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Procedia CIRP 44 (2016) 233 – 238

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6th CIRP Conference on Assembly Technologies and Systems (CATS)

Development of Automated Flexible Tooling as Enabler in Wing Box Assembly

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Abstract

Flexible tooling has been a focal point of investigation for various industries with an emphasis on cost and time effectiveness. Previous research has shown that when combined with the general requirements of tooling such as rigidness and repeatability, the implementation of flexibility can be a very daunting task. Therefore, LOCOMACHS (Low Cost Manufacturing and Assembly of Composite and Hybrid Structures) project has dedicated a work package for the creation of an automated flexible tooling to meet the demands of future aerospace production. The work package focuses on a creation of a tooling technology that can facilitate the process requirements of an automated wing-assembly by using flexible tooling and intelligence support from a force sensor. Hence, this paper aims to present the framework for automated flexible tooling development and results on a hexapod fixture as a case study.

Keywords: Flexible; Tooling; Fixturing; Aerospace; Wing; Assembly

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1. Introduction

Along with the evolution of production systems regardless of industry type, several paradigms played a major role in understanding of how to cope with continuously fluctuating customer demands. On a business and networking approach, agile manufacturing created a definition of how all elements of production can be connected in a low cost and flexibility-oriented approach [1]. When reflected on hardware level, the concept of flexibility further found application in flexible and reconfigurable manufacturing paradigms – later called as either flexible (FMS) or reconfigurable (RMS) manufacturing systems respectively [2]. In FMS, production equipment are conceptualized to have a built-in set of functionalities that can handle variations in products and processes in all steps of production [3]. On the other hand, reconfigurable manufacturing systems focus on the limitation of flexibility to reduce the cost and focus on a more modular approach – which is the reconfigurability of hardware and software systems to provide additional functionalities only when needed [4]. Whether aforementioned paradigms concentrate on the either limitation or generalization of flexibility, they stress the importance of using flexibility with low cost and shorter time windows to correspond to changing business paradigms.

Another important aspect of a production paradigm is to create a link between business and manufacturing strategies so that each constituting element coherently responds to uncertainties and shifting demands [5]. An example of such is to evaluate the important drivers behind a business model where each driver is reflected by cost and time so that these drivers can easily be associated to all components of a production system. Therefore, it was evaluated by researchers that this association through drivers can facilitate a framework to evaluate the applicability of manufacturing equipment whether they are process machinery or fixtures [6]. Hence, different strategies regarding this link were assessed [7, 8] and a common conclusion was on the inclusiveness of agile manufacturing paradigm as it creates a networking model spanning from production technologies to enterprise level operations; thus, defining the required structure for the missing link [9]. An example of such is seen in the study conducted by [10] where parameters for a fixturing equipment are quantified in time and cost limits for fixturing design and operations in aerospace wing box assembly procedure. Furthermore, same

doi:10.1016/j.procir.2016.02.065

alignment between business and manufacturing was also reflected on different types of industries. In car manufacturing industry, the study conducted by [6] breaks down the concept of agility drivers by cost and time on both investment and operational level to create a methodology for the implementation of affordable and time effective flexibility in all aspects of production spanning from machining to assembly fixtures. Another example is aerospace industry's efforts to cope with changes in the market with agile manufacturing paradigm as focal point [11]. Particularly, the assembly of wing structures has been investigated with efforts to create a tooling concept that can enable flexibility in terms of modularity, reconfiguration and easy correction of part variations where automation concepts in both design and operation were essential [12-14].

Whether the result of the alignment is towards the concept of customized flexibility as with RMS philosophy or more generalized one as in flexible manufacturing systems, it is often conceptualized for a solution initiated by a business requirement; then, complemented with technical knowledge; and finally, verified by using the same requirements. When this cycle of creating production equipment is reproduced for aerospace industry, a particular element of manufacturing often draws attention in the attempts of various researchers to provide flexibility. Particularly, assembly operations in aerospace industry is often comprised of dedicated and modular tooling components where the nature of the operations is manual labor oriented [15, 16]. Even though these dedicated fixtures provide satisfactory amount of robustness and performance in assembly of wing structures, the same nature of dedication requires excessive amounts of design/procurement times and investment cost both for infrastructure and tooling hardware [17]. Furthermore, the assembly of large scale units, particularly aircraft wings, requires corrections in terms of shimming of the non-rigid materials to secure robust process within tolerance limits. Thus, aerospace industry copes with the variation manually due to the dedicated nature of the conventional tooling. Therefore, there is a certain need for active fixturing solution that is reconfigurable and supported by intelligence to adapt to different products and variations within a workpiece [18].

LOCOMACHS (Low Cost Manufacturing and Assembly of Composite and Hybrid Structures) is European Union project to address the aforementioned problems with a work package for the creation of a flexible tooling concept that has built-in reconfigurable capacity to automate, actively evaluate, and fixate a large scale wing structure within acceptable tolerance limits. Hence, this paper aims to present the methodologic design approach and preliminary results on the development of an automated flexible tooling concept with a Stewart platform as a case study. The organization of the paper is as follows. Section 2 aims to provide a process description. In section 3, the automated flexible tooling (AFT) concept is presented in terms of overall methodology whereas sections 4, 5 and 6 disclose the mechanical, control and intelligence aspects of AFT.

2. Automated Flexible Tooling

Automated Flexible Tooling (AFT) is a methodology developed in order to create a framework that harmonizes agility input generated by business requirements with conventional fixturing design techniques as depicted in [19]. Furthermore, AFT utilizes this input to design the fixture units by selecting the components from various types of fixturing concepts such as modular, reconfigurable and affordable reconfigurable tooling (ART) to complement automated reconfiguration.

The first step of the methodology is to identify agility drivers relevant to the industry type and provide a conversion approach that facilitates meaningful information in fixturing design. As described with a literature review by [20], enterprise level agility drivers are directly defined by enterprise level cost effectiveness, time for design and deployment, and satisfying functionality values. Therefore, AFT methodology inherits a similar approach and uses aforementioned time and cost items to describe the relevant technology. Time relevant inputs are created for limits in design, lead, installation, reconfiguration and workpiece set-up whereas cost relevant limits are drawn for initial investment, maintenance, quality and reusability.

Later, AFT complements the design procedure with general fixturing requirements such as rigidness, accuracy and repeatability as researchers [19, 21] identified. Moreover, the design process for fully automated tooling solutions is first broken down into two categories as from static and dynamic perspectives where static units represent the components that are either fixated or require relatively less flexibility such as framework or base. Dynamic units, on the other hand, represent the fixturing elements that constitute the connection between the workpiece and framework; and these units provide the functionality for reconfiguration, automation and intelligence.

Additionally, agility, product and process inputs are reflected on both dynamic and static units in terms of component design and/or selection. Particularly in this phase, fixturing concepts such as modular, reconfigurable and ART become a key-enabling factor to establish the fixturing design where selection of technological features is investigated. For example, in a case where reconfiguration is required to be conducted on a part family level with a narrower workspace, certain units in the framework and base can be selected or designed to have manual labor intensive modular units. Furthermore, the reconfigurable element of the tooling solution can be somewhat fixated to a certain position on the framework through stronger joint solutions. Also, the automated dynamic components in the reconfigurable tooling can be chosen through standardized products that both fit the fixturing requirements such as rigidness, repeatability and accuracy as well as time and cost limits considering operation and design phases. Therefore, AFT methodology aims to elaborate on conventional approach on fixturing by creating a synergy between a business paradigm and tooling solution; that is not only flexible, cost and time effective but also compliant with operationally effectiveness from labor and hardware perspectives where a summary of this section can be seen in Fig. 1.

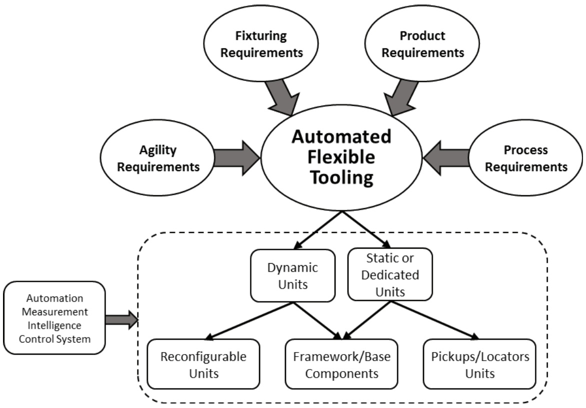

Fig. 1. Automated Flexible Tooling

3. Requirements on Agility, Fixturing, Process and Product

The assembly procedure of a wing structure highly relies on the construction of the build-philosophy, yet a common approach for the process is described by [22] as four levels in assembly. Firstly, respective parts of the wing box such as skins, stingers, fasteners are premanufactured. Later, panels and ribs are assembled via ribs creating a pattern required to provide integrity of a wing box. Thirdly, panels are installed on the patterns to create a wing box. Finally, multiple wing boxes are assembled to each other to form the complete wing structure. Particularly, this paper focuses on the first level of the assembly for the installation of a rib in a wing box assembly. In this process, a rib is inserted onto a sub assembly of lower panel with stingers, front and rear spars where this operation is repeated with steps to create a pattern within the wing. Meanwhile the insertion of the rib is conducted, the rib is best fit to surface generated by set of stingers complemented with sealant on the surface. Moreover, after the installation is completed, a rib is expected to maintain its position and orientation while fastening operations such as riveting are conducted (Fig. 2.).

After the process and product description, relevant agility limits can be drawn for design and operational aspects of tooling. However, a meaningful conversion from agility drivers to design inputs must be made. On operational level, this conversion can constitute process relevant inputs and how humans operate whether near or with the respective fixture. In the case of rib assembly, these relevant inputs can be categorized as:

- Allowable cycle time for reconfiguration, set-up and process
- Allowable maintenance load
- Required knowledge level to operate the fixture
- Quality and safety expectations

Throughout the discussions with project partners, cycle time is determined as less than one minute for reconfiguration, set-up of the rib and assembly. Secondly, introduction of an automated flexible tooling is expected to create a certain amount of maintenance load where it is anticipated for any business or production system to set this limit as minimum as possible. However, there is a possibility that maintenance-free dynamic components might increase the cost rapidly – which eventually contradicts the investment cost limit; therefore, a tradeoff between maintenance load and investment cost is required. Another important aspect is to determine the amount of investment must be made in order to provide the operators to execute operations on the designed fixture. This aspect of the agility inputs directly relates to how autonomous the AFT solution should be. An example of such is that lower levels of knowledge requirement means less dependency of the fixture on human intervention to operate. In this case, such a limit was drawn by the project that operators are only expected to initiate the process and acknowledge the set-up – which requires the AFT to be completely autonomous. Finally, quality expectations are categorized as the demands on AFT for intelligence and extra metrology systems whereas safety demands qualify whether an operator can work closely to AFT while fixturing process is autonomously conducted. In the rib installation procedure, AFT is expected to have intelligence and automation to handle process variations. As the complete wing assembly cell requires manual labor, the solution should also include a rapid on/off functionality for safety reasons after the installation of the rib is completed.

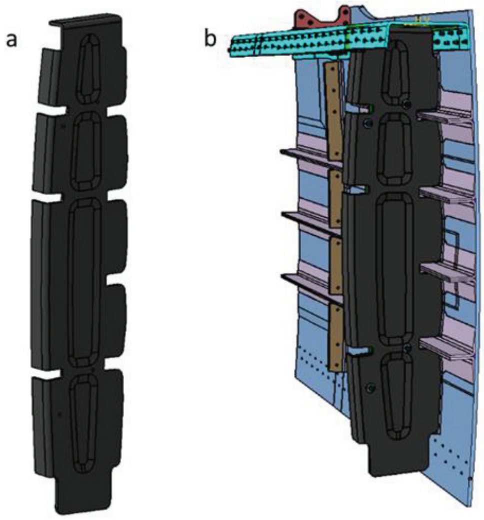

Fig. 2. (a) Rib product (b) cross section of front spar, rib and lower panel

On design level, agility inputs for fixturing comprises of time and cost limits as well as unquantifiable inputs such as reusability and virtual enterprise. The boundaries drawn by cost values can be grouped under design and investment costs whereas limits for time relevant inputs focus on lead, concept, detailed design and installation. In the development of the AFT for rib positioning, conceptual/detailed design and lead-times are determined as six weeks in total. Allowable installation time is set as maximum four weeks in which a section of production is allowed to halt. Due to business related restrictions, a certain investment limit cannot be disclosed; however, a threshold can be set on the notion that AFT solution should not exceed the amount of overall hardware investment and operational costs required for a manual labor oriented dedicated or modular fixture. From reusability perspective, AFT solution’s mechanical and control elements should have the structural capacity to be used in different settings in a narrow time window. Finally, fixturing solution must be able to communicate with the general production system architecture in terms of sharing data and signals with other processes for virtual enterprise integration.

4. Mechanical Design in AFT

Even though the product and processes vary with respect to each other, automated flexible tooling hardware aims to have a short lead time and cost effective approach. Moreover, each new product with its unique manufacturing steps or build philosophy will require different specification of the hardware. However, when standardization of equipment is required to drive the cost and lead time to lesser amounts, the same need to have a more effective business alignment creates a conflict. Therefore, AFT methodology focuses on designing tooling solutions rapidly by using the same manufacturing steps with modular, common and proven range of components. Via parametrization of these respective components, the design and lead time would be minimized.

Finding its foundation on above-mentioned paradigm, a certain framework of AFT design can be created. In this framework, the first step is to identify what type of agility inputs can be utilized and reflected on particular elements of pickup, reconfigurable and framework units. In the case of wing box assembly, the following inputs were conceptualized to gain competitive advantage over conventional tooling solutions:

- 90% of the parts had to be available on the market with a shorter lead time than four weeks
- The component range selected is expected to have at least three different sizes available
- The parts to be manufactured should be rapidly designed with parameters to adapt when different components are selected.
- Quick design drawings should be generated
- The new designed AFT is expected to be installed within six weeks.

By aligning the design process to the given input, the next step is to introduce certain fixturing requirements harmonized with process inputs. For example, in the wing box assembly, PKM machines, specifically Stewart solution, can be selected to constitute the kinematic structure due to its advantages in stiffness over serial robots [23]. Later, depending of the direction of process forces, Stewart platform’s base plate leg positions can be optimized in order to increase the stiffness of the parallel kinematics machine in static status. Along with geometrical changes, certain stiffness expectations were reflected on standardized components to have the capacity to remain rigid during the operation. Furthermore, motion requirements can be used to select or upgrade motors and linear actuators. The matrix of design variations for the Stewart platform as AFT have been summarized in table 1 and corresponding designed products reconceptualized with respect to different requirements are disclosed in Fig. 3.

Fig. 3. Multiple hexapod solutions

Table 1. Stewart platform design matrix (A, B and X_i represent brand names)

Part selection	Standard part (yes/no)	Choice 1	Choice 2	Choice 3
Actuator Brand/Model	Yes	A	B	X_i
Actuator Modular Size	Range	Small	Medium	Large
Stroke Length	Yes	100	200	500
Motor Brand/Model	Yes	A	B	X_i
Motor Size And Power	Range	Low Torque	Medium Torque	High Torque
Base Joint Type	Yes	Balljoint	Universial Joint	▨
Base Joint Size	Range	Small	Medium	Large
Base Plate Shape	No	Thickness, Joint Position, Features Etc.		
Base Plate Material	N/A	Steel	Aluminium	Carbon Fibre
Top Joint Type	Yes	Balljoint	RRR Joint	▨
Top Joint Size	Range	Small	Medium	Large
Top Plate Shape	No	Thickness, Joint Position, Features Etc.		
Top Plate Material	N/A	Steel	Aluminium	Carbon Fibre
Locking Type	N/A	Motor Brake	Hydraulic	Mechanic
Pickup Type	Yes	Zero Point	Capto	Force Sensor
Color	N/A	🟪🟦🟩🟨🟧🟥		

5. Flexible Control System Design

Flexibility in a control system is perceived by researchers as a control system’s capability to adapt to different processes and products on both design and hardware levels through modularity – as with RMS approach – or with a set of already built-in functionalities as FMS [2, 8]. In the case of RMS, a reconfigurable control system is descripted as a group of modular controller elements that can be immediately replaced and controlled via reconfigurable software systems to adapt the shifted paradigm [4]. AFT methodology inherits a rather similar approach to the one of RMS and mostly focuses on providing flexibility through transfer of functionalities from hardware to software level as the dependency on hardware for reconfiguration is more costly and restricting than having an open software architecture. Therefore, AFT conventionally applies the general control system that has the architecture of motors, drives, PLC and user interface. Even though the basic structure is preserved, a cost reduction and functionality transfer can still be reflected via the use of already available resources. For example, if the process involves the use of external metrology system without relying on synchronized motion of limbs, AFT method employs rather simpler architecture to reduce the cost such as by open-loop control in the motor and drive interaction without interpolation functionalities. However, in the case that synchronous motion is required without utilizing external metrology system, interpolation functionality with closed loop control becomes a necessity. Consequently, AFT's flexibility implication in the creation of a control system has an impact on the overall design along with the constituting elements.

For the wing box assembly and fixturing case, AFT solution focuses on providing synchronous motion with servo control due to the demand on intelligent assembly where path planning plays a key-enabling role in achieving robust motion. Therefore, the chosen control system structure is comprised of drives and servo motors with *Ethercat* communication protocol to enable fast data transfer. Even though a system of such sophisticated elements increase the applicability of the process, the investment limit is overreached in case of multiple hexapods. Therefore, a system with a single Stewart platform for each rib in wing box becomes uncompetitive compared to current tooling solutions in aerospace industry. At this point, AFT methodology creates a framework by making tradeoffs between operational and design level agility inputs, and since the assembly process does not require synchronized motion of multiple hexapods, the control system is designed such that a stand-alone control box can be connected to any hexapod and perform the motion individually. Therefore, a rather simple *Plug&Play* type connector between motors and drives can be installed to complement the aforementioned functionalities.

Another important aspect of control system development for AFT solution is the cost reduction through transfer of functionalities from hardware to software level. An example of such can be seen in the use of internal motor current and torque feedback; and their use on responding to process related forces where series of tests conducted to improve the drilling process quality via internal force/torque feedback on a robot [24]. In this design concept, the controller is complemented with a functionality that calibrates each axis via peak torque values at mechanical ends of each linear actuator in order to eliminate the dependency on the use of external sensors or metrology system. The first step of developed algorithm is to initiate a continuous motion towards the mechanical end of a linear actuator that is designated with an absolute value. In the second step, torque values on each axis is monitored separately where a moment of peak in torque triggers the position recording; and once the mechanical end is reached, the respective encoder feedback value is adjusted to the previously specified value; thus; completing the calibration repetitively. Another functionality developed in order to be compliant with the agility and fixturing inputs is reading stored final leg positons and coordinates; recalibrating each axis and overriding the numerical approximation of forward kinematics. These features particularly correspond to the replacement of absolute encoders in a robotic application which is one of the main cost drivers in a control system. Accordingly, AFT aims to provide a framework for developing functionalities in order to increase the applicability of automation in fixturing solutions without comprising on flexibility where intelligent automation elements can also be implemented in an open structure.

6. Intelligence Integration

The concept of introducing intelligence whether into fixturing or process tools has been a topic of interest for researchers and the examples of which mostly focus on clamping force control and intelligent reconfiguration in order to reduce the variation in the workpiece [25]. In the case of hexapods, the expected capability from AFT solution is different than of above-mentioned paradigms where the respective Stewart platform is required to exhibit intelligence through the process of assembly rather than fixturing particularly due to the variation between the rib and lower panel.

Force/torque sensing algorithm developed for this case is formulated on the idea of plane sensing where methodology is inherited from the manual best-fit operation conducted at conventional solution. In this process, the alignment is achieved by finding the peak points of the surfaces on lower panel and front spar where initial contact is first made on the lower panel; and later, the gap between the spar and upper surface of the rib is cleared. By following same technique, the hexapod (I) initializes a contact-point finding procedure by translation at a tool offset point; (II) at contact moment, the motion is converted to rotation in order to complete the alignment; (III) (a) in case the plane surpasses the force sensor's center axis origin, a reduction in the corresponding torque value (b) if the alignment's expected point remains on one side of the force sensor origin, a sudden peak in the respective torque vector component relative to previous step completes the alignment (Fig. 4). By repeating the same algorithm, AFT method ensures that the variation in all the workpieces is securely compensated in the assembly process.

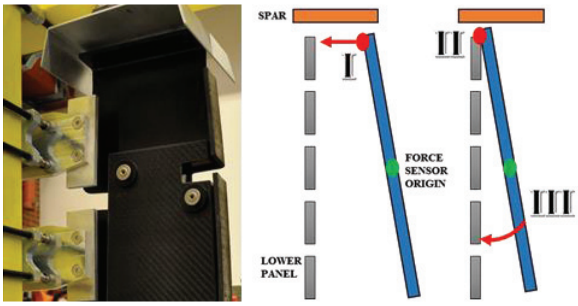

Fig. 4. Force sensor algorithm in wing box assembly

7. Results and Discussion

The evaluation framework of AFT is also a step in general fixturing strategy where verification of the tooling solution is investigated on the compliancy to the inputs stated earlier. From fixturing requirements perspective, a verification matrix can be conceptualized on rigidness, repeatability and accuracy

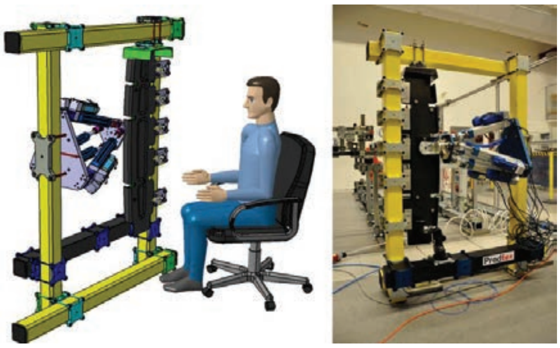

Fig.5. Test rig for hexapod solution

of the hexapod – the resulting test rig of which can be seen in Fig 5. An important difference that was contradictory to general fixturing design was that most dynamical components such as universal joints and linear actuators on the market are designed with respect to providing accuracy and repeatability rather than stiffness; and therefore, the amount of generated play in the hexapod surpassed the limits of fixturing requirements. The main sources of play on the end effector were observed to be on two basis where process forces constantly caused structural deflection on linear actuators and play on the bearings of the universal joints.

Secondly, the flexible controller and open architecture software capabilities were one of the major cost drivers of the AFT solution in a case where each fixture was expected to have a unique controller. It was observed that one of the viable solution to reduce the cost was to use a single controller that had a switch capability between different Stewart platforms. However, intelligence integration into open architecture software – either for switch or sensor type functionalities – required the investment of a unique robot language such as the ones used in commercial articulated robots. This particular situation corresponds to an increase in engineering time and knowledge requirement on operators; and therefore, increased the cost of AFT and surpassed the scope of what was expected from agility perspective. As a result, from both agility and fixturing perspectives, there is a certain need for a framework to design dynamic and controller elements for fixturing such as a controller unit that allows a rapid wake-up functionalities for a variety type of motors; and also, a linear actuator where rigidness plays the main design criteria along with precision.

8. Conclusion

This paper presented the preliminary results on the development of automated flexible tooling concept for aerospace industry where the developed hexapod solution clearly showed capacity to compete with conventional tooling solutions. However, from a timewise perspective and capability to be integrated into manufacturing, AFT solutions must be complemented with affordable fixturing technologies where elements of dynamic and controller units require to be reconceptualized for static capabilities as in fixturing. Therefore, the harmonization of agility and fixturing techniques with current robot technologies can fortify the applicability of AFT in any given manufacturing paradigm.

Acknowledgements

This work was supported by LOCOMACHS project in WP34.

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