An adaptive, repeatable and rapid auto-reconfiguration process in a smart manufacturing system for small box assembly*

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Abstract— **With increasing demand for productivity, flexibility, and sustainability, there is the need for a flexible manufacturing system that is auto-reconfigurable for variations in product types and assembly processes. However, the repeatability of reconfigurable components needs to be controlled and quantified in order to achieve the critical product tolerances required. High levels of repeatability for reconfigurable components are often achieved by a lengthy calibration. Besides, automated processes would rely on the precise tool and part positioning or an adaptive process approach. In this paper, an adaptive, highly repeatable and rapid auto-reconfiguration process in a smart manufacturing environment is proposed for small box product assembly, such as rudders, elevators and winglets. The process involves a reconfigurable tooling system for physically supporting different products, robots and end effectors to perform automated processes, programmable logic controllers to orchestrate cell safety and robotic tasks, an autonomous guided vehicle (AGV) to provide jig mobility, and a metrology system to realise cell-level positional layout. The rapid reconfigurable tooling system was tested and quantified for repeatability and configuration time, and the adaptive auto-reconfiguration process was validated by moving the jig frame in a lab environment simulating inaccurate AGV parking. The repeatability of profile board positioning can achieve a value smaller than +/-0.04mm, with an estimated between-product changeover time less than 10 minutes. With an external metrology system, the positional layout of the cell was captured and used to adapt robot programs. Successful engagement was observed, proving the feasibility of the adaptive process.**

I. INTRODUCTION

The aerospace manufacturing industry has been relying on manual processes and dedicated tooling systems for decades. Although the current manufacturing system is stable, reliable and proven to produce quality products, it is extremely wasteful, inflexible to changes and requires high capital investment and large amounts of manual labour. With increasing demand for productivity, production flexibility, safety and sustainability, there is the need for a smart and flexible manufacturing system that is auto-reconfigurable for variations in product types and assembly processes. However, as production flexibility increases, the repeatability of reconfigurable components needs to be controlled and quantified in order to achieve the critical product tolerances required. Reconfigurable tooling would enhance production flexibility, increase use of capital assets and promote sustainability. However, the repeatability of reconfigurable components is often achieved by a lengthy calibration process. Similarly, autonomous guided vehicle (AGV) would provide jig mobility, however, repeatability of automated processes would rely on the precise AGV positioning or an adaptive process approach. Therefore, the manufacturing system requires adaptive processes to accommodate the flexibility of tooling and machines involved.

In this paper, an adaptive, highly repeatable and rapid auto-reconfiguration process in a smart manufacturing environment is proposed for small box product assembly. The process involves a reconfigurable tooling system for physically supporting different products, robots and end effectors to perform automated processes, programmable logic controllers (PLCs) to perform cell safety and robotic tasks, an AGV to provide jig mobility between manual and automated work stations, and a metrology system to realise cell-level positional layout. The reconfigurable tooling system proposed is designed for small box assembly, which includes 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. Profile boards, upper and lower hinge beams and root brackets are reconfigurable components that can be robotically pick and placed. The rapid reconfigurable tooling system is tested and quantified with regards to repeatability and reconfiguration time.

The proposed tooling is a part of a smart manufacturing system, where they are to be mounted on an AGV moving in between auto-reconfiguration, manual and automated workstations as illustrated in Figure 2. An adaptive pick-and-place process is presented here, in which the robot control is made aware of the physical cell layout through metrology data. Combining the reconfigurable tooling system with inaccurate AGV positioning, the adaptive auto-reconfiguration process was validated in a lab environment. It is a key enabling technology for a smart manufacturing system, with the capabilities to reconfigure between products, account for automated and manual processes, and be self-aware of machine/component positional layout and process and machine status. The proposed smart manufacturing system is currently under development at the University of Nottingham as part of the FA^{3}D2 (Future Automated Aircraft Assembly Demonstrator Phase 2) project [1].

As for the structure of this paper, Section II reviews the application of reconfigurable tooling system with regards to repeatability and configuration time, and the use of metrology data in positional correction in aerospace manufacturing. After that, Section III and IV introduces the

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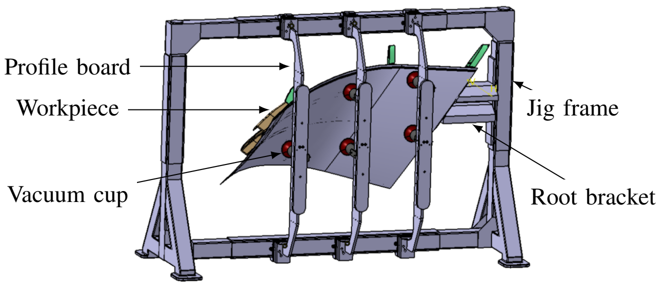
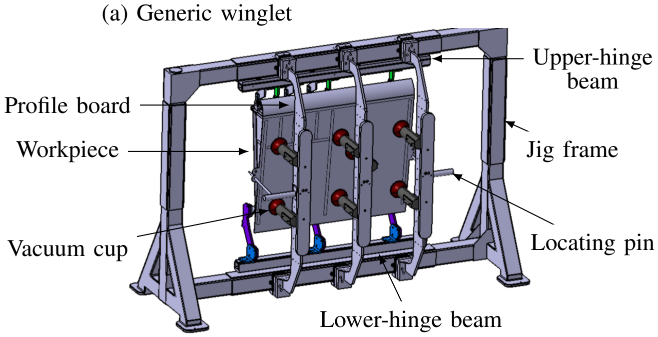
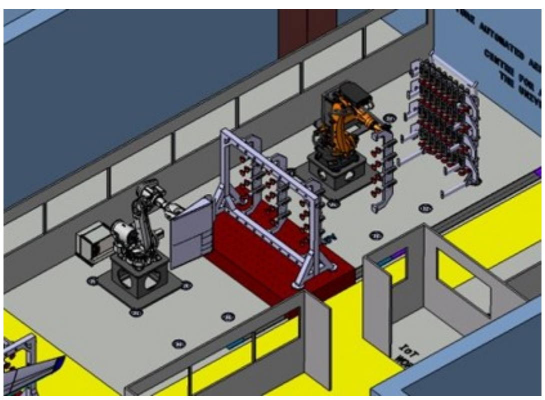


(a) Generic winglet

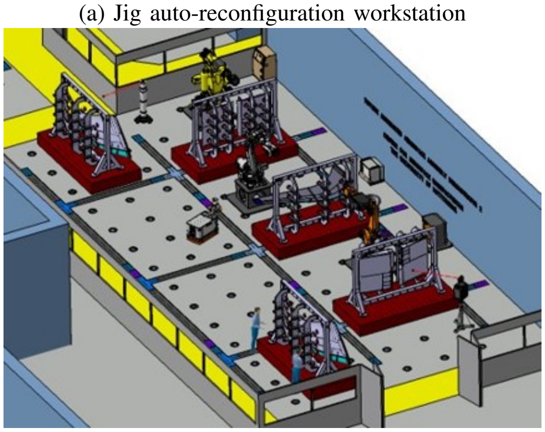


(b) Generic hinged product

Fig. 1: Reconfigured jig for two different products



(a) Jig auto-reconfiguration workstation



(b) Auto and manual assembly workstations

Fig. 2: Multi-product and reconfigurable factory with moving jigs and stationary robots

reconfigurable tooling system and connection mechanism. The auto-reconfiguration process and adaptive environment is described in Section V. Lastly, the experiment setup and results are presented in Section VI

II. RELATED RESEARCH WORK

In the topic of reconfigurable tooling systems, Kihlman and Engström first introduced the concept of affordable reconfiguration tooling (ART) concept in [2], which consists of a static frame and dynamic modules. Dynamic modules were attached through a coordinated hole pattern or rails, where robots are used to configure the dynamic modules. Based on ART concept, ReFlex demonstrator for wing assembly is built, see [3]. A robot was used to pick and place a fixture. The average clamp setup time is at an hour with the positional tolerance of 0.15mm. In [4], ART was applied with BoxJoint and Flexapod. BoxJoint replaces the coordinated pattern of hole and rails, and provides mechanical connection on Box-section beams. They are highly reconfigurable, however not repeatable and take long time to assemble/dismantle. Flexapod is a six degree of freedom adjustable unit, on which different pick-up tools can be mounted. With aid of dedicated software package, a repeatability of $\pm$ 0.05mm was reported, with configuration cycle of 24 minutes. The same concept was applied for automotive industry in the work of Erdem with +/-0.5mm repeatability and 15 minutes reconfigure time, see [5]. A finely-adjustable unit, compatible with box-joint system, was designed for locating and clamping. In [6] and [7], an automated flexible tooling system, consisting of BoxJoint and Flexapod/Hexapod, were developed for wing box assembly. While the BoxJoint framework is often developed for panels and wing-box structures, cylindrical components assemblies, such as fuselage, are considered in the work of [8], [9] and [10]. Repeatability and configuration time of +/-0.075mm and 60 minutes were reported respectively. One can easily observe the trade-offs are between reconfiguration time, repeatability and level of flexibility. In this paper, the adaptive auto-reconfiguration process with the proposed tooling system can achieve a local repeatability smaller than +/-0.04mm, being reconfigured within 10 minutes and still maintain the jig mobility between work station.

There are also a number of research works that utilise external metrology system to improve robot capability for aerostructure manufacturing and assembly. The AWBA (Automated Wing Box Assembly) project used laser tracker to correct spar toolings offset [11], [12]. The TI^2 system for airframe subassemblies used photogrammetry cameras to aid part location in robotic drilling and milling [13], [14], [15]. In project ADFAST (Automation for Drilling, Fastening, Assembly System and Tooling), laser tracker was used to calibrate robot tool centre point (TCP) and reached accuracy of +/-0.05mm [16], [17]. Whereas, laser stripes and laser seam finder were used to measure part location in the robot base coordinates with a best-fit algorithm to correct pre-programmed robot path for fuselage skins and aero-engine components [18], [19], [20]. In the FA^3D (Future

Automated Aircraft Assembly Demonstrator) project, real-time control of the robot TCP and in-process inspection with adaptive robot control (ARC) camera system and a laser radar [21], [22]. Majority of the metrology assisted processes are focused on part locating and machining. Its use in cell layout awareness and automated system reconfiguration is very limited.

III. RECONFIGURABLE ASSEMBLY TOOLING

The assembly tooling solution consists of a jig frame, profile boards, upper and lower hinge beams, root brackets, interface plates, and pick-up toolings. While the jig frame provides a basic framework, profile boards, upper and lower hinge beams, and root brackets are removable supports. They can be configured in-between products and between assembly stages. The interface plates are adjustable connections that provide location, clamping and transfer of services (i.e. compressed air) between the jig frame and removable supports. On the profile board, various pick-up toolings, such as vacuum cups and locating pins, can be arranged differently via a coordinated hole pattern.

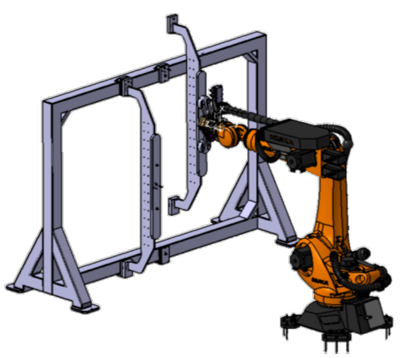


Fig. 3: Pick and place process: Robot load and unload profile boards onto the jig frame

In this paper, we focus on the adaptive pick and place process as illustrated in Figure 3. This process happens both in between products and within product build. Therefore, it is a core operation for the proposed small-box assembly system, and its ability to adapt to inaccurate AGV positioning and local repeatability between the jig frame and profile board directly related to the production quality, flexibility and efficiency. In this section, detailed features for the jig frame, interface plates and profile boards are described. In order to perform the pick-and-place process automatically, a pick-and-place end effector is also developed and described here.

The jig frame is bolted onto a AGV through its four feet. Since no frame rebuild is necessary between products, a welded frame is chosen for its integrity and stability. On the jig frame, there are 16 machined faces, and a grid pattern of holes were tapped on the machined faces and used for mechanical mounting of the adjustable interface plates. In Figure 4, the machined faces are highlighted, with interface plates mounted for profile board connections.

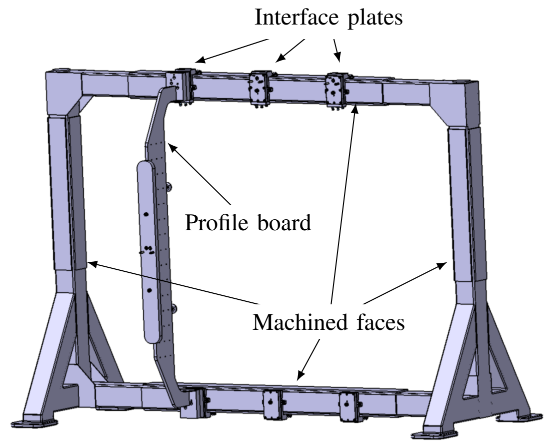


Fig. 4: Jig frame machined faces and interface plates mounted

The interface plates are used to connect the profile boards to the jig frame through zero-point clamps. Zero-point clamps operate pneumatically and provide quick, reliable and repeatable clamping within 0.005mm [23]. Proximity sensors were mounted to detect presence of the mating surface. The upper plate provides connecting stud, air services and locating pin alignments, while the lower plate is only required for its connecting stud. At the same time, the upper and lower interface plates can be adjusted finely via grub 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, and the interface plate position can be moved both in vertical and horizontal directions. Orientation of the front face can also be adjusted.

The designed profile board is to be picked up by an end effector and loaded onto the jig frame. On the top and bottom, there are two zero-point clamps, air coupling and locating bushes. The similar mating features, such as zero-point pull-studs, locating pins and air coupling are also present on the back. 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 with a grid pattern of holes tapped for pick-up tooling attachment.

IV. PICK-AND-PLACE END EFFECTOR AND PROCESS CONTROL

The pick and place end effector is developed for the robot to handle removable tooling and configure the jig. As shown in Figure 5, two zero-point clamps and proximity sensors are placed at either end of the end effector. On the same plane, air coupling 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 unlocks the zero-point clamp, 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 the successful clamping between two components. In addition, proximity sensors are mounted to detect contact faces. Lastly, four solenoid valves are used to channel compressed air into the right path.

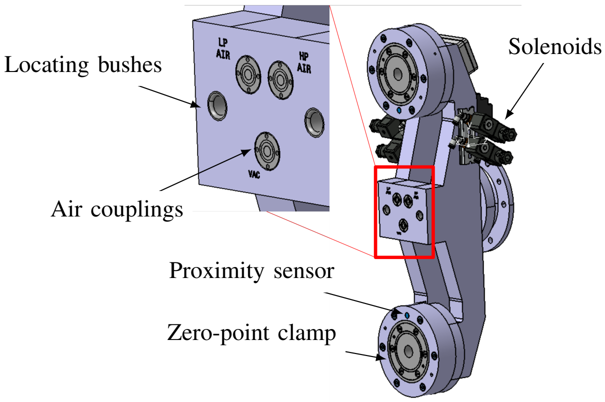
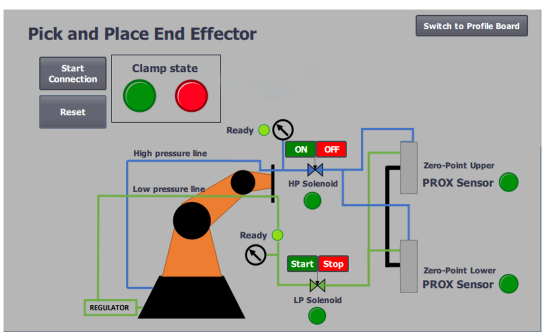
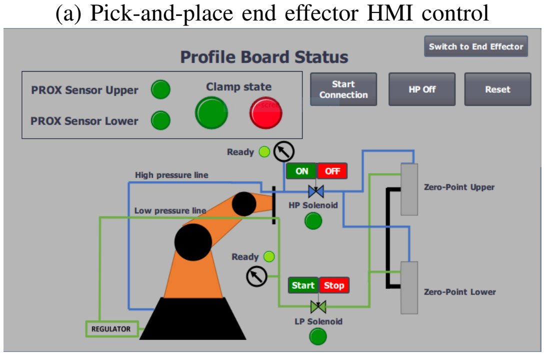


Fig. 5: Pick and place end effector with detailed service interface block

The main body of the end effector also houses airline plumbings, solenoid valves and a Siemens LOGO! PLC. The PLC allows controlling, monitoring and decision-making during the auto-reconfiguration process, and enables the end effector plug-and-play in the factory network. A HMI (Human-Machine Interface), displayed in Figure 6, was developed via TIA portal, to visualise process status and support control at the process level.



(a) Pick-and-place end effector HMI control



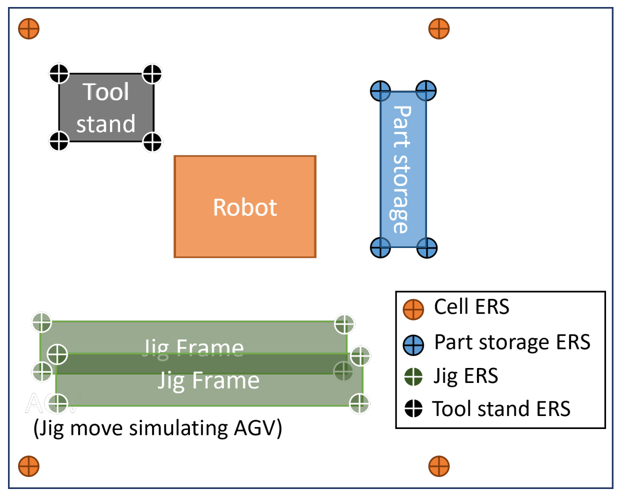
(b) Profile board connection HMI control

Fig. 6: Process control interface

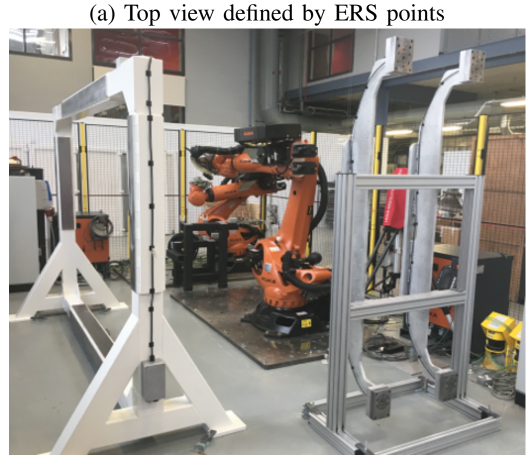
V. CELL PHYSICAL LAYOUT AND COMMUNICATION

A physical cell was set up at the University of Nottingham in order to demonstrate the adaptive reconfiguration process. The cell consists of controller units and hardware tooling as listed below, with its physical layout illustrated in Figure 7.

1) Cell level PLC
2) KUKA KR270 ultra robot
3) Pick-and-place end effector with tool changer
4) End effector PLC
5) Reconfigurable tooling system
    a) Jig frame with interface plates attached
    b) Profile board
6) Storage hardware
    a) Profile Board Storage
    b) Tool stand for end effectors
7) Metrology system (laser tracker and photogrammetry cameras)



(a) Top view defined by ERS points



(b) Physical environment

Fig. 7: Cell Layout

In order to safely and accurately perform the reconfiguration task, the robot needs to know the actual position of the end effector, the profile board and the jig frame. Hence, the metrology system measured the characterised enhanced reference system (ERS) points in the cell. The ERS points were analysed and updated the robot program. During the process, process status can be monitored and controlled from the HMI. The communication between the robot, the cell-level PLC, the end effector PLC and the metrology system is shown in Figure 8.

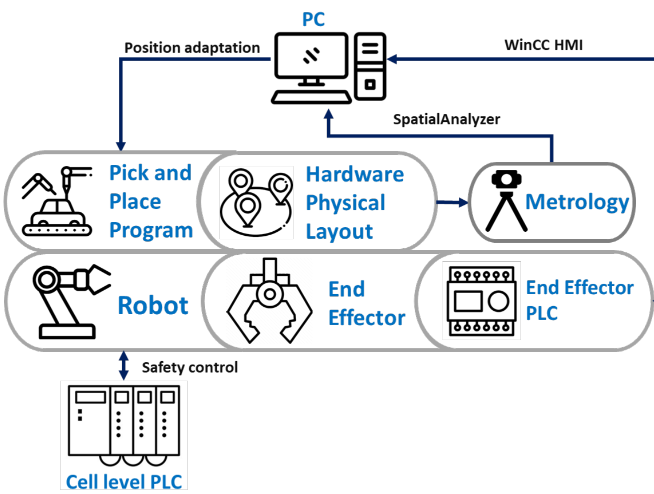


Fig. 8: Communication in testing cell

In the smart factory environment, the jig frame will be bolted on a AGV. Hence, the jig ERS point would also represent the AGV position. Part storage and tool stand position can also be flexible depending on the compactness requirement under different production scenarios. By measuring the ERS point changes relative to the cell ERS points as illustrated in Figure 7a, one can obtain real-time layout of the cell and robot programs can be adapted accordingly.

VI. EXPERIMENTS AND RESULTS

The automated pick-and-place demonstration was setup in order to prove the adaptive auto-reconfiguration concept, within which the key attributes are repeatability, process cycle time and the feasibility of the adaptive approach.

In the process cycle, robot picks up the pick-and-place end effector from the tool stand, then picks up the profile board from its storage rack, load the profile board onto the jig frame, robot arm retracts and releases the profile board. Repeatability was characterised by measuring the position of the profile board relative to the jig frame 50 times of being loaded and unloaded. One cycle of profile board pick and place takes around 1 minute. For between-product reconfiguration, the changeover time was estimated to be within 10 minutes, including picking and placing of the end effector and three profile board positions.

In the repeatability test, the jig was being fixed on the floor in order to understand the uncertainties brought by the metrology systems used. Two metrology systems, namely VSTARS photogrammetry camera system and a LEICA AT-960 MR laser tracker, were used to assess their suitability for this particular application. The adaptive approach was

TABLE I: Measurements by photogrammetry

		Max deviation measured (mm)	3 sigma (mm)
Profile board	Mean	0.044	0.064
	Max	0.073	0.096

validated by moving the jig frame and carry out the pick-and-place process after the positional robot program adaption. The jig move simulates the inaccurate AGV parking positions and the successful pick-and-place process would prove the feasibility of the adaptive approach.

A. IN-JIG REPEATABILITY TEST

Measurements were taken on both the jig frame and the profile board. As the jig is fixed on the floor, the variation in measurements taken for the jig reflects the measurement uncertainties of the metrology setup.

For the photogrammetry system, 108 retro-reflective target points were attached on to the jig, and 32 on the profile board. With regards to the laser tracker, five spherically mounted retroreflector (SMR) positions were used on the jig frame and three on the profile board. For each measurement point, the average point of the 50-point cloud was computed and deviation calculated.

The photogrametry system used was the Geodetic Systems VSTARS D12 cameras. The measurement uncertainties on the jig frame was provided by the VSTARS bundle algorithm. It showed the maximum deviation magnitude of +/-0.082mm and the 3-sigma (three times of standard deviation) deviation of +/-0.084mm. Amongst all the target points on the profile board, the maximum deviation measured and the 3-sigma value are listed in Table I. It is noticeable that the profile board deviation measurement is very close to the uncertainties given for the jig frame. Therefore, it is hypothesised that the variation observed in the profile board measurements was due to the significant uncertainty from the photogrammetry camera setup. Although the photogrammetry system is time-efficient in measurement of large-volume point cloud, the measurement accuracy relies heavily on its field of view. Within the robotic cell, the robot has taken the prime location for visibility and accessibility, therefore the robot arm can obstruct visibility of a few target points, which then brings down the measurement accuracy of the photogrammetry system. The optimised view point for photogrammetry cameras is to be investigated for the next phase of testing. As for the laser tracker, the measurement is only possible with visibility of the SMR location. Therefore, the use of laser tracker is introduced here. Amongst five jig ERS points and three profile board measurement points, the maximum deviation measured and the 3-sigma value was obtained and listed in Table II. 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 was calculated. Similarly, it is reasonable to conclude that the variation observed in the jig frame and profile board measurement was

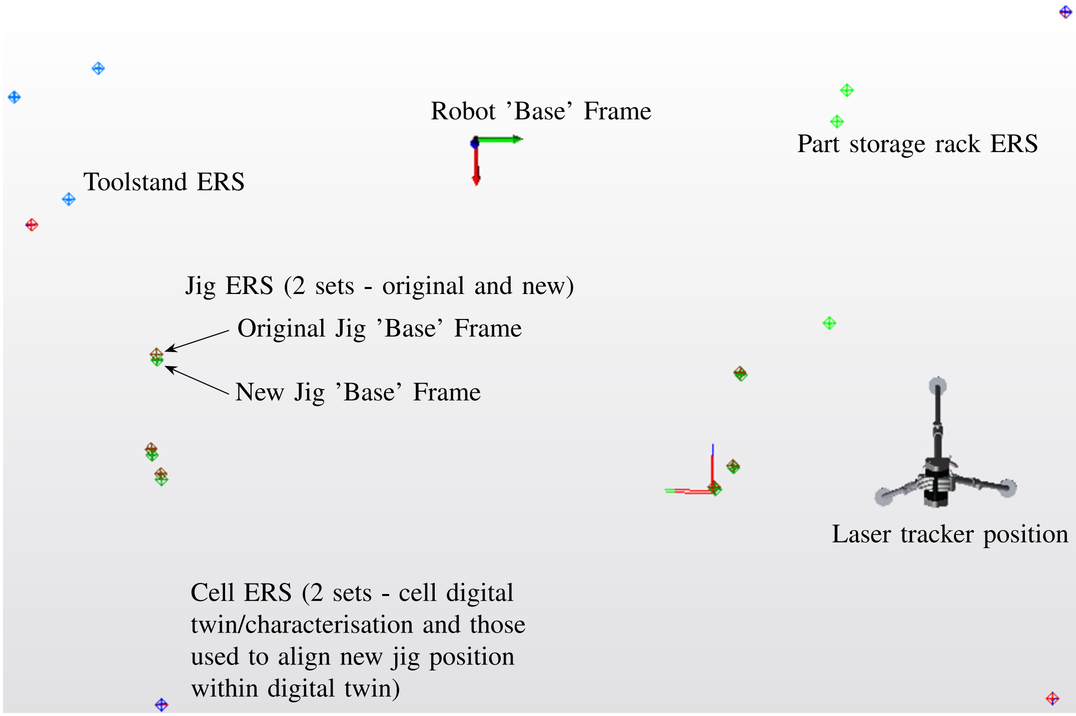


Fig. 9: Workstation layout captured by ERS points

TABLE II: Measurement by laser tracker

		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

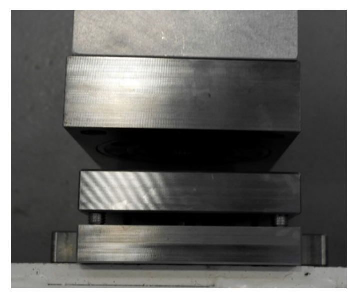
due to measurement uncertainty of the laser tracker. Comparing to the photogrammetry system used, the profile board measurement variation improved as measurement uncertainties decreased. In conclusion, a high degree of positional repeatability was observed for profile board relative to the jig frame via zero-point connection, with calculated ±3 sigma variations within ±0.040mm.

B. INACCURATE JIG POSITIONING TEST

Inaccurate AGV parking was simulated by moving the jig within the cell without positional control. In this case, the robot would not be able to find the engagement position between the new jig frame position and the profile board. Figure 10a and 10b show the jig movement and gap between the original and new jig positions.

The overall cell layout was captured by ERS points in the cell, presented in Figure 9. In the four corners, two set of cell ERS (red and blue) were captured, one being the original digital twin layout and the other being the new layout after the jig move. Since the shop floor itself was stationary, two sets of ERS points are aligned. On the top left corner, the tool stand ERS were captured in cyan. On the top right side, profile board storage rack position is shown with bright green

(a) Position movement

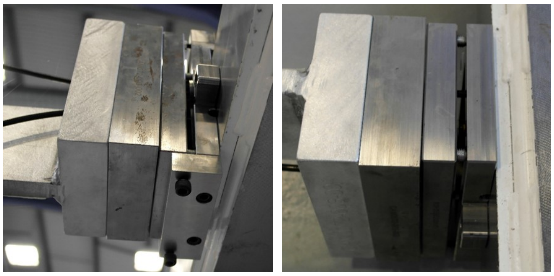


(b) Gap between mating surfaces

Fig. 10: Simulated AGV inaccurate positioning by moving the jig frame

ERS points. The original jig position is illustrated in brown, and the new jig position in dark green.

The ERS points capture the new workstation layout and it is evident that the relationship between the robot and the jig has changed. Based on the ERS measurements, a new jig 'base' frame is calculated (6 degrees of freedom position relative to the robot 'base' frame) and updated in the robot controller. Given that the robot pick and place process locations (where jig interaction occurs) are programmed relative to this 'base', updating this frame leads to adaptation of the required process locations in the robot program to match the new cell layout/jig position. Therefore, the automated pick-and-place process can be executed. Figure 11a and 11b show the successful engagement of the profile board and the jig frame on the upper and lower interface plates after cell layout being updated and the adaptive approach for the pick-and-place process was proven to be feasible.



(a) Upper side (b) Lower side

Fig. 11: Successful pick and place engagement after the jig position adaption

VII. CONCLUSIONS

An adaptive, highly repeatable and rapid reconfiguration process is proposed for a multi-product smart factory. A reconfigurable tooling system that consists of a jig frame, interface plates and profile boards was introduced. The reconfigurable tooling system is to be reconfigured automatically between products and mounted on an AGV to facilitate automated and manual processes. Due to flexibility brought by reconfigurable tooling and AGV, an adaptive auto-reconfiguration process was proposed and tested. The repeatability of profile board positioning can achieve a value smaller than +/-0.04mm, with an estimated between-product changeover time less than 10 minutes. Besides, two metrology systems, namely photogrammetry cameras and a laser tracker, were used. The laser tracker has less measurement uncertainties, however can only measures SMR locations sequentially. While the photogrammetry system is much more time-efficient capturing all visible targets simultaneously, its optimal setup position still requires investigation in order to improve its field of view. The optimal view point for photogrammetry cameras is to be investigated for next-stage testing. With the laser tracker measuring ERS points, the positional information of the cell, jig frame, tool stand and profile board storage was captured and used to adapt robot program to the actual cell layout. The process was proven by a jig move simulating inaccurate AGV parking. Successful engagement was observed, proving the feasibility of the adaptive process. The automated commissioning and program adaption process is also to be investigated for the FA^{3}D2 system.

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