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A Digital Twin Approach for Smart Assembly of Aircraft Skin Panels with Mechanical Fasteners

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Abstract. The current best-practice in the assembly process of aircraft skin panels involves several manual measurement-fit-adjust quality loops, such as loading part on the assembly frame, measuring gaps, off-loading parts, adding be-spoke shims and re-positioning parts ready for the fastening operation. The consequence is that the aircraft is re-assembled at least twice and therefore this process has been proved highly inefficient.
This paper describes the framework developed under the "Integrated Smart Assembly Factory" (ISAF) project in the "Intelligent Factory" specialization area in Italy. Taking advantage of the emerging tools brought by Industry 4.0 the ISAF framework spearheads innovation in the assembly process of aircraft skin panels by integrating smart and digital technologies such as in-line measurement systems with highly accurate sensors, large-scale physics-based simulations, multidisciplinary process optimisation and additive manufacturing. The proposed methodology allows predicting and fabricating shims using in-line measurement data with no need to iterate the measurement-fit-adjust quality loops. This will undoubtedly reduce inspection/measurement time and costs, enabling operators to virtually test assembly operations before installation in the field. The results were demonstrated during the assembly process of a vertical stabiliser for commercial aircrafts, and findings showed a significant time saving of 75%.

Keywords: shimming, smart factory, in-line measurement, digital twins, physical simulation, flexible alignment, additive manufacturing.

1 Introduction and background

The assembly of a modern aircraft requires thousands of custom shims to fill gaps between structural components in the airframe [1]. Gaps are the consequence of accumulated variations during the assembly process itself. Due to the need to deal with large, thin and compliant parts - even when parts are manufactured to specification - part-to-part gaps can appear. Cheng et al. [2], studied the tensile response of mechanical fasteners in case of shims with different materials and thicknesses. They reported that shims can considerably reduce the assembly stress on mechanical fasteners and improve the joint stiffness and load capacity, and this effect is more remarkable with the increase of gap values. So, a strict control method must be implemented to ensure the part-to-part gaps are within the targeted control limits (typically below 1 mm).

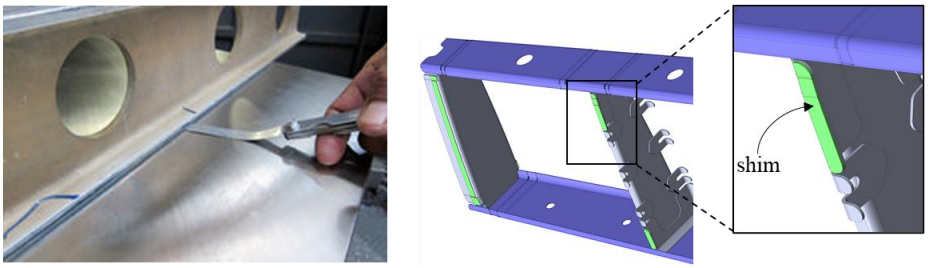


Fig. 1. (Left) example of gap measurement using manual filler gauge.
(Right) visualisation of shims.

The current best-practice is to manually measure the gap around the fastening points of the pre-positioned parts and, based on these measurements, shims are first machined and then inserted between parts (Fig. 1). Lastly, mechanical fasteners are inserted and secured. This operation is known as *shimming*. A critical element during shimming is the measurement of part-to-part gap which currently relies on manual gauges such as filler gauges, as shown in Fig. 1, or capacitive sensors. This approach has three main limitations and challenges. *Challenge - C1*, the measurement, being manual, is inaccurate and unable to follow the 3D profile of the gap. *Challenge - C2*, the bottom surface of the shim to be manufactured is assumed flat, and this does not correspond to the actual gap distribution between parts. *Challenge - C3* , since gaps are measured in a "closed-configuration", where parts are aligned on the same jig to form a closed structure, access to each fastening point may be cumbersome and therefore the measurement accuracy would be affected. Alternative solutions to shimming were also proposed and are discussed as follows: (1) *in-situ printing of shimming* - in [3] shims have been manufactured directly on the part being joined by a 3D printer attached to an anthropomorphic robot moving over the structure. (2) *Liquid shimming* - since cracking and delamination can appear around the mechanical fasteners of composite structures due to unpredictable re-distribution of loads, *liquid shims* (epoxy-based adhesive) have been introduced as alternative to mechanical fasteners [4]. They are commonly used in bonded applications, such as composite rib-to-skin assembly. Altought they offer high compressive strength properties, the suffer under shear and traction loads. (3) *Local*

machining of panels - In [5] a method has been described to eliminate the shimming requirement by developing automated processes to remove excessing material from the appropriate interfaces using rapid metrology techniques and robotic systems. This technique was claimed to be more advantageous than working with shims. On the same line, in [6], a possible solution to the high variability of the manufacturing process of an aircraft wing assembly was described by using an adaptive assembly process which was shown to be highly repeatable.

More recently, Manohar et al. [7] demonstrated the ability of machine learning to optimise sensors to reduce the number of measurements required to accurately predict shims in aircraft assembly. Emerging tools and technologies brought by Industry 4.0, digital technologies (machine learning/artificial intelligence) such as in-line measurement systems, highly accurate sensors, large-scale physics-based simulations, additive manufacturing and process optimisation offer the possibility to speed up the quality check, take the process variability under control and reduce production costs.

This paper presents the framework developed under the "Integrated Smart Assembly Factory" (ISAF) project in the "Intelligent Factory" specialization area in Italy. The results are demonstrated during the assembly process of a vertical stabiliser for commercial aircrafts.

The remainder of this paper is organized as follows: Section 2 outlines the ISAF framework. Section 3 described the developed key enabling technologies, while Section 4 describes the case study and the related results. Finally, Section 5 draws the conclusions.

2 ISAF framework

In order to overcome the three aforementioned challenges (C1 to C3), the ISAF framework is hinged on the idea to accurately measure in-line the mating surfaces of parts being assembled while they are in an "open-configuration" (Fig. 2). This opposes the state-of-the-art approach which manually measures gaps only when parts are positioned and aligned together on the same assembly jig. The proposed approach allows to predict and fabricate shims using in-line measurement data with no need to iterate the measurement-fit-adjust quality loops. This will undoubtedly reduce inspection and re-work costs, enabling operators to virtually test assembly operations before deployment and installation in the field. The ISAF framework has shifted the problem from a metrology-driven challenge to a prediction model. For instance, ISAF implements a digital twin-driven approach in the sense that a symbiotic integration between in-line measurement data (*physical* domain), embedded computation and physical assets (*digital* domain) is deemed. The technological challenge now is the need to predict the geometrical configuration of parts once they are moved from the open-configuration to the closed one. The challenge is driven by the fact that (1) skin panels may deform under the effect of gravity; (2) and/or, be pushed away by the pressure exerted by the ribs subject to manufacturing tolerances.

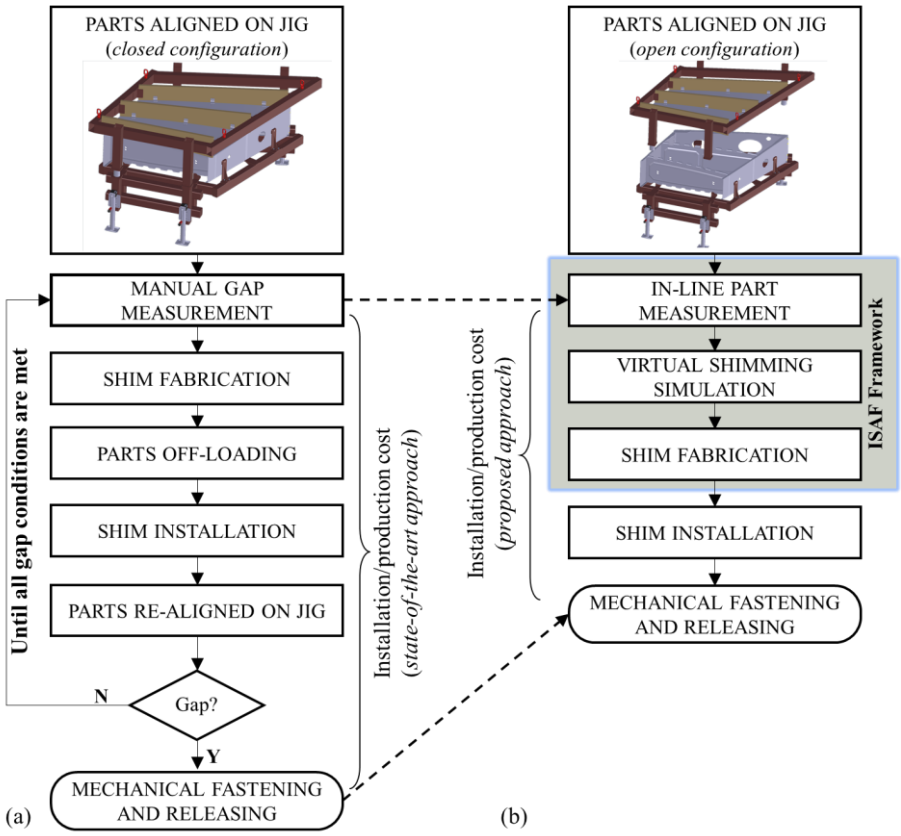


Fig. 2. (a) State-of-the-art approach for shimming operation – *closed configuration*. (b) Proposed approach for shimming operation – *open configuration*.

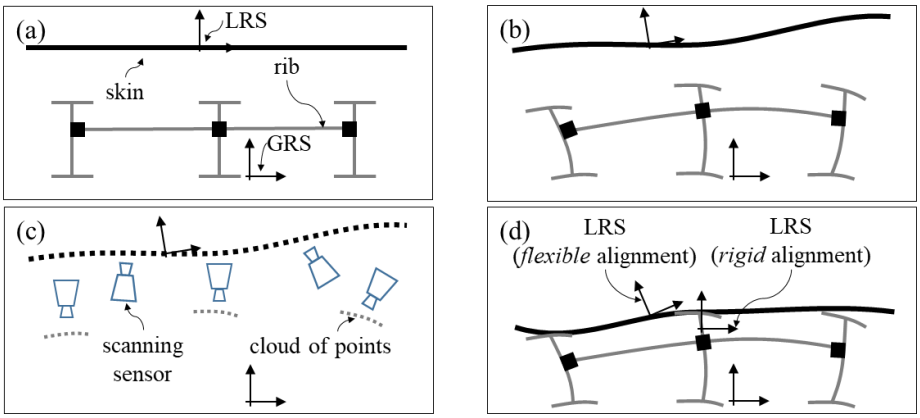


Fig. 3. (a) nominal parts; (b) actual parts; (c) in-process measurement; (d) accumulation of deviations when skin panels are moved from the *open configuration* to the *closed configuration*.

The concept is illustrated in Fig. 3, where GRS and LRS are the Global and Local Reference Systems, respectively. Once parts are scanned (Fig. 3(c)), the gathered cloud of points (defined into LRS) is aligned to GRS. Finding the correct alignment is the technological challenge. State-the-art methods, based on rigid rotations/translations (for example, iterative closest points or best fitting alignments) are un-capable to model physical effects, such as gravity and part deformations (i.e., elastic deformation induced by part-to-part contact). In this regards, the ISAF framework overomes that challenge and implements a *flexible alignment*, which combines both rigid rotations/translations and local deformations to account part deformations.

A portfolio of three enabling technologies has been developed in the ISAF framework: (1) in-line part measurement; (2) virtual shimming simulation; (3) shim fabrication using additive manufacturing/3D printing.

3 Key Enabling Technologies

3.1 Key Enabling Technology (1): in-line part measurement

The main goal of the *in-line part measurement* module is to provide an automated and intuitive tool to scan the surface of mating surfaces of those parts being assembled. The challenge lies in the fact that large parts (a typical skin panel may be more than 10 m long) need scanning and therefore an accurate tracking and registration method needs to be implement in order to generate repeatable and reliable measurement data.

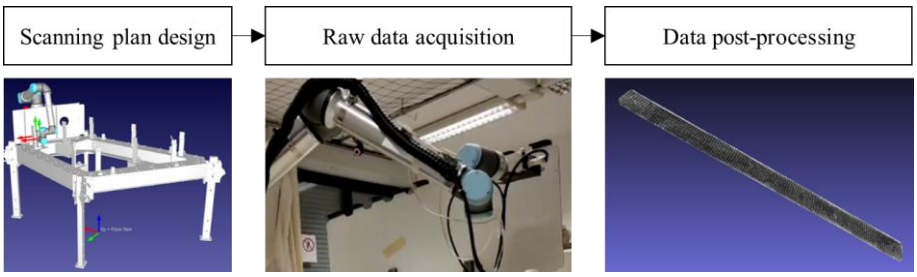


Fig. 4. Work-flow of the in-line part measurement module.

The technological solution relies on a mobile Automated Guided Vehicle (AGV) equipped with a 6-DOF robotic arm (Universal Robot UR10e) and a 3D scanning sensor. The AGV consists of an omni-directional mobile platform; a navigation/positioning system based on an optical sensor for the localization/following of a suitable tape with QR-code; an industrial PC for the management of aspects related to navigation; a battery and its inverter. The 3D scanning sensor is a LMI Gocator 3210 and is capable of reconstructing surfaces with high accuracy at micrometric precision, producing about 2.5 million distinct points for a single acquisition (accuracy in Z approx. 35 µm, and resolution in X/Y plane approx. 80 µm).

The scanning methodology is mainly composed of three tasks, as shown in Fig. 4. First of all, a scanning plan is defined based on the 3D CAD models of the parts. Then, raw data acquisition is performed every time the robotic arm is moved in a new

scanning position. Since the sensor is capable of acquiring 3D cloud of points with a scanning window of about 100 x150 mm, the role of robotic arm is to locate the 3D scanning sensor in the appropriate viewpoint to ensure the full coverage of the parts being scanned. After a certain number of acquisitions is carried out, each viewpoint is registered in order to perform the subsequent data post-processing. In this respect, the registered clouds of points are lastly merged into a single and dense cloud, ready to be exported for further analysis by the virtual shimming simulator.

3.2 Key Enabling Technology (2): Virtual Shimming Simulator

The main goal of the *virtual shimming simulator* module is to generate a Pareto Set of optimal design solutions which fulfil the part-to-part gap requirements and simultaneously generate 3D geometry of shims. The proposed methodological approach is illustrated in Fig. 5. The developed module combines statistical data obtained from a CAT (Computer-Aided Tolerance) simulation with scanning data to predict critical areas where the gap may exceed specifications limits. The result of this simulation is presented in the form of a sensitivity matrix. This matrix is then passed to the physics-based simulation which allows simulating the physical contact between parts and hence solve the flexible alignment (Fig. 6). The approach integrates an FEM kernel with an iterative contact solver [8] which makes use of the node-to-surface contact search approach [9]. The contact solver converges only if the gaps of all the active contact pairs are lower than a pre-set gap tolerance all pairs are in compression (negative load). A penalty method has been implemented to enforce these conditions [10].

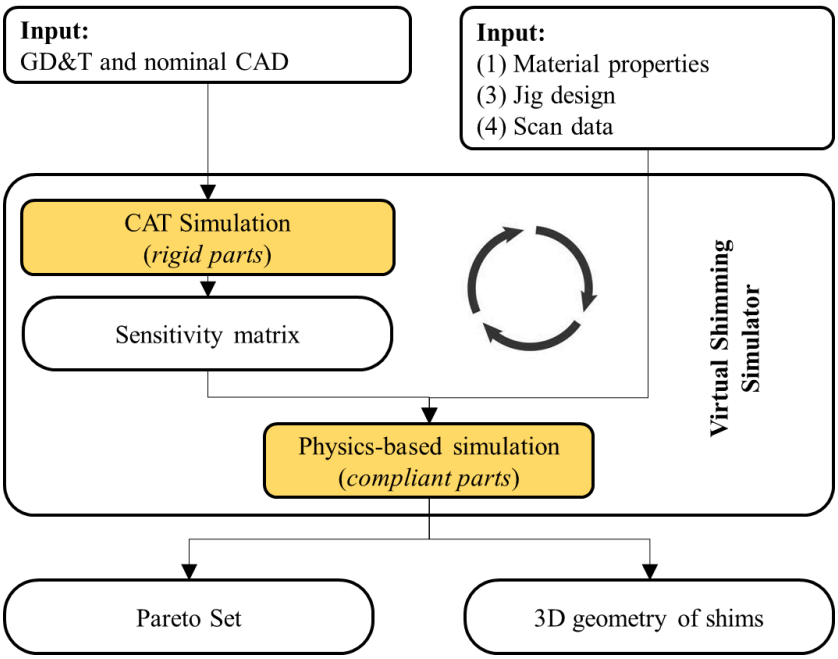
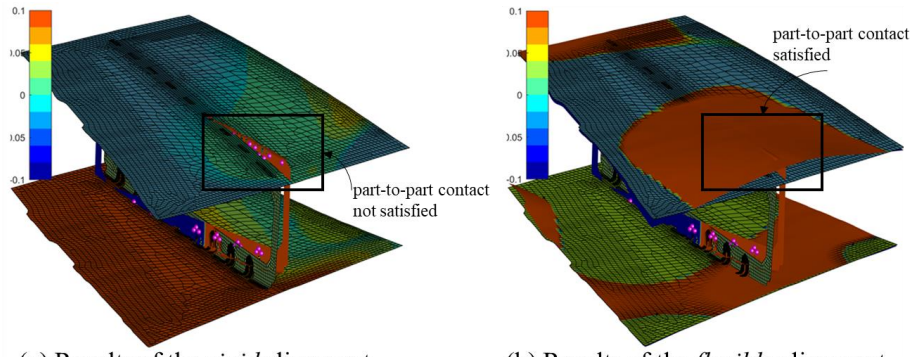


Fig. 5. Work-flow of the Virtual Shimming Simulator.

The work-flow for generating 3D shims from scanned data is shown in Fig. 6. The idea is that, once the scanned data of both parts (i.e., rib and skin) has been aligned using the flexible alignment, a regression alghoritm seeks to find the analytical surface which best fits the scanned data. Multiple formulation can be used for the analytical surface (i.e., spline, nurbs, etc.) pending upon the distribution of scanned data, accuracy and geometry topology. Shims are then generated as polygonal meshes and exported in STL format.



(a) Results of the *rigid* alignment (b) Results of the *flexible* alignment

Fig. 6. Visualisation of rigid vs. flexible alignment on vertical stabiliser.

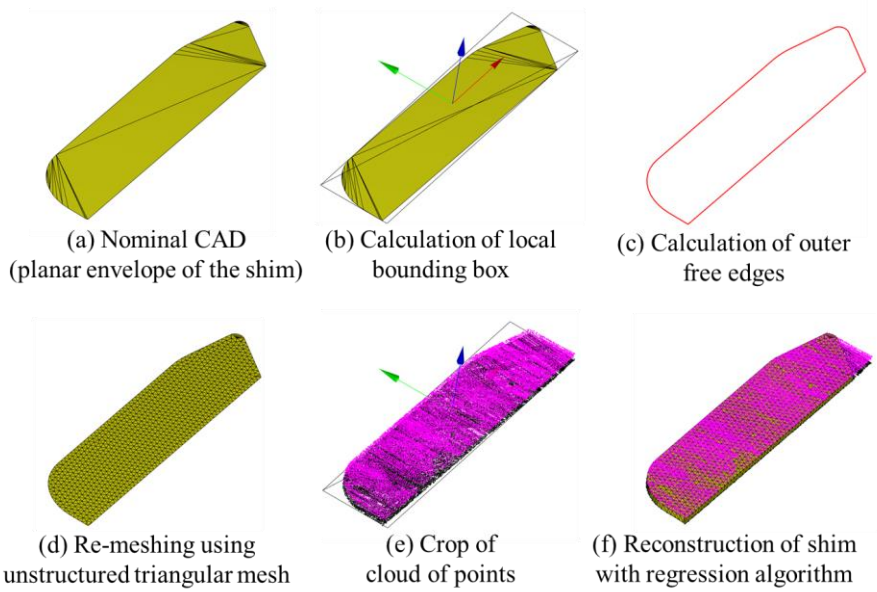


Fig. 7. Work-flow for generating 3D shims.

A user-friendly GUI has been implemented (Fig. 8) which allows to set up the work-flow and import inputs data including scanned data. Nominal CAD data are provided in STL format and include the reference surfaces, where shims are located.

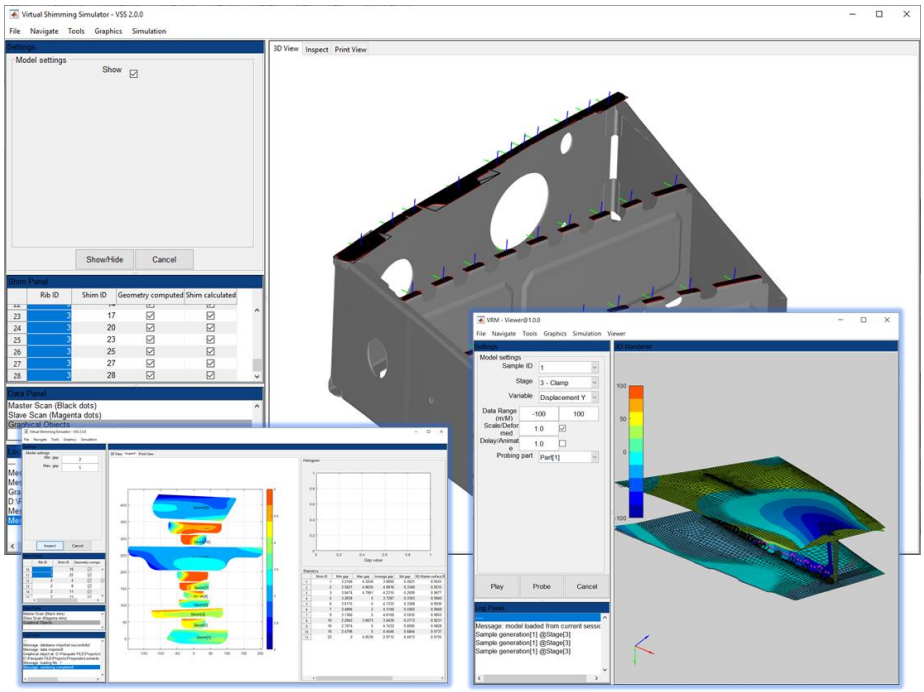


Fig. 8. Graphical User Interface of the Virtual Shimming Simulator.

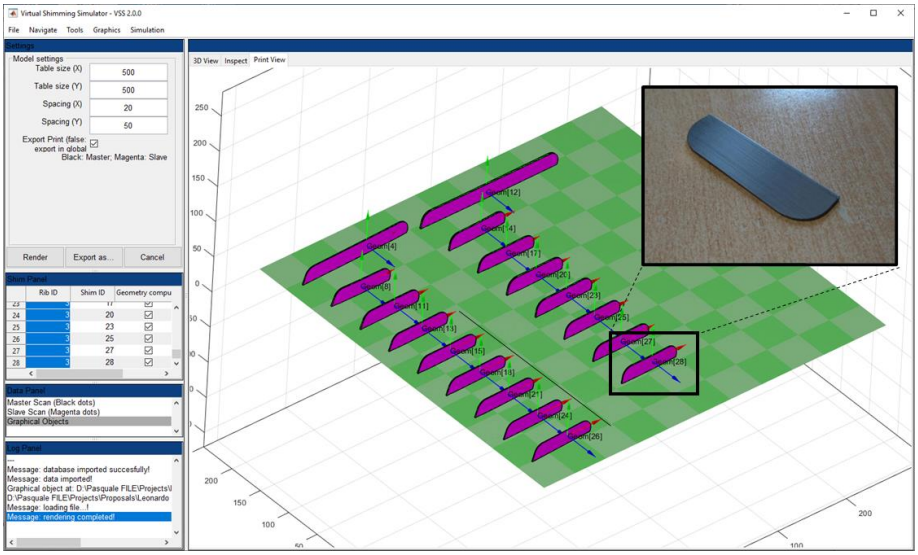


Fig. 9. 3D printing layout with example of printed shim.

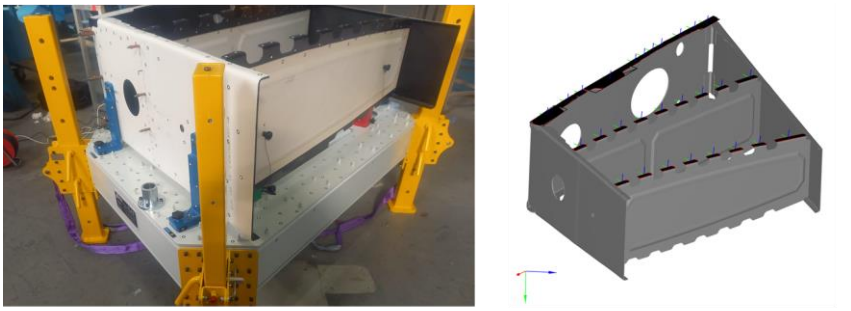
3.3 Key Enabling Technology (3): Shim Fabrication

Shims generated by the Virtual Shimming Simulator are exported in STL format (Fig. 9 shows the printing layout automatically generated in the GUI) and fabricated by

a 3D printer. 3D printing is considered with a great interest for the many advantages it offers. First of all, it is a tool-free process, and it offers the possibility to achieve significant weight reductions (40-60%) by manufacturing very strong and, at the same time, lightweight structures, in combination with the use of specialised materials to meet the safety-relevant hazard levels commonly used in aerospace. The adopted material for 3D printing of shims is the high performance carbon PEEK, a composite material reinforced with carbon fiber, with extraordinary characteristics in terms of mechanical, thermal and chemical resistance [11]. Shims are manufactured with a Reboze Argo 500 3D printer, by Reboze, US [12].

4 Verification and Validation using Vertical Stabiliser

The ISAF framework has been been tested and validated on the vertical stabiliser of the aircraft assembly system, shown in Fig. 10. The aim of the study is to compare the results obtained with the current best practice approach using manual filler gauge, against the predictions obtained using the ISAF framework. Total 40 shims were generated as shown in Fig. 10(b) between skin (not shown in figure) and ribs/spars.



(a) Vertical stabiliser (b) Location of shims (total 40 shims)

Fig. 10. Vertical stabiliser used to validate the ISAF framework.

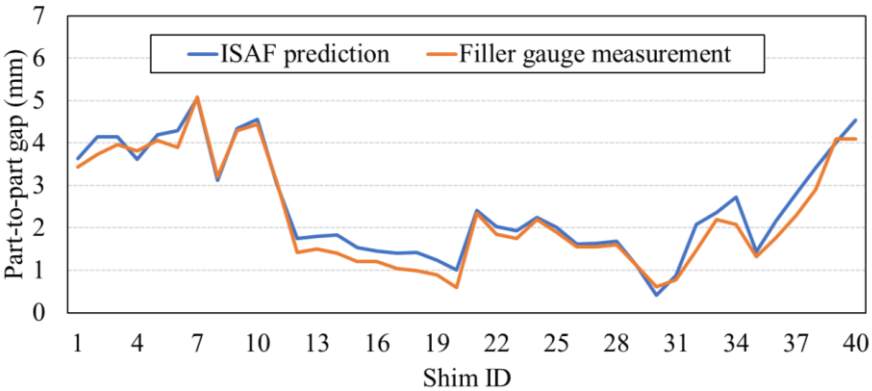


Fig. 11. Average part-to-part gap (shim thickness) measured by filler gauges and predicted using the ISAF framework.

Results are discussed as follows:

- *Accuracy of the prediction* - results are illustrated in Fig. 11 and findings show a strong correlation (approx. 98%) between the average shim thickness measured by filler gauges and predicted using the ISAF framework, with mean squared error of just 0.08 mm. This confirms the viability and accuracy of the methodology.
- *Time saving for measurement of part-to-part gaps* – it was reported that 2 hours were spent to gather the scanned data of both ribs/spars and skin. Whereas, near 8 hours were required to collected individual measurements using manual filler gauge. This equates to a significant time saving of 75%.

5 Conclusions

The ISAF framework aims to transform the current manual measurement-fit-adjust quality loops into a smart process powered by smart and digital technologies such as in-line measurement systems, large-scale physics-based simulations, multi-disciplinary process optimisation and additive manufacturing. This research will help reducing inspection and re-work costs, accelerate the adoption of digital manufacturing and drive towards the principles of zero-defects and right-first-time. Designers and manufacturing practitioners will benefit of this tool to automatically predict the part-to-part gap and will be able to “virtually” generate the 3D geometry of the shims.

The experimental validation corroborates the fact that a digital twin approach is a viable solution for handling assembly of aircraft skin panels and deliver a smart shimming operation, with a significant time saving of 75%.

Future research will be devoted to study and optimise the 3D printing operation in terms of accuracy and repeatability, and eventually additional cost saving.

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References

1. Esposito, C., Cosenza, C., Gerbino, S., Martorelli, M., Franciosa, P.: Virtual Shimming Simulation for Assembly Process Optimisation of Aircraft Skin Panels Based on a Physics-Based Digital Twin, Int J Interact Des Manuf (2022)
2. Cheng, L., Wang, Q., Ke, Y.: Experimental and numerical analyses of the shimming effect on bolted joints with nonuniform gaps. Proceedings of the Institution of Mechanical

Engineers, Part C: Journal of Mechanical Engineering Science 233(11), 3964-3975 (2019), https://doi.org/10.1177/0954406218809139.

3. Antolin-Urbaneja, J., Livinalli, J., Puerto, M., Liceaga, M. et al.: End-Effector for Automatic Shimming of Composites. SAE Technical Paper 2016-01-2111 (2016), https://doi.org/10.4271/2016-01-2111.
4. Dhôte, J.X., Comer, A.J., Stanley, W.F., Young, T.M.: Investigation into compressive properties of liquid shim for aerospace bolted joints. Composite Structures 109, 224-230 (2014), https://doi.org/10.1016/j.compstruct.2013.10.041.
5. Chouvion, B., Popov, A., Ratchev, S., Mason, C. et al.: Interface Management in Wing-Box Assembly. SAE Technical Paper 2011-01-2640 (2011), https://doi.org/10.4271/2011-01-2640.
6. Vaughan, D.W., Branson, D., Bakker, O., Ratchev, S.: Towards Self-Adaptive Fixturing Systems for Aircraft Wing Assembly. SAE Technical Paper 2015-01-2493 (2015), https://doi.org/10.4271/2015-01-2493.
7. Manohar, K., Hogan, T., Buttrick, J., Banerjee, A.G., Kutz, N.J., Brunton, S.L.: Predicting shim gaps in aircraft assembly with machine learning and sparse sensing. Journal of Manufacturing Systems 48 (Part C), 87-95 (2018), https://doi.org/10.1016/j.jmsy.2018.01.011.
8. Franciosa, P., Palit, A., Gerbino, S., Ceglarek, D.: A novel hybrid shell element formulation (QUAD+ and TRIA+): A benchmarking and comparative study. Finite Elements in Analysis and Design 166, 103319 (2019), https://doi.org/10.1016/j.finel.2019.103319.
9. Wriggers, P.: Computational Contact Mechanics. 2nd edn. Springer-Verlag Berlin Heidelberg (2006).
10. Russo, M.B., Greco, A., Gerbino, S., Franciosa, P.: Towards real-time physics-based variation simulation of assembly systems with compliant sheet-metal parts based on reduced-order models. In: JCM2022 International Joint Conference, Lecture Notes in Mechanical Engineering, Springer, 1-3 Jun, Ischia, IT, (2022).
11. REBOZE Carbon PEEK Homepage, https://www.roboze.com/en/3d-printing-materials/carbon-peek.html, last accessed 2022/02/13.
12. REBOZE Argo 500 Homepage, https://www.roboze.com/en/3d-printers/argo-500.html, last accessed 2022/02/13.