifest a z-axis step outside a predefined threshold range.
- Gaps pertain to the proximity measurement along a designated axis (e.g., x, y, or z) between the closest ends of adjacent panels, with reporting triggered when exceeding specified tolerance ranges.
- Mismatch of tolerances involves deviations in the collective assessment of gaps between more than two panels. While individual panel gaps may meet standards, the overall mismatch arises when considering their combined distances.
- Parallelism defects occur when adjacent panels exhibit improper alignment, visually lack parallelism, and display discrepancies in the gaps at their shared edge.

Even with pristine panels, robotic manipulation during installation could introduce surface defects. Among them, the most important ones which could be introduced are:

- Scratches refer to linear surface panel damages commonly resulting from contact with sharp objects. They are characterized by alterations in both color, appearance, and shape.
- Bumps and dents are localized concave or convex deformities, typically rounded, often arising from improper assembly or impact with a non-sharp object.
- Texture inhomogeneities, or color deviations, refer to anticipated variations in color or texture on a panel that is otherwise uniform. These irregularities and deviations in color and texture signify alterations in the overall appearance of the panel.

4. Methodology

Finding a solution to the semi-automated aircraft lining inspection required a thorough investigation of the performance of different vision sensors able to detect geometrical and surface defects and whether a single sensor could address all the needs or a more sophisticated approach would have been necessary. The sensor's performance was judged against the set of use cases identified as project requirements. The analysis was based primarily on a literature review and market research using evaluation matrices as in Tables 1 and 2, and other practical considerations.

For instance, sensors working on areas were preferred to the ones acquiring a line or profile at a time due to their speed advantage and a looser dependence on the robotics parts for movements.

Once the most promising technologies were identified, preliminary tests were conducted at the Fraunhofer IFAM facilities in Stade by comparing the performance of vision sensors from different manufacturers, where experiments showed that structured light performed better than stereo. With the enabling vision technologies selected, the focus shifted to choosing the components for the robotic platforms, with a preference for consumer-off-the-shelf devices already tested and ideally certified for industrial operations. With no easily customizable and already integrated robotics platform identified on the market, it was necessary to incorporate different robotics components with the objectives of a) navigating in narrow environments and b) the ability to reach all the necessary panel parts.

Environment and lining constraints, as well as improving synergies with other partners' projects in the ACCLAIM framework, ultimately meant that the VISTA project benefited from using one of the AGVs employed in the EURECA project. In fact, the custom AGV developed by EURECA based on holonomic movements was already successfully used as the base for assembling aircraft panels in the same narrow spaces, suggesting its fruitful employment also for inspection purposes. A lifter, the robotic arm, and the sensing payload were added on top of the AGV base.

Project requirements limited the possibility to perform acquisition, processing, long term storage and results presentation all on the same device. A more sophisticated architecture was necessary, as reported in the next section.

Table 1
Evaluation matrix of different enabling vision technologies on geometrical defects.

Enabling technology	Sensor	Gap	Step	Parallelism	Mismatch of tolerance
Laser profile scanner	LMI Technologies Gocator 2880	PASS	PASS	PASS	PASS
	Zeiss Optotechnik T-Scan	PASS	PASS	PASS	PASS
	Sick Ranger3	PASS	PASS	PASS	PASS
	Sick ScanningRuler	FAIL	FAIL	FAIL	FAIL
Structured Light	Zeiss Optotechnik Comet	PASS	PASS	PASS	PASS
	ShapeDrive G3 Series	PASS	PASS	PASS	PASS
	Creaform Handyscan	PASS	PASS	PASS	PASS
	PhoXi 3D Scanner M	PASS	PASS	PASS	PASS
Time of flight	Sick 2D LiDAR TiM5xx	FAIL	FAIL	FAIL	FAIL
	Basler ToF camera	FAIL	FAIL	FAIL	FAIL
	Ifineon CamBoard pico monstar	FAIL	FAIL	FAIL	FAIL
	Sick Visionary-T	FAIL	FAIL	FAIL	FAIL
Stereo	IDS Ensenso 3D camera	PASS	PASS	PASS	PASS
Color cameras	ALL	FAIL	FAIL	FAIL	FAIL

Table 2
Evaluation matrix of different enabling vision technologies on texture inhomogeneities.

Enabling technology	Texture inhomogeneities	Color deviation
Laser profile scanner	FAIL	FAIL
Structured light	FAIL	FAIL
Time of flight	FAIL	FAIL
Stereo	FAIL	FAIL
Bayer color area scan cameras	PASS	PASS
3 Sensor color area scan camera	PASS	PASS
Line scan cameras	PASS	FAIL
Color line scan cameras	PASS	PASS

5. Overall architecture

Project constraints contribute to defining the architecture of the inspection system, sometimes in contrasting ways, for example:

- The cabin area requires that the sensor payload reach a height of about 2 m. However, the cargo area provides a different challenge: the robotic platform must fit in a very narrow and small area, with a maximum height of 1.2 m;
- Vision algorithms needed for quality control checks can be computationally intensive, yet navigation requirements and platform dimensions suggest that power consumption must be carefully considered.

These considerations lead to the definition of an architecture where tasks are performed on different nodes. In particular, the main task handled by the robotic platform is related to data acquisition. The latter uses both color cameras, mostly for detecting surface appearance issues, and a 3d snapshot camera, better suited for evaluating geometric issues, related to the arrangement and alignment of panels. These sensors suite are mounted as the end effector of a robotic arm [31], enabling to move and orient the data acquisition equipment in the most effective way. However, due to the airplane size and other constraints, the robotic arm itself needs to be mounted on a small elevator, capable of enhancing its reach in the height dimension, and anyway mounted on an AGV (automated guided vehicle) base, kindly shared by EURECA team [32], which can room freely inside aircraft passengers' and cargo floor.

While acquisition and temporary storage is performed by the robotic platform, abstracted in the form of a freely roaming acquisition node, a different node, known as the supervisor, handles processing and storage. Data are wirelessly exchanged between these two entities. The supervisor sends commands to the acquisition node to navigate the environment and trigger sensors for acquiring data. It also coordinates data exchange for transferring acquired data. These commands are organized like sequences of steps. Additionally, the supervisor processes acquired data and stores raw data and quality control results. Different reporting options are then available and connect to the supervisor for access to the results and enable inspection officers to validate them.

5.1. Sequences of steps

Specific commands are directed towards the AGV base, such as commands for forward or backward movement, while others pertain to adjusting the pose of the robotic arm. Specific commands are dedicated to acquiring new point clouds or images. Notably, there are also commands designed for transferring acquired data on the supervisor and initiating the processing phase.

Processing can occur at the level of individual point clouds or images. Alternatively, it can involve considering the results from different point clouds simultaneously, particularly in cases involving high-level measurements, like assessing parallelism. Evaluating conditions such as parallelism and tolerance mismatches often requires analyzing an area spanning multiple acquisitions.

While sequences of steps are associated with particular procedures, such as 'basefloor_to_lift,' 'goto_floor1,' 'goto_floor2,' 'goto_basefloor,' 'transfer_data,' and 'start_processing,' these sequences can be linked together within a single program script, such as 'inspect_aircraft.' However, they are also available separately.

When a sequence of steps is related to acquisitions for inspection purposes, it essentially constitutes an inspection plan.

Before being performed by the robotic platform, these steps are automatically generated through a solver, which considers all AGV components and the constraints to be satisfied. These lists are then tested and tweaked in a simulator before being registered in the supervisor and handled by the acquisition subsystem.

5.2. Data acquisition

At the heart of the assembly inspection two sensors are employed, one devoted at capturing color information and the other used to evaluate the depth of the acquired data.

In the field of scientific and industrial imaging, high-performance cameras are essential tools for capturing and analyzing data. Post-assembly inspection for detecting surface defects is no different. In the VISTA project, a Teledyne Dalsa Genie Nano XL 5100 [33] is used. It is a GigE camera that offers the required image quality for the task. Its compact form factor is also very useful for the particular constraints of the project and hence well-suited for this quality-control application. Images, with a resolution of 5120x5120 pixels, were acquired with the support of a flash lamp, triggered during acquisition, providing more consistency in the illumination.

On the other hand, 3d data acquisition is performed using an LMI Technologies Gocator 3210 snapshot sensor [34]. The Gocator 3210 features a field of view of 79° x 63°, allowing it to capture a substantial area in a single snapshot, facilitating the examination of large parts and intricate assemblies. With a resolution of 2 megapixels, it achieves precise measurements down to 35 μm, enabling the detection of minute imperfections and ensuring product quality. Provided its field of view, and additional sensor capabilities and constraints, a single acquisition from the sensor can cover a surface that goes from 71x98 mm at the closest range to 100x154 mm at the furthest measurable range, with a clearing distance of about 20 cm. In this particular project, the sensor has been kept at a reference distance of about 20 cm from the target surface, since the provided precision in 3d measurements were well within required specifications for detecting the set of possible defects considered.

Structured light technology is at the core of the Gocator 3210's accuracy. A projected light pattern distorts the object, and the sensor captures this pattern, using advanced algorithms to reconstruct a 3D point cloud that represents the object's geometry. Hence, since the sensor already relies on this built-in mechanism for illuminating the scene, no additional artificial lighting is triggered during the acquisition of 3d data.

5.3. Navigation

Inspecting a panel patch necessitates periodic commands directed to the robotic arm or the moving robot base, requiring the system to navigate its environment.

Concerning the moving base, over the years, both ready-made AGVs and prototypical robots have been proposed for industrial contexts, as discussed in [35,36]. Each of these AGVs is equipped with heterogeneous sensors useful for navigating in the environment. Some AGVs can operate in structured and unstructured environments by performing constrained and unconstrained movements. One of the main requirements of this use case is to perform repetitive constrained movements to locally gather the data of interest by the acquiring sensor fastened on the robotic arm. The AGV base has to move according to specific imposing commands by following orthogonal paths. This aspect limits the use of some types of AGVs because proprietary software is sometimes used, thus not allowing to perform the required movements. Also, some of the proposed AGVs are not suitable as they use locomotion systems that do not allow on-site rotations. Moreover, some solutions need the use of exteroceptive sensors or to properly infrastructure the environment. In this regard, the installation costs are not always accessible, and the complexity of installation might make the deployment not easy. Last but not least, a very high positioning accuracy is required (sub-millimeter precision). This accuracy is not ensured by using some of the already available solutions. Consequently, all these considerations have driven us to use a more precise alternative because an open-source off-the-shelf solution having all these wanted requirements is not currently available.

Tight spaces in which the robotic platform is required to operate have oriented the choice of a navigation solution toward holonomic vehicles. This enables the AGV to rotate on the spot and to perform lateral movements, greatly simplifying trajectory planning. However, since precise positioning is another important constraint which needs to be met, it is necessary to supply the system with the means to achieve it. Considering the industrial context, in which the environment surrounding airplane manufacturing can be appropriately structured, the solution pursued in the VISTA research project takes advantage of this by designing and providing some logical lanes to be followed during the inspection phases and while transitioning from one environment to the other.

In this work, a solution based on a fixed path was chosen to ensure precise positioning and localization due to the assured operation within a predominantly structured environment. The selected solution utilizes Pepperl-Fuchs PGV (Position Guided Vision) [37], which comprises a QR-printed routing tape known as the 'data matrix tape' and a Read-Head, a compact sensor capable of detecting the position on the tape and providing guidance for alignment. The tape consists of a long row of positions encoded in millimeters using standard QR codes. The Read-Head can perceive multiple markers simultaneously, enhancing robustness and accuracy. The data matrix tape is easily installable and removable from the environment. Navigation paths are inherently based on the traversable environment. One consideration is that the tape lacks flexibility for enabling curved trajectories. To address this constraint, the developed solution implements three basic maneuvers on the AGV:

- Forward/backward lane following
- In-place rotation
- Lateral movement

These simple yet effective behaviors allow navigation in the structured environment. Forward/backward lane following involves instructing the Read-Head sensor with the final position. The sensor, capable of detecting multiple markers simultaneously, provides its actual position on the tape, the direction to follow for reaching the desired position, and small heading corrections if needed. ROS drivers packages and standard ROS conventions are employed in the system.

In-place rotations are achieved by briefly allowing the robot to "detach" from the tape and initiate a rotation around its center of mass, clockwise or counter-clockwise. The controller for in-place rotation halts the movement upon detecting another "lock" on the tape signaled by the Read-Head. Lateral movements follow a similar approach, enabling the robot to move laterally, transitioning from one tape to another. Fig. 3 shows the PGV unit, and the rest of the acquisition platform, while using the mostly white QR-coded lane for navigation purposes.

5.3.1. Inspection strategies

In addressing the cabin area, the initial challenge lies in navigating through the narrow front door. The robot accomplishes entry and exit exclusively through forward/backward lane following movements. It is crucial to note that the robot arm UR10e must be in a "rest" pose, minimizing its footprint in all directions during this kind of maneuver. Once inside, the hatracks and sidewalls require inspection from different lanes.

The hatrack, positioned furthest from the ground floor, requires particular attention. Although the sidewall is notably taller, the hatrack's location necessitates the use of the internal lifter mounted between the robotic base and the arm. This lifter enables the UR10e to carry cameras and reach the high vantage points required for certain measurements. The Ewellix Lift Kit, in particular the LIFTKIT-UR [38], was included as a practical solution for addressing this issue.

A second challenge arises from the hatrack's extended length of about 1.1 m. This issue cannot be resolved by simply adjusting the UR10e joint configuration. Additionally, the weight distribution of the mobile robot, including its payload, requires careful control to maintain platform balance and stability by preventing the center of mass from shifting too far. This concern also extends to inertia and other movement-related issues. To address these, a strategy was implemented to avoid simultaneous movements of different subsystems. In the VISTA case, the holonomic movements of the mobile base, the lifter (which holds the UR10e arm), and the robotic arm itself are executed sequentially, and movements of the mobile base and lifter are minimized. Most commands focus on adjusting the UR10e joints or using the 3D and color sensors. While this approach may seem limiting, potentially slowing acquisition times, it improved testing and reduced the risk of accidents during real-world execution. Considering the basic strategy, and limiting the inspection analysis to the UR10e movements to cover large panels, or at least part of them, using a serpentine path using the longer panel axis as the primary guide seemed like the most sensible decision. After several experiments, the optimal inspection strategy logically splits the hatrack into two halves, corresponding to the two luggage storage compartments. Initially, the robot positions itself so the robotic arm is almost centered on the first of the two compartments, to enhance static stability. UR10e speed movements were tweaked to avoid exces-

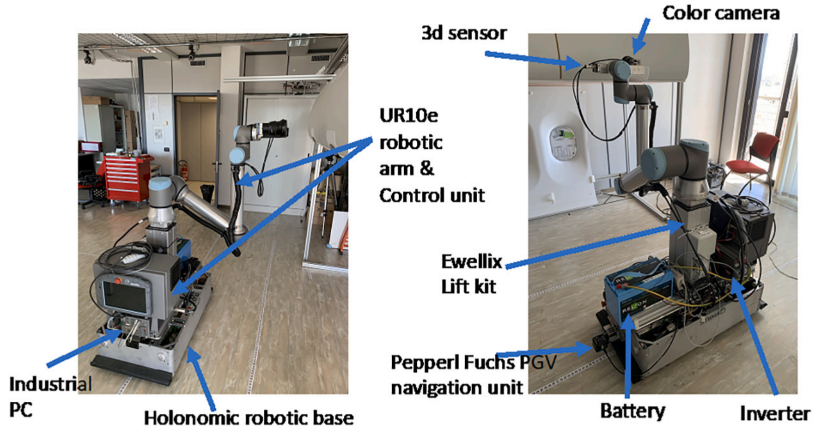


Fig. 3. Acquisition platform comprising the robotic base, the robotic arm, and all the perceptive sensors useful for navigation, localization, and visual inspection of aircraft components.

sive oscillations due to inertia, negatively affecting both robotic stability and acquisition steps. Split of seconds delays before acquisition were included to avoid catching blurry data as well.

It is worth noting that the 3D sensor and the color sensor have different fields of view, with the 3D sensor having the narrower one. Consequently, the inspection strategy and path are constrained by the 3D sensor. The color camera follows the same acquisition pattern but, due to its larger field of view, is triggered fewer times.

Addressing the sidewall imposed constraints present considerable challenges owing to sidewall dimensional complexity, encompassing both horizontal and vertical dimensions. Notably, the sidewall exhibits pronounced curvature, requiring periodic adjustments in the distance and orientation of the sensing payload for optimal scanning.

Additional complexity arises from the inherent limitations of finding a singular root arm starting position capable of reaching all points on the panel, even with the platform's lift fully descended. In response to this challenge, a dual-pronged strategy has been devised.

First, each sidewall is conceptually divided into two halves, each centered on distinct windows. This segmentation facilitates the UR10e payload's comprehensive access to the upper sidewall. However, this approach alone proves insufficient for addressing the lower section. To remedy this, an additional lane positioned in closer proximity to the sidewall has been introduced. These four logical parts are then inspected in sequence using a serpentine path for each one. This systematic approach allows for a nuanced exploration of the sidewall's intricacies, ensuring a thorough inspection despite its challenging dimensions.

The inspection of cargo panels requires a different inspection strategy, due to the constrained environment, primarily characterized by a low ceiling and a limited pavement area. The restricted space poses considerable obstacles, emphasizing the need for meticulous planning.

While the cargo area inspection offers the advantage of reduced emphasis on surface quality, as it remains unseen and inaccessible to passengers, it remains crucial to detect and report geometrical defects and any other issues that might impact the efficient loading and unloading of aircraft containers. This area can be addressed with a simplified strategy focusing on gaps detection only.

5.4. Activities coordination and supervision

Coordination of all these activities is performed on a separate node. A physical split between those activities on different hardware has been motivated by different factors:

- Data processing can be computational intensive and not suitable on mobile, battery-powered platforms;
- Long term storage and access for on-demand presentation are ill-suited for being guaranteed on a battery-powered platform too.

A separate node, known as supervisor, is therefore tasked with all activities except acquisition and navigation between inspection points. Since each module has its own peculiarities and most of the communications between different subsystems would have taken place over a wireless connection, during the initial design it was established that each subsystem would have been developed independently from the other, choosing its own programming language and supporting libraries, with the only constraint of being able to communicate with other subsystems using sockets and web-sockets. Most of the communications taking place over the network happen using the JSON format. When different processes run on the same device, they can also be launched separately, exchanging data though JSON payloads.

The supervisor is responsible for sending commands to the robotic platform and for interpreting its responses. During acquisition, data are temporarily stored on the robotic platform. No processing is performed on the spot and the mobile platform is directed toward the next acquisition spot as soon as the acquisition of the current one is completed. This is done for preserving battery and ensuing faster acquisition times. Moreover, some of the geometric processing requires access to data coming from multiple acquisition spots.

When all data have been acquired, the supervisor triggers the acquisition platform to copy raw data for later use, including processing and presentation. Given its bridge role between acquisition and presentation of processed results, the supervisor is the sole logical entity able to access the database. Moreover, considering the performance benefits, the processing server, the supervisor and the database, are sub-systems running on the same physical machine but handled by different processes. RESTful API are available for accessing raw data and process results.

5.5. Data processing

Data processing is performed using different modules, taking care of geometric and surface defects. However, subdivision of tasks between modules do not strictly follow the logical split presented previously. This is due to the nature of the measurements needed, with some tasks performed with the depth data, others with color data and in some cases, by interpreting measures at an higher level, based on some intermediate results. This subdivision of roles is presented in Table 3.

This remapping of responsibilities is suggested by the type of processed data and by the nature of the process itself. Some assignments are straightforward: gaps and steps require three-dimensional analysis and are handled accordingly. Handling texture inhomogeneities by using color is immediate too. In other cases, some explanations are needed. Scratches fall under the latter group. Indeed, scratches are defects that certainly affect the geometry and, in most cases, show a change in the local coloration of the panel. They can therefore be detected as 3d or color changes. Experiments have shown that processing them by using

Table 3
Mapping between defect types and handling module.

Defect type	Module
Gap	3D Processing
Step	3D Processing
Scratch	3D Processing
Texture inhomogeneities	Color Processing
Parallelism	Supervisor Processing
Mismatch of tolerances	Supervisor Processing

3d data, while being more computationally expensive, is more robust and accurate and enables to analyze scratch depth as well. In other cases, finding 3d defects is better suited to be performed by a higher level entity, like the supervisor, since it requires interpreting data from a more extensive collection of acquired data, like for parallelism and mismatch of tolerances.

The three-dimensional analyses conducted within the VISTA project utilize a dedicated processing subsystem tailored for this purpose. Specifically, the software operates as an independent process that can be activated from the supervisor. Developed in C++ for the Microsoft Windows operating system, it is deployed as a command-line utility capable of communication through JSON files.

Input requests from the supervisor and output responses in the 3D module adhere to a JSON syntax, encompassing attributes with explicit data types as in Fig. 4:

```
{
  "NSurfaces": (Integer number),
  "ThrDistance": (Floating point number),
  "defect_types": (String array),
  "filename": (String),
  "zone": (String),
  "paraboloid_window": (Integer array)
}
```

Fig. 4. Input JSON Structure for information exchange. Different defect checks can be required for different shots.

Upon completion of the processing, results based on the specific request are associated with the input. The supported defects include gap, step, and scratch. The output JSON is structured accordingly, as in Fig. 5.

```
{
  "defects": {
    "gap": {
      "Gx": (Floating point number),
      "Gy": (Floating point number),
      "Gz": (Floating point number)
    },
    "step": {
      "maxZStep": (Floating point number),
      "minZStep": (Floating point number)
    },
    "scratch": [
      {
        "depth": (Floating point number),
        "length": (Floating point number),
        "x": (Floating point number),
        "y": (Floating point number)
      }
    ]
  }
}
```

Fig. 5. Output JSON Structure for information exchange. One or more measurements can be provided as output, depending on the specific request.

5.6. Data presentation

The proposed solution is built upon a client-server configuration, where a supervisor oversees interactions with distributed sub-systems across various physical devices. Processing results and reports are accessible through diverse means:

- **Tablet App:** Reports are accessed through an Android or iOS application, providing a graphical 3D representation of aircraft interiors based on Computer-Aided Design (CAD) models or scanned data.
- **Windows App:** Accessible via a Universal Windows Platform (UWP) application compatible with Windows 10 and above.
- **Hololens App:** Tailored for Hololens 1, this UWP application allows users to access reports and overlay measurements of defects in an augmented reality environment.

5.6.1. Decision factors

The project prioritized a VR-like experience using a tablet or desktop application over a full-fledged VR environment, such as Meta Quest family of devices. This decision was influenced by the perception that VR immersion might lead to a sense of "disconnection" from the physical environment. Additional costs, development complexity and other factors, without clear counter-balancing benefits, further cemented this choice.

5.6.2. Application-specific details

The tablet application leverages the inspection environment for camera setup, enabling users to examine panels in the cargo or cabin closely. In landscape mode, the app presents a list of defects on a left pane, with the 3D environment and the selected defect highlighted on the right pane. Users can seamlessly navigate the virtual environment and choose candidate spots ofdefects to inspect. The choice of inspection area (cargo or cabin) is intelligently handled based on the acquisition context.

The Windows application provides a user-friendly interface through Universal Windows Platform (UWP) on Windows 10 and above. Users can access reports and navigate the 3D environment efficiently. The development in Unity ensures flexibility, allowing for easy adaptation to different platforms.

The Hololens application requires a more customized solution due to its nature. The user interface is tailored to accommodate the head-mounted display, incorporating natural commands such as gestures. To align the virtual representation with the real scene, image markers for cargo and cabin are utilized. These markers, placed at known positions, allow for precise tracking and data overlay, even when the markers are out of sight, thanks to Hololens' sensors. Further details are available in [16].

6. Experiments and results

Before delving into the details of the experiments, it is essential to state that the project occurred during the COVID-19 outbreak. This affected the final tests, which did not take place at the Topic Manager Facilities but were performed in the robotics laboratory of the authors' institute, with all other partners and guests connected through a video call.

Additionally, due to logistics constraints and available parts, tests have been performed using available parts at the authors' robotics lab (in Bari, Italy) sent in 2019, at the beginning of the project. The ramifications of this situation are twofold: a) available parts in Bari differ from the ones mounted in the demonstrator at the Topic Manager facilities in Stade; b) there are fewer available panels in Bari. In particular, while some of the differences do not directly affect VISTA measurements since they are related to the mounting points and not the inspected sides, in other cases, this "independence" cannot be guaranteed, such as in the case of the sidewall coating. Regarding the number of available parts, the installation in Bari comprises just one sidewall panel, one hatrack

Fig. 6. Entrance door for the passengers' area at TM facilities in Stade, used for checking the setup constraints.

for the cabin area, and just another cargo panel for the cargo area. They are also performed in a single laboratory, instead of separate passengers and cargo areas and floors. The performed tests, whenever possible, have tried to circumvent these logistics issues. Notes and observations about the impact of these differences and how they were handled will be reported in the appropriate sub-sections.

6.1. Testing methodology

The Mobile Robotics Laboratory at CNR-STIIMA in Bari conducted final functional tests on the entire mobile system. The laboratory environment was suitably configured to support the navigation of the mobile AGV equipped with sensors and computational capabilities. These tests focused on verifying core functionalities, including three-dimensional data processing capabilities and 2D image-based surface measurements and defect detection, following the integration of the AGV into the overall architecture designed within the VISTA project.

6.2. Specific challenges for areas and panels

There was a need to reschedule the final testing experiments, which were originally planned to take place in Stade at the facilities managed by the topic manager. Instead, these tests were conducted at VISTA partners' facilities in Bari. In light of this rescheduling, comparing the available experimental environments at the topic manager (TM) facilities and the VISTA partners' laboratory is crucial. This comparison helps highlight preserved key aspects and identify necessary adjustments to align with the target environment, Stade's testing environment. The challenges mentioned here are addressed in detail for measurements and inspection strategies, ensuring sensors can access valid and usable inspection spots.

TM facilities provide the benchmark for the test. A realistic simulacrum of an AIRBUS A320 was built. In particular, a section of the central part of the fuselage was acquired and installed in a large shelter. A structure enabled the aircraft hull to be mounted at about two meters from the ground. Additional structures were devised around the aircraft section. The objectives were twofold: 1) delimiting the experimentation area; 2) enabling safe access to cargo and passengers' floor, both using stairs and an industrial elevator. Entrance doors enabled access to both areas. When empty, the passengers' floor appears as in Fig. 6.

Access to the cabin and cargo areas is provided by doors, with their size reflecting their primary purpose and usage. For the cabin area, there is a narrow and high entrance door (only one is needed for the prototype). Since the cargo area is devoted at storing luggage, a wider entrance is required.

A schematic view of the aircraft section, extracted from AIRBUS A320 specification, is shown in 7. Considering the environment, the primary constraints that must be taken in consideration regard:

- Cabin door entrance width, about 800 mm (not reported in the drawing)
- Cargo door entrance height, limited to 1195 mm
- Cargo height, limited to about 1250 mm
- Cargo width, limited to 1450 mm

These constraints have been considered and accounted for in designing and constructing the prototype test environment at TM facilities. Unfortunately, for logistics reasons related to COVID-19 outbreak, testing at TM facilities could not occur during final testing. It was therefore important to identify them so they can be replicated in the test environment at the partners' facilities, enabling a proper test of the VISTA AGV during the inspection procedures.

The testing environment in Bari consists of a relatively large laboratory room with a ceiling about 4 m high. The laboratory is formally devised for robotics experiments, including ground vehicles and drones. The room is L-shaped, with the most significant part measuring 7.3 meters by 6.5 meters and a smaller area of about 2.9 meters by 3.5 meters, like in Fig. 8 (the desk position does not mimic the current arrangement).

Hence, given the available room, it was not possible to replicate the TM testing environment perfectly.

However, preserving all the most important aspects was possible while condensing both cargo and passenger area experiments in a single-floor area. In other words, inspection procedures were kept the same, with logistics commutes from one place to another being adapted.

6.2.1. Cabin panels

Both panel types and numbers vary from the test location originally planned at TM facilities when compared to the partner's facilities, with the panels available in Bari being the early prototypes of more advanced and refined parts. Panels in Bari were sent in May 2019, with sister projects like CALITO (involving panel redesign) being still in progress.

Regarding the hatrack, there are differences between the panels in Bari and those in Stade, as shown in Fig. 9, both in quantity and quality. In Stade, there are two hatracks, which are the final versions created in the CALITO project. The hatrack in Bari is from an earlier prototype. Despite some redesigns, such as more robust hinges and a new mounting clamping mechanism, the overall geometric shape remains similar between the iterations.

From a surface perspective, the frontal surface of the hatrack in Bari is grayish, while the final prototype has a lighter coloration. Additionally, 3D-printed white parts are visible in Bari but absent in the Stade prototype. Another difference is in the bottom part of the hatrack, where the Bari version has a wood-like finish while the final prototype has a white finish.

Furthermore, only a single hatrack panel is available in Bari, making it impossible to measure the gap between two pieces directly. However, the gap between the two hatrack compartments can be measured to simulate the same functionalities.

Differences are present for the sidewall too. Comparing the newer prototype with the older one, the main change attracting attention is again related to the clamping mechanism. In this case, however, the old prototype, available in Bari, lacks anything for aiding the panel arrangement at all. The newer one, instead, shows a new area that is used both for refining its appearance, and for enabling a safer fastening to the aircraft hull.

Wrapping up, as shown in Fig. 10, there is a stark contrast in the visual appeal between the passengers area setup tested in Bari and the final version available in Stade. However, from a practical and functional point of view, differences are strongly reduced and, in the end, acceptable.

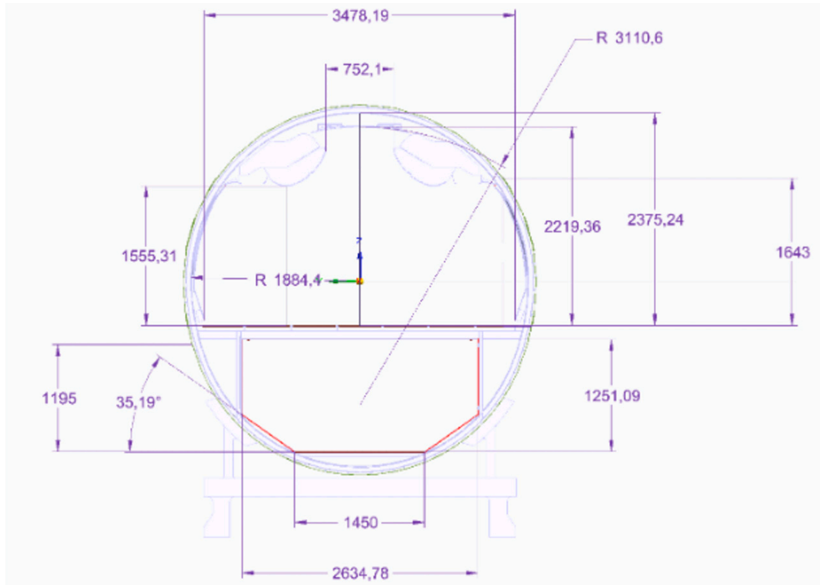


Fig. 7. Schematic view of the aircraft section, with the most relevant project measures, used for hardware dimensioning.

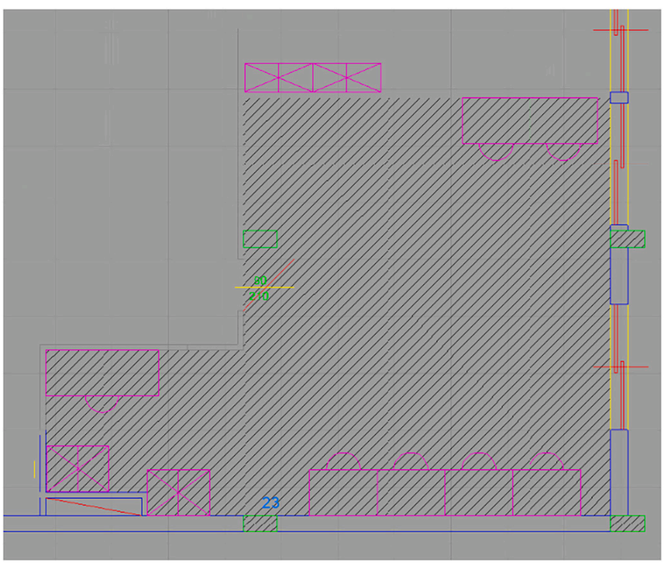


Fig. 8. CAD model of the robotics lab before being re-purposed for VISTA final tests.

6.2.2. *Cargo panels*

Differences also exist for panels concerning the cargo area. However, these disparities are significant enough that a visual comparison between the two areas is unnecessary. The partners' facilities received only an initial panel sample of limited size without any finish. Conversely, the cargo panels installed in Stade for demonstration and testing are approximately 100 cm by 80 cm, arranged in a 2 by 2 grid.

The focus on identifying defects in the cargo area primarily revolves around geometrical considerations, for efficient loading and unloading of baggage. For this reason, geometrical defects are the main parts of interest, while surface and visual appearance considerations can be safely ignored.

Nevertheless, the cargo area and its panels pose a unique challenge due to the limited space in which the robotic platform operates. The low ceiling height and the panels running along the wall's entire height present constraints. While some geometrical measurements can be obtained within the robotic arm's reach, a solution that covers the entire inspectable area is preferable.

To test the feasibility of using the same system in the actual test case in Stade, and considering the less stringent requirements regarding surface appearance defects, it was decided to build four new panels for the final demonstration. These panels maintain the full height but are shortened in length to be compatible with the testing environment in Bari, using simple materials such as plywood. This decision was possible because the need to assess surface appearance is less critical.

6.2.3. *VISTA testing area*

The whole testing environment is shown in Fig. 11. Considering the environment, the primary constraints that must be taken in consideration regard:

- Cabin door entrance width, about 800 mm
- Cargo door entrance height, limited to 1195 mm
- Cargo height, limited to about 1250 mm
- Cargo width, limited to 1450 mm

These constraints have been considered and accounted for in the design and construction of the prototype test environment at TM facilities.

It was impossible to account for a fifth notable difference between the two test environments: the elevator's presence (or lack) since the two areas are hosted in a single room. It is worth noting that the test environment is smaller w.r.t. TM facilities, and some changes were needed to fit all the "furniture" and the necessary pathway for the testing system. Both entrances are different but are shrunk versions of the real ones and adhere to previously reported constraints. In particular, the cargo entrance (on the left) retains the height of the real cargo area entrance, but its width is reduced.

On the other hand, the cabin door is lower than expected, while the width is preserved. That is, entrance door constraints for the VISTA testing room are more stringent than for the real installation in Stade, also due to the more limited space available in the room.

6.3. *Working plan definition*

Panel inspections follow a step-by-step procedure, each typically addressing a specific hardware or software component and involving commands or actions. Inspections may pertain to one or more panels within a particular area, like a cabin or cargo hold. When creating a new inspection, a customized plan is developed to establish the sequence of steps. Initially, plans are simulated, requiring a CAD model or 3D re-

(a) hatrack in the robotics lab (b) hatrack at TM facilities

Fig. 9. The two hatracks are overall similar. The main differences being mainly visible in the white 3D printed parts that were necessary in the previous prototype (the one in Bari, on the left). Another notable difference is related to the bottom finish. All differences are related to the appearance of the objects to be inspected.

(a) Passengers area setup in Bari (b) Passengers area at TM facilities

Fig. 10. Comparison between the available setup in Bari and the one in Fraunhofer IFAM Stade. Although, quantity and quality finish contrast is stark, the scaled-down version in Bari is still a valid testbed from a functional point of view.

Fig. 11. VISTA partners facilities testing room. Position of the routing tape is highlighted in green and red. Green lanes are transit area on which the testing system moves to reach the inspection areas, where the lanes are instead highlighted in red. The AGV follows the lanes using the PGV optical head once properly programmed.

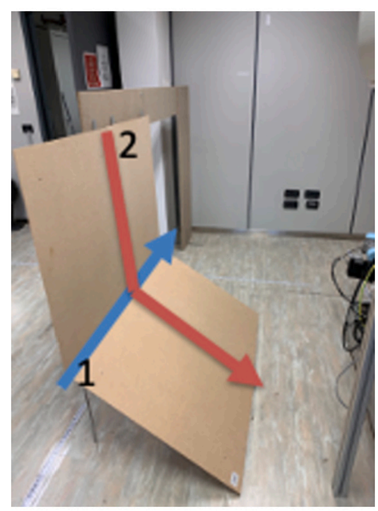


Fig. 12. Example of an inspection plan related to the cargo area, composed of two basic single profile working plans.

construction of the panel(s) and knowledge of the robotic arm's initial position. In cases where CAD models are unavailable, environmental 3D reconstructions are utilized, generated using LIDAR scans. These reconstructions are then simplified for planning and reporting purposes. Once simplified, points for inspection are selected, typically addressing two scenarios: scanning for geometrical defects along a single profile or over an entire area for geometrical and surface defects. Complex situations may require dividing the plan into multiple segments with additional commands for the robotic base. Various inspection plans are derived from combinations of these scenarios. For example, in the cargo area at Bari, inspections follow a "cross +" pattern, involving horizontal and vertical scans between panels, as in Fig. 12.

6.3.1. *Working plan over a single profile*

Scanning over a single profile requires the user to select a few points on the CAD model or the reconstructed model/point cloud. While scanning a single profile, the number of acquisitions corresponds exactly to the number of selected points.

Once the acquisition points are known, the working plan subsystem can operate. The working plan objectives are two:

- Identifying valid sensor payload position so that the point being inspected is at the optimal distance for acquisition, considering, for example that the 3D sensor needs to be a certain distance apart from the scanned patch;

• Identifying the best sensor payload orientation so that the sensor is roughly perpendicular to the small area being inspected.

To achieve its objectives, the working plan needs to perform a series of automatic processing steps for each point:

1. Surface identification
2. Normals computation
3. Acquisition points back-projection
4. Inverse Kinematics solver
5. Processing commands definition

The first step consists of identifying the surface (or nearby surfaces) to which the selected point belongs, as well as preparing for the following steps.

The second step computes a normal to the surface, starting from the selected point. Since two directions are possible, the one pointing closer to the robot arm is selected.

The third step is back projection, considering the optimal distance the sensor (3D or color) needs to stay away from the scanned point/area.

Once these end effector points are known, the fourth step can take place. It uses the 3D positions of the identified points, arm joints configuration, base joint position, and the last known position of the end effector. It employs an inverse kinematics solver to compute a deterministic solution, aiming to minimize the number and degree of movements needed to reach a goal point from a starting point.

A valid solution might not be found considering the base joint position in some cases, perhaps because the required end effector position is too far. Refining parameters such as viewing a different base joint position, requires additional commands to the robotic base or the arm lift kit.

The fifth task includes instructions for the processing steps and defect identification. For example, computing parallelism involves a processing row to compute parallelism and identifying points at the extremes of two adjacent panels for checking parallelism.

The final result is a list of commands executable with Moveit! Commander, consisting of joint position variables and “go” commands for moving to points, intertwined with external commands interpreted by other VISTA subsystems.

Last but not least, if a solution can be found, the user can visualize it in simulation by using ROS tools such as rviz and check that the movement is indeed what is expected to be.

6.3.2. Working plan over a surface

Another option involves scanning an entire surface. The user specifies a starting and end positions (e.g., the top-left and bottom-right corners of the area to investigate), and the working plan solver handles the rest. Here, the subsystem undertakes a few extra tasks with minimal user input. Specifically, the subsystem identifies a set of “waypoints” to cover the entire surface. These tasks include:

• Considering surface curvature to identify waypoints on the surface;
• Identifying waypoints along a serpentine path that are evenly spaced with minimal overlap.

Additionally, since the working plan likely addresses both geometrical and surface defects, the subsystem also identifies borders for finding geometrical defects while inspecting for surface defects during each acquisition.

6.4. Working plan execution

Once the working plan, or steps sequence, has been verified, it can be shared with the supervisor and imported. If the working plan has been created and verified with the working plan solver, creating a new steps sequence is automatic and does not require any intermediate steps.

Fig. 13. The PGV read-head in the process of following the routing tape.

However, if the list of commands still includes cartesian movements, the commands need to be preprocessed to perform additional tasks:

1. Retrieve and save all UR10e inspection positions using joint configurations;
2. Retrieve and save the arm’s end effector relative position with respect to the arm root joint.

When a working plan containing scanning commands is executed, the system creates a new timeline. The supervisor interprets the command list and sorts them into the appropriate subsystem. Commands can be broadly split into four categories:

• AGV navigation
• Arm and lift (AGV elevator)
• Acquisition
• Processing

6.4.1. AGV navigation

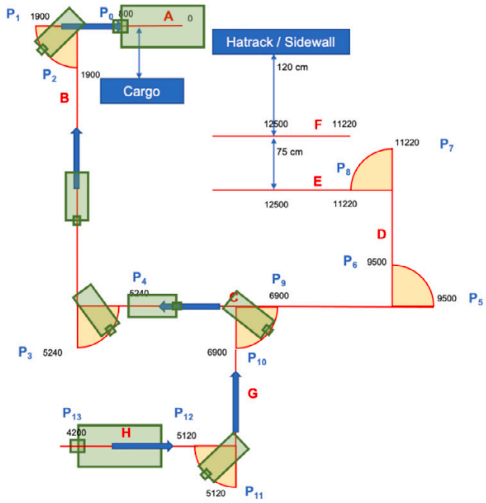
As mentioned before, to reduce complexity while guaranteeing high reliability, the positioning system relies on the Pepperl-Fuchs system named PGV (Position Guided Vision), which consists of an optical reading head and a QR-code tape (the data matrix tape), as in Fig. 13.

The tape has an adhesive side, thus, the path that the robotic platform will follow can be realized easily by attaching the tape to the floor before the testing phase begins and as easily removed after it ends.

The navigation task is simplified to a line following, intertwined with some rotations and parallel movements. The positioning accuracy is estimated at 0.2 mm, much higher than onboard odometers can provide, and without any drift effect. It is worth noting that the positioning system is fault-tolerant to a few scratches on the tape itself. As an example of the commands required to move the testing system at VISTA partners facility from a “home” position to the initial scanning position for the cargo area, shown in Fig. 14.

6.4.2. Arm/lift coordination

Arm-elevator coordination is essential for accurate scanning and subsequent analysis of the entire hatrack. However, the UR10e arm’s workspace is insufficient to scan all parts of the hatrack. A 120 millimeter elevation is required to achieve a complete scan without missing any sections. The supervisor issues a command to the Ewellix lift kit installed in the VISTA prototype to lift the robotic arm appropriately. Referring to the sequence of steps, the command `vista liftkit {"value": 120}` raises the UR10e to a height of 120 mm from the base. Similarly, after hatrack scanning, the command `vista liftkit {"value": 0}` lowers the arm back to its initial height, facilitating scanning of the sidewall and cargo area. The supervisor coordinates




```
Home2Cargo
(Start at 4200, near H)
vp_publish_goal 5120
vp_publish_rotate 0
vp_publish_goal 6900
vp_publish_rotate 0
vp_publish_goal 5240
vp_publish_rotate 1
vp_publish_goal 1900
vp_publish_rotate 1
vp_publish_goal 800
```

Fig. 14. Example of ROS navigation commands for reaching the cargo area “A” starting from home position “H”. The sketch allows for a clear understanding of the main steps that need to be implemented by the AGV for performing the movements.

lift kit movements to ensure the UR10e reaches the expected height before moving to inspect 3D points. Arm-related commands, like `go intermediate_joints`, are directly coded using Moveit! Commander syntax. Each arm movement corresponds to a different Moveit variable, typically created, used, and deleted due to the potentially long list of intermediate positions.

6.4.3. *Data acquisition*

Data acquisition and storing are commands reported in the same step sequences file described beforehand and triggered adequately by the supervisor. Every time the robotic arm – and consequently the payload, i.e., the sensors – reaches one of the positions inserted in the file, 3d or 2d data acquisition can occur.

The supervisor interprets specific commands to trigger one or both acquisition events. `vista 3d_camera` command is used to perform a Gocator point cloud acquisition. Each acquisition is unique in the database and can be referred with its id. The action specifies that the 3d camera must acquire a snapshot (the point cloud), whilst the positioning information is collected for reporting purposes. In fact, to correctly display data in the virtual and augmented reality applications, the accurate positioning of the arm end effector as well as the offset given by the Ewellix Liftkit must be properly considered. Finally, the processing parameters are given in the homonym section of the command.

`vista color_camera` command is used to perform an image acquisition with the Dalsa Genie Nano XL 25Mp camera. Similarly to the previous acquisition class, 2D images are unique in the database and can be referred using their id. The action specifies that the camera must acquire a snapshot (the high-resolution image). The positioning information is collected for the same purpose of the 3D ones.

6.4.4. *Processing*

Data processing takes place on the supervisor machine after the data storing step described beforehand. The goal of data processing is to compute accurate measurements using the 3D sensor LMI Gocator 3210 and the Dalsa vision color camera to detect defects according to the AC-CLAIM acceptance criteria of lining document. Before going on through the details of each type of processing, it is worth highlighting that all the reference measurements (as well as the tolerances) evaluated in VISTA project are customizable (for example, a GAP can be considered OK if the measure lies in the range “SetPoint ± tolerance mm”). The next paragraphs give an insight on the techniques used for data processing.

The detection of geometrical defect takes place after a comprehensive analysis of a 3d point cloud acquired by the LMI Gocator 3210. An example of point cloud taken from the cabin area is shown in Fig. 15, referring to the gap area between two storage compartments of the same hatrack (in this case, simulating the gap between adjacent hatracks).

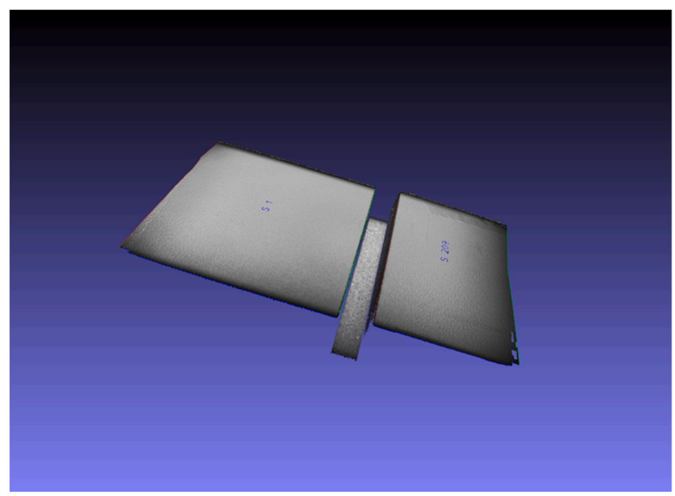


Fig. 15. 3d point cloud of a gap area between two storage departments of the same hatracks. This signal is processed by the algorithms developed in VISTA project in order to automatically perform geometrical measurements.

The scanned area is a surface of about 100 x 150 square millimeters sampled with roughly 2.5 million points. This means that the processing software needs to take into account a huge amount of data to produce a single measurement. Geometrical defects can be summarized as gap, step, parallelism and mismatch of tolerances. The processing software performs common operations on all the point clouds to compute the measurements. Each 3D point cloud is analyzed looking at the sampled surfaces (in this case two surfaces: one left, one right), giving them a specific identifier (S1 and S209 in the example). For each automatically identified surface, the aim is to extract the four edges (top, right, bottom and left) that are appropriately compared depending on the specific measurement to perform. With reference to Fig. 15, gap and step measurements can take place after the comparison of the right edge of surface S1 (green points) with the left edge of surface S209 (red points) on a proper reference system. Due to the high number of data collected in a single gocator snapshot, each edge is made of about 1000-1200 different 3D points. For this reason, the measurement is the result of a robust statistic evaluated on all the points of the edges. The most frequent value is returned to the supervisor and considered as the measurement for the entire snapshot. The differences between gap and step are ba-

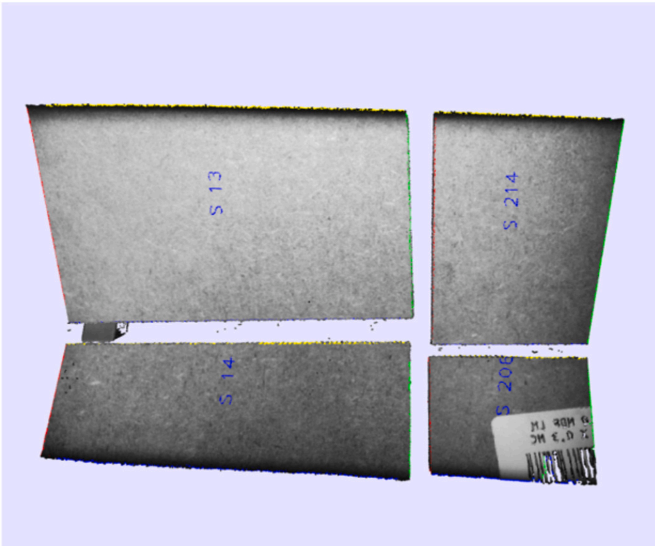


Fig. 16. Example of 3d point cloud from the cargo area. This signal is processed by the algorithms developed in VISTA project in order to automatically perform geometrical measurements.

sically on which coordinate is considered while computing the relative distances between the points of the two edges.

Fig. 16 depicts an example of point cloud from the cargo area, where four different panels are sampled in the scanned area. The software logic is the same with the main difference in the number of identified surfaces, namely S13, S214, S208 and S14. In this case, the processing consists of computing all the edges as detailed before, as well as the gaps between each pair of subsequent surfaces. The special case of mismatch of tolerances can be considered here evaluating the differences between the gaps. A final remark should be given about the parallelism measurement. Since this kind of measurement takes place on longer surfaces, it is not possible to compute it directly relying on a single Gocator snapshot.

For this reason, the supervisor needs to evaluate the gap measurements at the beginning and at the end of a bigger panel in order to evaluate the parallelism, either in the horizontal or vertical direction. Specific instructions are provided to highlight how to group them to extract these higher-level geometrical measurements.

The detection of scratches, bumps and dents is evaluated also on 3D data coming from the Gocator 3210 sensor as well as the color camera. Rather than focusing on aspects better managed during manufacturing and quality assurance, such as material differences or surface textures, VISTA tests have been focused on understanding issues arising from automation, especially in assembly tasks.

The project adopts a pragmatic approach. It emphasizes task allocation between robots and human operators based on their respective strengths, recognizing the continued importance of human judgment.

Due to hardware limitations, precise color evaluation tools like X-Rite's color checker could not be integrated. Thus, human operators are responsible for assessing anomalies, often providing qualitative evaluations due to challenges in quantifying defects accurately.

Surface appearance tasks are divided between a color camera and a 3D sensor, with the color camera used for color and texture anomalies not fully captured by the 3D sensor.

Indeed, we noticed that three-dimensional data could also be effectively exploited to analyze the defects on the surface when the defect is identified as a proper outlier with respect to a 3D surface model, with an accuracy of the order of 0,1 mm.

Further details about the methodology used for exploiting depth data captured from Gocator 3210 are available in [13].

However, there are cases where the data captured from a depth sensor are not suitable for detecting specific defects, as shown in Fig. 17. Such is the case of surface defects related to color alterations but not showing any changes on the depth sensor. These cases need to be captured through a color camera. It is also worth noting that formalizing what kind of color and texture anomalies should be classified as defects, and, vice versa, what is passable, is particularly challenging. For this reason, an approach based on a training set has been deemed a natural approach for addressing this kind of challenge.

Deep learning, a type of data-driven machine learning, has gained popularity for its flexibility and effectiveness, particularly in image classification tasks where its accuracy rivals human discernment.

In the context of the VISTA project, a convolutional neural network was trained using image tiles of 256x256 pixels. This enables the system to process images of varying sizes by treating them as smaller tiles categorized as either "good" or "bad". A training dataset of images was manually labeled to create image masks, dividing images into normal ("good") and anomalous ("bad") parts, a process needing only initial manual intervention for reuse during system operation.

Using these labeled images, appropriately sized examples were extracted using a sliding window technique with a 25% overlap. Each sample tile was automatically classified based on the proportion of white pixels, with tiles containing over 20% white-labeled pixels marked as "bad". These anomalies often corresponded to temporary markers or "dirty" areas on panels at partner facilities. An example image pair demonstrating this process is illustrated in Fig. 18.

The network architecture consists of four convolutional layers, intertwined with pooling layers, and followed by two "dense" linear fully connected layers, with the final nodes corresponding to the "good" and "bad" classes. Intuitively, the convolutional layers, mixed with the pooling layers, are able to model the spatial relations between different parts of the tile and extract features of gradually higher level. The final fully connected layers then "connect" together all the "pieces" for providing the final classification. Forty training "epochs" were necessary for getting a training accuracy of about 97%.

Further detail about this methodology and its comparison with other techniques like SURF descriptors can be found in [14].

6.5. Presentation layer

Reporting is loosely coupled to the inspection phase: reporting enables to visualize inspection results and express a judgment on them, enabling inspector officers to decide what is correctly be considered a defect, triggering actions outside VISTA system boundaries, and what, instead, has misclassified, so that VISTA judgment can be fine-tuned for successive inspections.

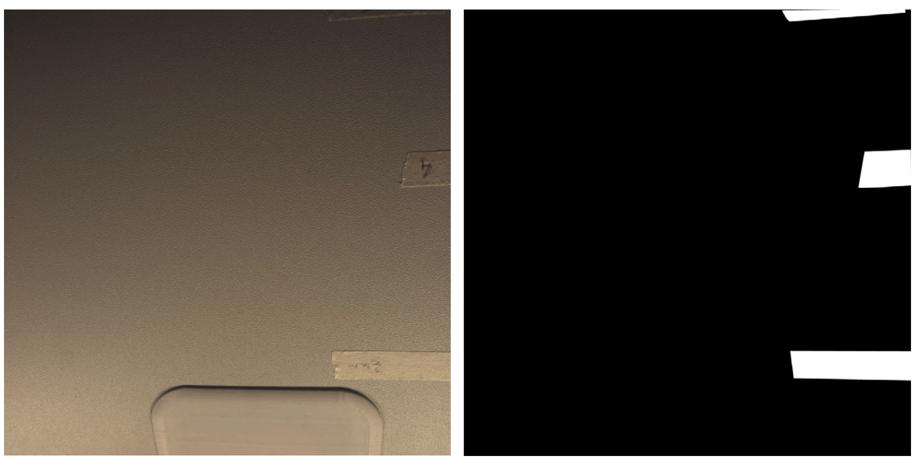
In addition to a web interface enabling access to the backend for configuring and inspecting supervisor results tailored to the development and debugging of the system, there are additional frontends available for the presentation of defects to human inspector officers.

Three ways are available to list the defects: as text; on a 3D model; or over imposed in augmented reality.

A list of defects is available on the different versions of the reporting tool, and consists of the "list view" that is reported after the user has selected a processing timeline to inspect. An example of reporting in list format is available in Fig. 19.

Most of the time, however, data must be considered in the proper context. To ease the work of the quality inspection officer in evaluating the list of measurements and possible defects, it is possible to select the "3D view" mode. This enables to split the screen in two parts, with the left side continuing to host the list of defects, while the rest of the screen is used for a "virtual reality" representation of the environment. As previously reported, it was required to get a 3D reconstruction of the two areas (cabin and cargo) in Bari. The two areas have been segmented and extracted from the point clouds provided by the LIDAR sensor and "remapped" in a virtual aircraft section, meaning that cabin and cargo area defects are listed separately. An example is shown in Fig. 20.

Fig. 17. Surface anomalies can be detected with both 3D and color cameras, with each one providing benefits in specific cases. For instance, subtle surface issues like the scratch in the orange box are better handled by the 3D acquisition and processing pipeline.



(a) Color image (b) Labeled image

Fig. 18. An example of images for the neural network training set. The image on the left is acquired from the camera, the one on the right is the labeled mask with the anomalous areas in white.

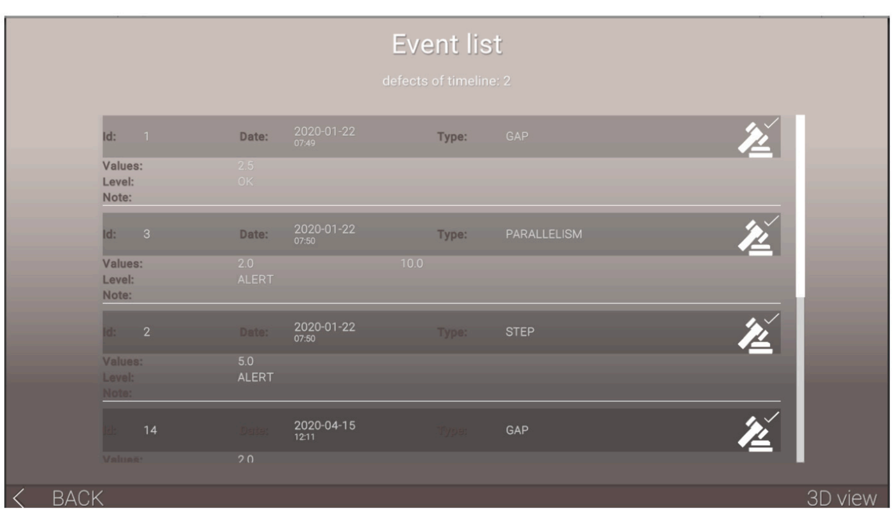


Fig. 19. Example of event list in the Windows version of the reporting tool.

Fig. 20. Desktop version of the reporting system for the cabin area. A lidar-based reconstruction of the real world, as in this case, or a cad model, can be used for the virtual world. Measurements are reported in the event list and shown in different colors, considering the classification provided by the inspection modules (red: alert, yellow: warning, green: ok).

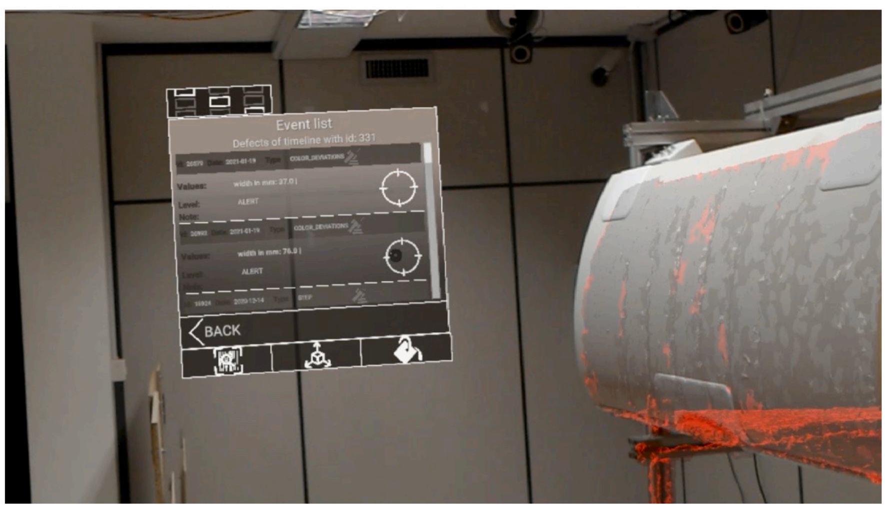


Fig. 21. Floating window reporting the list of measurements in the event list on the mixed reality device.

While the VR-like application has been devised for analyzing the measurements when the user/quality inspection officer is away from the production site, another solution is possible if the officer can work from the production site. A particular version of the application is indeed capable of running on mixed-reality devices, such as kits of the Microsoft Hololens family, where, following an augmented reality approach, it is possible to walk freely in the area being inspected and "see" the position of the performed measurements and possible defects directly over imposed on the image of the environment.

While using the VISTA application on Hololens, the vision specs are capable of showing text, images and 3D models "co-existing" on the same scene, as visible in Fig. 21. Since it is a stereoscopic device, virtual objects can be projected at a specified distance. The user is free to move in the environment, with some additional sensors (such as inertial sensors) taking care of tracking the user and updating the position of the virtual objects from the new point of view. Good measurements or possible defects can be seen directly on the involved panel. Further information is available in [16].

7. Discussion

The proposed system allows us to semi-automatically inspect the quality of aircraft components during the final production steps of single-aisle aircraft assembly by using robotics, computer vision, machine learning, and VR/AR as enabling technologies for this purpose. Specifically, the novelty of our solution resides in the main points presented in Introduction, namely: i) a multi-modal assembly lining quality control, comprising both 3D and color imaging; ii) a unified script-based automation for all robotics-related tasks as well as quality control ones; iii) the use of innovative reporting systems powered by AR and VR technologies, aimed at a human-centered semi-automated approach for assembly lining inspection. This approach has the objective of freeing the domain experts from repetitive actions, whilst improving safety and inspection consistency. It is worth broading the discussion about repeatability and reproducibility, as well as highlighting the limitations of the proposed solution. As for the repeatability of the tests, it is ensured both from a hardware and software viewpoint. In this regard, the use of suitable hardware that is compliant with the main requirements in terms of resolution and accuracy allows to accomplish precise quality control during the assembly of components. The accurate positioning and localization of the mobile platform are guaranteed by the use of the PVG system, which is the reference standard for several industrial applications. The positioning accuracy is ± 0.2 mm. The robotic arm in charge of moving the perception systems has a pose repeatability of ± 0.05 mm according to the standard ISO 9283. Finally, the 3D sensor used for acquiring the geometries and shapes of aircraft components ensures a repeatability of 4.7 μm along the depth (Z-axis) and an in-plane (XY-axes) resolution of 75 μm. In addition, the developed software for analyzing both 2D and 3D data is based on methods and algorithms – consolidated and validated by the scientific community – that return back deterministic outputs, implicitly ensuring the repeatability of data processing. Differently from non-deterministic methods that may produce different outputs in different runs given the same input, the deterministic methods always yield the same output. A similar observation can be made regarding the deep learning–based models. Although the training process involves introducing stochastic elements such as weight initialization, dropout, and batch sampling, after the training phase, the inference output is always deterministic and inline with the project specifications. Therefore, these aspects enable us to affirm that the repeatability of measurements and data processing is ensured. Similarly, the reproducibility is proven by the fact that using the proposed architecture, it is possible to extensively simulate the behavior of the robotic platform as well as the intermediate quality control steps, resulting in multiple positively run tests carried out in different locations. These tests allowed to validate the robustness and effectiveness of the proposed solution.

However, some limitations still hold:

- Limited duration of the battery for the power supply of the robotic arm. One key aspect revolves around the nature of the UR10e robotic arm. While tolerable for a research prototype, it became evident that certain design choices align more with industrial applications where the robot can be powered from a wall socket rather than relying solely on a battery. An inherent issue lies in that even when the arm is resting, still, the robot is operational and ready to receive commands, and its joint actuators continuously consume power. The only way to mitigate this power draw is to power off the entire arm, which is impractical since it lacks a "fast resume" capability. This limitation is exacerbated by the arm's ROS driver and associated tools not facilitating a quick restart.
  This continuous power consumption, even during idle states, implies that the UR10e consumes energy consistently, reducing the overall operational time on a single battery charge. Considering the current testing system implementation, it was estimated that it is practical to inspect more than fifty complete aircraft components (both hatrack and sidewall) before the battery requires recharging. Moving from a research to deployment, production ready state, poses a challenge.
- Power consumption of Ewellix Lift kit. While not as critical as the UR10e, it exhibits some power consumption in motion. Fortunately, it ceases to draw power once it reaches the required position. In contrast, the sensors, illuminators, and industrial PC exhibit modest power requirements, offering energy-efficient operations.
- Required processing time of acquisition by the 3D sensor and limited snapshot area. Processing speed emerged as a critical factor, particularly in 3D measurements. While basic optimizations have been implemented, further development can capitalize on hardware and software improvements.

8. Conclusions and future work

While our research was conducted a few years ago, it is essential to highlight that, to the best of authors' knowledge, in the meantime no comparable works have been undertaken by other researchers in the field. The absence of subsequent studies addressing similar challenges reinforces our investigation's unique and pioneering nature. The insights gained from our work continue to serve as a foundational framework for understanding and managing the design of an integrated solution for automatizing quality control post-assembly, one of the last parts in the automation chain for more efficient manufacturing in the aerospace industry. Our findings remain timely and relevant, providing insights for ongoing advancements in aircraft assembly lining quality control.

To sum up, the utilization of a semi-automatic system offers significant advantages in terms of safety, consistency, and enhanced usability for both on-site and off-site scenarios. The integration of innovative reporting and validation methods allows experts to provide input remotely, thereby increasing the system's flexibility. The use of a 3D camera enables the collection of more detailed and accurate data, facilitating statistical analysis of measurements such as steps, gaps, parallelism, and tolerance mismatches. This approach is likely to yield more consistent results compared to traditional manual measurements. Furthermore, the contactless nature of color and 3D cameras is particularly beneficial for detecting defects without risking damage to the inspected parts. While the system remains a research prototype and requires further validation and engineering refinements, the preliminary results indicate promising progress in the right direction.

Future activities can be led to solve some of the limitations currently in place. UR10e and the Ewellix Lift kit power draw, emphasize the need to address power efficiency in future iterations of the VISTA testing system. Possible solutions include exploring alternative robot arms that are more battery-friendly or designing a custom robotic arm specifically tailored to the requirements of the testing system. These considerations, along with other identified challenges, highlight the ongoing relevance and importance of our research in guiding the evolution of automated inspection systems in industrial applications. Includingpecialized accelerators for optimizing the processing speed, particularly in 3D measurements, can also prove beneficial. For instance, enhancements such as utilizing graphic cards for parallel tasks could significantly expedite processing times.

Other possibilities could be investigated while considering the HW redesign. Project timing within the ACCLAIM framework did not allow for the investigation of further synergies of simultaneously assembling aircraft parts and performing quality control. Potential benefits of this approach include a timely discovery of at least some of the defects to be identified, potentially saving time and increasing the speed of the overall process. On the other hand, the effort seems challenging from the start. For instance, different panels require different manipulators and robots during assembly, and the integration of further sensors, which also requires an unoccluded view of the parts to inspect, certainly adds to the complexity.

More ambitious redesigns, for instance, inspecting the lining with a sensors-equipped drone, due to the characteristics of sensors available now, considering limits related to time (the seconds required while standing still for the 3D camera to acquire each area snapshot), or the weight, or the energy consumption, could be investigated only in the long term.

Additional considerations can be made for the actual quality control task taking place. Considering the inspection strategy, during the project inception, all parties agreed that the best phase in which passenger area inspection could take place was before any seats were added. This situation enables complete sidewall visibility and allows the robot to perform inspections from the best spots. An interesting future work could investigate how to relax this constraint. Enabling inspection after seats are assembled, even considering the impossibility of checking sidewalls integrally and other compromises, could allow the use of the system in periodic maintenance scenarios, further expanding the desirability of such a system.

Moreover, while what was described here is a research prototype, additional checks for evaluating data integrity before and possibly during inspection can be added to improve reliability. In particular, adding some processing on the AGV could avoid wasted acquisition and processing times, should something go wrong, like the flash lamp not working properly. The system architecture, and in particular the capability of devising a working plan in the form of a script, enables to easily address these scenarios by integrating and executing these checks on the mobile robot before any inspection missions start.

In addition, our research touched upon the reporting modalities, and there is potential for porting the software to Hololens 2 or more recent AR devices. Hololens 2 already showcases processing power, resolution, tracking responsiveness, and reliability improvements. Moreover, further improvements to the user interface design selection and validation of defects can contribute to achieving a more efficient, intuitive, and immersive experience.

In conclusion, despite its current limitations, even considering these potential developments, the VISTA project has proved that defect detection in the post-assembly phase is an area where automation can significantly increase productivity and measurement consistency over prolonged periods. The enduring relevance of our work, underscored by the absence of comparable studies in subsequent years, positions it as an important contribution to the field of computer-aided quality control. As the technology landscape evolves, addressing the identified challenges will be crucial for realizing the full potential of automated inspection systems in industrial applications.

CRediT authorship contribution statement

Nicola Mosca: Writing – original draft, Validation, Software. Methodology, Investigation, Conceptualization. **Vito Renò:** Writing – review & editing, Validation, Software, Methodology, Investigation, Conceptualization. **Massimiliano Nitti:** Writing – review & editing, Validation, Software, Methodology, Investigation, Conceptualization. **Cosimo Patruno:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Simone Pio Negri:** Writing – review & editing, Methodology, Investigation. **Ettore Stella:** Validation, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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