Development of an affordable and auto-reconfigurable solution for small box assembly ⋆

Z. Wang [*] **P. Kendall K. Gumma A. Smith** [**] **A. Turner S. Ratchev**

[*] *Centre for Aerospace Manufacturing, Advanced Manufacturing Building, Jubilee Campus, University of Nottingham, Nottingham, UK, NG8 1BB (e-mail: Sara.Wang@nottingham.ac.uk).*
[**] *GKN Aerospace Services Limited, East Cowes, Isle of Wight, UK*

Abstract: The aerospace manufacturing industry has been using dedicated assembly systems with manual processes for decades. Not only is this labour-intensive, it is also extremely wasteful as no reuse is possible at the end of a product life cycle. As automation technologies evolve, a flexible/reconfigurable assembly solution is needed to reduce tooling and manual hours in the process. However, a reconfigurable system is often perceived to be costly compared to a dedicated system. In this paper, an affordable and auto-reconfigurable assembly system is proposed for small box products. The proposed system consists of a jig frame, adjustable interface plates, reconfigurable profile boards and a pick-and-place (PnP) end effector. The jig frame can be robotically configured via a PnP process, in which the profile boards are loaded and unloaded onto the jig frame via the end effector. The process feasibility is proven with business case analyses and lab-based experiments regarding tolerance and process timing requirements. Through the business case analysis, cost-saving benefits can be achieved under realistic production scenarios, including a low-volume case. Process timing and repeatability of the jig configuration were also proven to be within the product and process requirements. The proposed tooling solution with automated robotic reconfiguration can be incorporated as a standard operation in a smart assembly factory.

Keywords: Smart manufacturing systems, Design and reconfiguration of manufacturing systems, Robotics in manufacturing, Performance analysis

1. INTRODUCTION

The aerospace manufacturing industry has been using dedicated assembly systems with manual processes for decades. While this traditional method provides excellent tooling stability and is proven to produce quality products, it is extremely wasteful as there is no reuse of major assets. With growing demands for production resilience and mass customisation, a flexible and reconfigurable manufacturing system is needed. Meanwhile, as automation and robotic technology evolves, material handling and assembly solutions are key enablers to minimise repetitive labour work and maximise the benefits of a flexible manufacturing system. The production of small-box components, which include winglets, rudders and elevators, is no exception. However, an automated reconfigurable system is often perceived to be costly compared to the traditional approach. This is due to the high capital investment cost of robots and associated tooling etc, which leads to the understanding that cost-saving benefit can only be realised with high production volume over a long period of time. Therefore, an affordable solution is needed for a next-generation production system. The main aim of this paper is to describe and assess a low-cost auto-reconfigurable tooling system developed to assemble multiple small-box products.

While automation and reconfigurable tooling offers opportunities to increase productivity, the system needs to be carefully designed to maintain product quality. Small-box products have a aerodynamic zone 2 profile tolerance requirement of 0.75mm. Therefore, the positional repeatability of the reconfigurable tooling needs to be proven with respect to such tolerance requirements. Minimised changeover time and effort is also required for a valid business case. Therefore, feasibility of the proposed tooling system is assessed in terms of process timing, business benefit and repeatability.

Although automation is commonly applied in drilling and fastening operations, its use in configuring aerospace assembly systems and component handling is limited. There are a few reconfigurable tooling solutions proposed in recent literature. Kihlman and Engström first introduced the concept of affordable reconfiguration tooling (ART) in Kihlman (2002), which consists of a static frame and dynamic modules. Dynamic modules were attached through a coordinated hole pattern or rails, where robots were used to configure the dynamic modules. Based on the ART

⋆ Innovate UK Project ELCAT (Enhaced Low-Cost Automation Technologies), GKN Aerospace

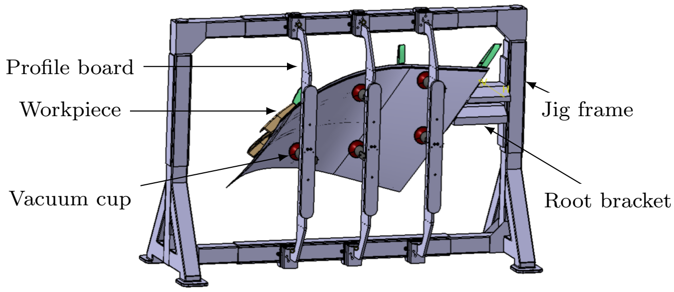
concept, the ReFlex demonstrator for wing assembly was built, see Millar and Kihlman (2009). A robot was used to pick and place a fixture between two work stations. The average clamp setup time was an hour with a positional tolerance of 0.15mm. In Kihlman and Engström (2010), ART was applied with BoxJoint and Flexapod. BoxJoint replaced the coordinated pattern of hole and rails, and provided mechanical connection on Box-section beams. Flexapod is a six degree of freedom adjustable unit, on which different pick-up tools can be mounted. A repeatability of ± 0.05mm was reported, while configuration cycle and business case were also analysed. The same concept was applied for automotive industry in the work of Erdem, see Erdem et al. (2015). A finely-adjustable unit, compatible with box-joint system, was designed for locating and clamping. In Erdem et al. (2016b) and Erdem et al. (2016a), an automated flexible tooling system, consisting of BoxJoint and Hexapod, was developed for wing box assembly. For cylindrical components, such as fuselage, linear actuated systems were considered by McKeown and Webb (2011), Müller et al. (2011) and Müller et al. (2013). While the BoxJoint framework is highly reconfigurable, fixture rebuild and calibration are extremely time consuming, making it impractical for a real-life production changeover.

In this paper, a novel, affordable, highly-repeatable and rapidly reconfigurable tooling solution is proposed for small box assembly. The proposed system consists of a jig frame, adjustable interface plates, reconfigurable profile boards and a pick-and-place end effector. The jig frame can be robotically configured via a PnP process, in which the profile boards are loaded and/or unloaded onto the jig frame via the end effector. This process occurs both between products, of the same and different types, and within a single product build. Between products, the profile boards are removed and configured to suit the next product scenario. While, during the build, profile boards are removed to enable workpiece access by human operators and robots. The process feasibility is validated by repeatability testing of the PnP process in a lab-based environment. Meanwhile, the calibration and configuration time are recorded to assess reconfigurability and to support business case analyses. The proposed tooling solution is a part of the ELCAT (Enhanced Low-Cost Automation Techologies) project, where UoN and GKN are collaborating in the development of a reconfigurable assembly system. With the developed system, multiple products can be assembled within the same facilities, distributing capital asset cost across multiple products and leading to major cost-savings in the forecasted work availability.

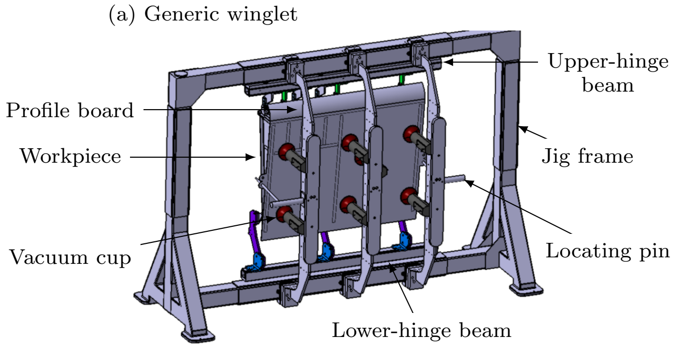
2. ASSEMBLY TOOLING DESIGN

The reconfigurable assembly system is designed for small box products, which include winglets, rudders and elevators. Rudders and elevators are both assembled against their hingeline datums, therefore are also called hinged products. An example of a generic winglet and hinged product in assembly is shown in Figure 1.

The complete assembly system consists of a jig frame, interface plates, profile boards and pick-up tooling. While the jig frame provides a rigid framework, profile boards are removable supports. They can be configured in-between products and between assembly stages. The interface plates are reconfigurable and adjustable connections that provide location, clamping and transfer of services (i.e. compressed air) between the jig frame and profile boards. On the profile board, various pick-up tooling, such as vacuum cups and locating pins, can be arranged differently via a coordinated hole pattern. For winglets, an extra root fitting is used as a datum and also to secure the workpiece, while the hinged products have an upper and lower beam to locate and support components to the hinge-line datum and at the trailing edge respectively.



(a) Generic winglet



(b) Generic hinged product

Fig. 1. Reconfigured jig for two different products

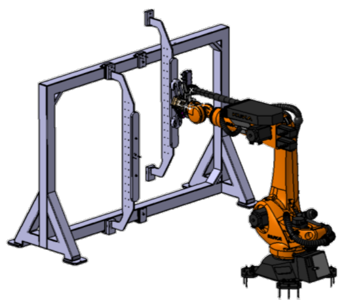


Fig. 2. PnP process: Robot load and unload profile boards onto the jig frame

In this paper, we focus on the PnP process between the jig frame and profile boards as illustrated in Figure 2. This process happens both in between products and within a product build. While the pick and place processes of the upper and lower beams for the hinged products, and the root fitting for winglets utilise the same principle. Therefore, the PnP process is a core operation for the proposed small-box assembly system, and its repeatability and process timing directly affect the productivity of the entire assembly line. While the reconfiguration of pick-up tooling (i.e. the vacuum cup locations and arrangement) is still important, it is done at a relatively lower frequency, only between products. Given that the configuration of pick-up tooling can be carried out pre-assembly, it has a smaller impact on the overall productivity, and is therefore not considered in this paper. In this section, detailed features for the jig frame, interface plates and profile boards are described. In order to perform the PnP process automatically, a PnP end effector is also developed and described here. Together they form an affordable and auto-reconfigurable tooling solution for small box assembly.

2.1 Jig Frame

Since no frame rebuild is necessary between products, a welded steel frame is chosen for its integrity and stability. The jig frame is sized to suit winglets and hinged products, at 1900mm in height and 3000mm in width. An estimated loading condition of the jig frame is illustrated in Figure 3 and a preliminary stress analysis was performed in ABAQUS with rigid joint conditions. The cross-section was selected based on the stress analysis with minimal weight amongst the standard box-sections. The optimal cross-sectional profile is found to be 150mm×150mm×5mm. The frame is fabricated by weld joining at four corners and feet with standard steel box beams and plates.

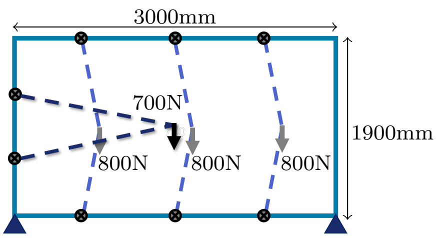


Fig. 3. Jig frame simplified loading condition

On the jig frame, there are 16 machined faces, and the front faces are highlighted in Figure 4. A grid pattern of tapped holes on the machined faces are used for mechanical mounting of the adjustable interface plates.

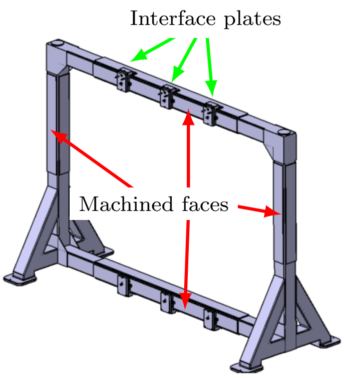


Fig. 4. Profile board connection upper interface to the jig frame

2.2 Interface Plates

The interface layouts are illustrated in Figure 5 and 6. The interface plates are used to connect the profile boards to the jig frame through zero-point clamps, which are off-the-shelf pneumatic clamps with repeatability within 0.005mm (claimed by manufacturer AMF). While the locating pins align the clamping surfaces, a proximity sensor detects the presence of the mating surface. The upper plate provides a connection interface, air services and alignments, while the lower plate is only required for its connection interface. At the same time, the upper and lower interface plates can be finely adjusted via screws and spherical washers. The level of flexibility not only enables a multi-product assembly line, it also allows relaxation of machining tolerances and helps to minimise tooling cost.

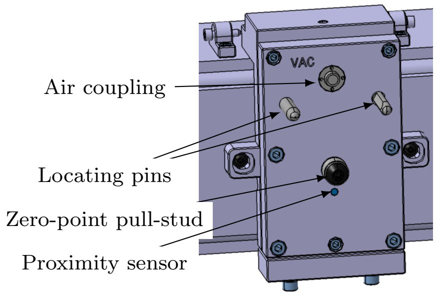


Fig. 5. Interface plate upper design

The interface plate position and orientation are fully adjustable in 6 degrees of freedom. Two adjustable designs were implemented on the upper and lower plates. On the upper plate, the front face orientation is adjusted through seven clamping screws around the edge as shown in Figure 5. The lower plate is adjusted by the three clamping screws and three grub screws located at the edge as displayed in Figure 6.

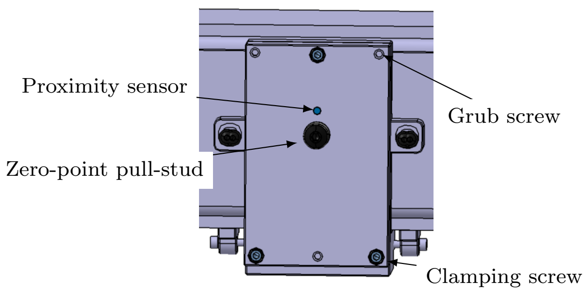


Fig. 6. Interface plate lower design

2.3 Profile Board

The designed profile board is to be picked up by an end effector and loaded onto the jig frame. Therefore, it has the corresponding interfaces on the front and back sides, for the jig frame and end effector connections respectively, as illustrated in Figure 7. On the top and bottom, there are two steel housings to accommodate zero-point clamps, air couplings and locating bushes. The similar mating features, such as zero-point pull-studs, locating pins and air couplings are also present on the back side. High and low pressure air is supplied via the end effector and air couplings to operate the various zero point clamps. Lastly, the profile board main body is fabricated in aluminium, with a grid pattern of tapped holes for pick-up tooling attachment.

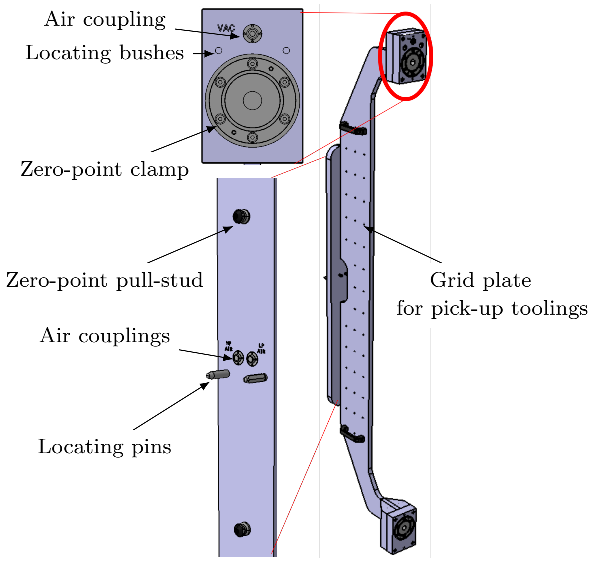


Fig. 7. The profile board with connection features to the jig frame and the end effector

2.4 PnP End Effector

The PnP end effector is developed for the robot to handle removable tooling and configure the jig. As shown in Figure 8, two steel rounds equipped with zero-point clamps and proximity sensors are placed at either end of the effector. On the same plane, air couplings and locating bushes are located in the middle. To support clamp operations, 24V DC power, high- and low-pressure air are supplied via a Staubli tool changer. The high-pressure air is to unlock the zero-point clamps, while low-pressure air is fed through the central cavity of the clamp. This cavity will be closed when a pull-stud is inserted correctly, resulting in a pressure increase in the low-pressure airline. Sensing this pressure increase gives an indication of successful clamping between two components. In addition, proximity sensors are mounted to detect contact faces. To channel compressed air into the right path, four solenoid valves are used. The main body of the end effector, fabricated with aluminium, houses airline plumbing, solenoid valves and a Siemens LOGO! PLC (Programmable Logic Controller). The PLC allows control, monitoring and decision-making during the PnP process, and enables the end effector to plug and play in a factory network. A HMI (Human-Machine Interface) was also developed via TIA portal, to support this feature.

3. PNP DEMONSTRATION

A PnP demonstration was setup in order to prove the auto-reconfiguration concept, within which the key attributes are reconfigurability and repeatability. Reconfigurability was achieved via tooling design and calibration and was assessed by the successful robot PnP operation. Meanwhile, repeatability was characterised by a metrology system measuring the profile board position each time it is being loaded onto the jig frame.

The auto-reconfiguration concept was verified and tested in a robot work cell as displayed in Figure 9. The work cell consists of a KUKA KR270 ultra robot, a KUKA KRC

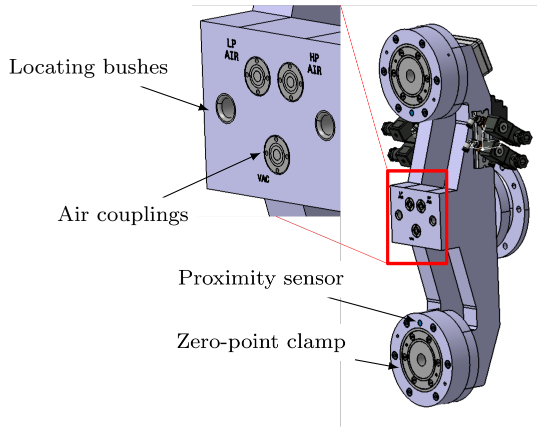


Fig. 8. PnP end effector with detailed service interface

controller, a Siemens S7-300 PLC (safety control) and reconfigurable tooling developed for small box assembly, as described in Section 2. Meanwhile other accessories such as a profile board storage rack, and a tool stand for end effector storage were also present. A Leica laser tracker was used for adjusting interface plates and tool alignments, robot movement calibration as well as taking measurement data to assess repeatability of the tool features.

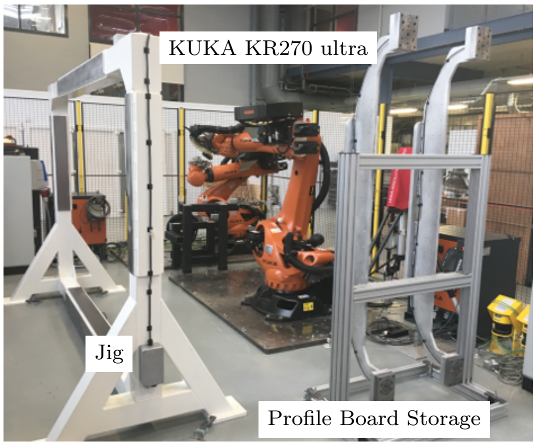


Fig. 9. Physical set up of the testing work cell

The PnP process was performed in several steps involving robot movement and end effector operations. In one cycle of PnP, the profile board is being picked up from its storage rack, loaded onto the frame, then removed from the frame and placed back into its storage rack.

4. RESULT AND DISCUSSION

In this section, the feasibility of the proposed tooling solution is investigated based on key product and process requirements, and these key requirements were assessed based on measurements, observation and findings from the PnP testing.

- Time for PnP process and estimated time for reconfiguration between products. The reconfiguration time between products is set to be within 10 mins. With three profile board locations, this requires the average PnP cycle to be around 3 minutes.
- Business case analysis with representative scenarios was carried out with the proposed reconfigurable

approach. It should show cost saving compared with a baseline process with dedicated tooling. A low production rate scenario should be considered to show business feasibility under impact such as the COVID-19 pandemic.

- Repeatability of the profile board PnP positions by robot movement and clamping. Repeatability is directly linked with key aerodynamic tolerance. For small box product family, the zone 2 aerodynamic surface tolerance is at ±0.75mm. The process repeatability requirement is then set to be 1/10 of the product requirement, which is 0.075mm.

4.1 Process Timing

The average time required for one cycle of PnP, excluding taking measurements and data export, is 1-2 minutes. With three profile boards and location datum brackets proposed as Figure 1, the whole jig reconfiguration will take no more than 10 mins. Therefore, this is satisfactory with regards to the reconfiguration time requirement of 10 mins between products. The main limitation associated with process time is the robot speed in teach mode and the manual pneumatic control of the clamps. To reduce reconfiguration time, the robot can be programmed at a higher speed in auto mode, and automatic clamp control can also be implemented to speed up the PnP process.

4.2 Business Case

The business case is outlined to investigate the benefit brought by the reconfigurable tooling solution and the automated PnP process only. Therefore, the baseline process is not a representation of the current production, and assumptions were made based on a like-for-like process. In the baseline process, dedicated tooling is used with manual configuration for every product type. As for the proposed process, the reconfigurable tooling system is used with automated PnP configuration between products. Both processes assume that the jig frame is mounted on an AGV (Automated Guided Vehicle) moving in between stations, where a static robot performs the automated processes, such as metrology, drilling and sealing etc. Because of this, the benefits of automated processes were not included. To summarise, business benefits were derived from

- Reduced design costs between several projects (due to standardisation)
- Re-use of tooling
- Automation of PnP process / auto-reconfiguration – reduction in man hours

Production scenarios are predicted based on GKN future profile and forecasted based on technology readiness and new work availability for the next 10 years. The associated cost-saving benefit are displayed in Table 1. Tooling cost between a reconfigurable assembly system and multiple dedicated assembly systems are considered. The labour cost-saving brought by automated configuration are also captured. Three scenarios with four different types of small box products are assessed. A low-volume production is assumed, in order to investigate the business feasibility under negative economic impact, such as the COVID-19 pandemic.

Table 1. Estimated production scenarios

Low-volume Scenario				
Product	Rate/yr	No. of jigs	Total build	Saving
Winglet1	0	0	0	45.92%
Winglet2	80	4	480	
Rudder	30	3	150	
Elevator	60	6	300	
Medium-volume Scenario				
Product	Rate/yr	No. of jigs	Total build	Saving
Winglet1	80	4	400	51.54%
Winglet2	80	4	480	
Rudder	30	3	150	
Elevator	60	6	300	
High-volume Scenario				
Product	Rate/yr	No. of jigs	Total build	Saving
Winglet1	360	18	1800	58.33%
Winglet2	80	4	480	
Rudder	30	3	150	
Elevator	60	6	300	

As the production volume increases, a larger cost-saving percentage can be achieved. The highest benefit is in the high-volume scenario, where the max re-use of tooling assets is achieved. However, the cost-saving is still evident for the low-volume scenario. The result presented is very conservative, since other business benefits, such as reduced factory real estate, environmental benefits through reduced factory footprint and overheads and reduced risk to health and safety etc., are not yet assessed. This shows a clear advantage of the proposed tooling solution compared to the dedicated system.

4.3 Repeatability

The position of the profile board was measured relative to the jig frame every time it was reloaded after removal. 50 measurements were taken using a LEICA AT-960 MR laser tracker and the repeatability of the profile board positioning assessed. Five points on the jig frame and three points on the profile board were measured. For each measurement point, the average point of the 50-point cloud is computed and deviation calculated. Amongst all the measurement points, the maximum deviation measured and the 3-sigma variation are obtained and listed in Table 2.

Table 2. Repeatability for jig frame and profile boards

		Max deviation measured (mm)	3 sigma (mm)
Jig	Mean	0.020	0.031
	Max	0.026	0.038
Profile board	Mean	0.026	0.035
	Max	0.032	0.040

The profile board positioning has a maximum ±3 sigma variation of ±0.04mm across its measurement points, however across the jig frame measurement points a maximum ±3 sigma variation of ±0.038mm is calculated. Since the jig frame was bolted down on the floor, it is assumed to be stationary. Therefore, the jig frame measurement variation would provide an indication of the laser tracker uncertainty. It is hypothesised that the variation observed in the jig frame measurements is due to measurement uncertainty of the laser tracker, and due to this significant uncertainty compared to the measured profile board variation seen, a reliable assessment of profile board repeatability is difficult to resolve. This hypothesis is supported when analysing the measurements for a single day and comparing with the variation seen in repeated measurements of a single reflector position on the jig frame (measured 20 times consecutively), with calculated maximum ±3 sigma variations of ±0.028mm and ±0.027mm respectively. This is within the typical accuracy range of laser tracker systems. In order to capture the repeatability of profile board positions, alternative methods can be utilised, such as photogrammetry system and laser radar.

In conclusion, a high degree of positional repeatability was observed for profile board relative to the jig frame, with calculated ±3 sigma variations well within requirements and therefore the use of the zero-points clamps is validated.

4.4 Other observation and improvement

During the testing process, both interface plate designs were proven to be functional, and their position remained stable. However, the lower plate design stands out as it is much easier to calibrate. This is because the grub screws can be adjusted against the direction of clamping screws. This helped to maintain the calibrated position while tightening up the clamping screws. As showed in Figure 10, the upper plate adjustment was achieved by threads in and out of the back plate, Spherical washers were secured by a nyloc nut. During calibration, the upper plate design often loses the calibrated position when tightening up the clamping screws. This is because the adjusting and locking mechanism works in the same direction. On the other hand, the nyloc nuts tend to loosen during calibration. This can result in screw head protruding the mating surface. The average time to adjust the lower plate is between 10-15 mins, while for the upper plate is around 45 mins or more. In the next stage, the combination of grub screw and extra safety support will be implemented in both the upper and lower interface plates.

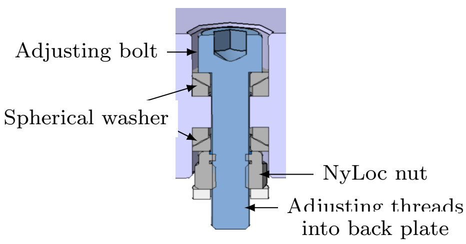


Fig. 10. NyLoc nut and spherical washer cross-section

5. CONCLUSION

In this paper, a novel, affordable, highly-repeatable and rapidly reconfigurable assembly system is proposed for small box products. The proposed system consists of a jig frame, adjustable interface plates, reconfigurable profile boards and a PnP end effector. The jig frame can be robotically configured via a PnP process, in which the profile boards are loaded and/or unloaded onto the jig via the end effector. The process feasibility is proven via a business case analysis and lab-based experiments regarding tolerance and process timing requirements. From testing, the average PnP cycle was captured to be 1-2 mins. This is within the process requirement, however the can be further improved by automatic control of robot speed and pneumatic clamps. For the business case analysis, a like-for-like baseline process was used to capture cost-saving benefit brought by reconfigurable tooling and the automated PnP process. It shows that business benefits can be realised under different scenarios, ranging from 45.92% for a low-volume scenario to 58.33% for a high-volume scenario. Cost-saving can be improved with larger production volume and shorter reconfiguration time. Lastly, a high degree of positional repeatability was observed for profile board relative to the jig frame, with calculated ±3 sigma variations well within requirements. However the actual repeatability is difficult to capture, alternative measurement methods can be investigated. To summarise, the proposed tooling system and process is a viable solution for the small-box assembly line and has the potential to be integrated in a smart multi-product factory. Future work should target a fully automated assembly, commissioning, digital awareness of the system, and its integration in real-life production.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from Innovate UK project ELCAT (ref 113235) and GKN Aerospace, and for the technical support from Geoffrey Bexon.

REFERENCES

Erdem, I., Helgosson, P., Gomes, A., Engstrom, M., and Ab, S. (2016a). Automated Flexible Tooling for Wing Box Assembly : Hexapod Development Study. *SAE Technical Papers*, 2016-01-2110.

Erdem, I., Helgosson, P., and Kihlman, H. (2016b). Development of Automated Flexible Tooling as Enabler in Wing Box Assembly. *Procedia CIRP*, 44, 233–238.

Erdem, I., Kihlman, H., and Andersson, A. (2015). Development of affordable reconfigurable tooling in car manufacturing cells - A case study. In *23rd International Conference for Production Research, ICPR 2015*.

Kihlman, H. (2002). Affordable Reconfigurable Tooling. *SAE Technical Papers*, 2002-01-2645.

Kihlman, H. and Engström, M. (2010). Flexapods - Flexible tooling at SAAB for building the nEURON aircraft. *SAE Technical Papers*, 2010-01-1871.

McKeown, C. and Webb, P. (2011). A reactive reconfigurable tool for aerospace structures. *Assembly Automation*, 31(4), 334–343.

Millar, A. and Kihlman, H. (2009). Reconfigurable flexible tooling for aerospace wing assembly. *SAE Technical Papers*, 2009-01-3243.

Müller, R., Brecher, C., Corves, B., Esser, M., Riedel, M., Haag, S., and Vette, M. (2011). Self-optimization as an Enabler for Flexible and Reconfigurable Assembly Systems". In S. Jeschke, H. Liu, and D. Schilberg (eds.), *Intelligent Robotics and Applications*, 179–188. Springer Berlin Heidelberg, Berlin, Heidelberg.

Müller, R., Esser, M., and Vette, M. (2013). Reconfigurable handling systems as an enabler for large components in mass customized production. *Journal of Intelligent Manufacturing*, 24(5), 977–990.