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Development of Affordable Reconfigurable Tooling in Car Manufacturing Cells – A Case Study

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Abstract

Assembly fixtures are one of the cost driving factors in automotive industry. Previous research have shown that the utilization of affordable reconfigurable tooling (ART) can be a key-enabling technology to reduce the cost and lead times. Inspired by the research results, Volvo Cars Corporation initiated an automated process control project, the aim of which is the automatic inspection and correction of the defects in Body in White (BIW). The project comprises of three stages – the first of which is the in-line measurement of BIW. Then, the results of measurements are transferred to a common database where process evaluation through case-based reasoning suggests corrective actions on the fixture. The last stage involves the development of flexible tooling to meet these changes in a cost and time effective way. Hence, the aim of this paper is to present preliminary results on the development and implementation of ART as flexible tooling.

Keywords: Affordable reconfigurable tooling, Automotive,Production, Manufacturing, Flexible tooling

1. Introduction

Flexibility in manufacturing systems has been widely investigated by various researchers; and the outcome was indicating that a manufacturing system is only qualified as flexible when all of its components can react to the constantly altering market requirements in a cost- and time effective way [1,2,3]. Particularly, the reason that the flexible manufacturing was complemented with cost and time was stemming from the experimentation of the automotive industry. The trials of car manufacturers to implement flexible production equipment revealed that the attempts to reuse these equipment were costly and often very time consuming in comparison to dedicated tools. Therefore, the conclusion was drawn that flexible manufacturing systems must be elaborated towards agility with cost and time elements – which eventually converted flexibility to agility in manufacturing [3].

These circumstances drove automotive industry to strive towards creating more agile production systems with a holistic approach. This collaboration between the components of a production system has been analyzed from different perspectives such as process, product, volume, and machinery [4]. However, one important point is the definition of what flexibility is in these perspectives and how they should be characterized. Koren et al. [5] explains these characteristics by stressing the importance that a manufacturing system must also be flexible enough to handle quality losses so that the overall quality of a production system can be satisfactory for the customers. Hence, a crucial feature of agile car manufacturing can be identified as providing high quality products through the means of agile technology where the application can span from sheet metal forming to other assembly operations. As a result, each operation requires attention to identify capabilities along with hindrances.

In a typical assembly line of automotive body in white (BiW), it is estimated to spot-weld 300 different sheet metal components to each other [6]. Throughout this assembly operation, Wärmefjord et al. [7] explains that variation in the part, fixture design and the process order in terms of spot welding can greatly affect the after-process quality. Therefore, in-line control of the car body is still a necessity even though variation simulation is widely

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evaluated by researchers to proactively increase the quality of the assembly [8].As an example, at Olofström plant of Volvo Cars Corporation the variation handling is done in two ways. The first method is to extract specific amount of subassemblies of BiW from a batch and measure them in a verification room. If any out-of-tolerance product is discovered during the verification process, the batch is traced backwards in production line and sent to rework. Meanwhile, operators shim the fixtures of the source process to correct the possible variation errors in upcoming products. The second method relies on the continuous measurement of the complete BiW per one batch. If the measurement process indicate defects, the respective batch is sent out to a rework station. When the batch is corrected within a specified tolerance zone, the products join back to production flow (figure 1.a).

AProC (Automated Process Control BiW) is a joint project developed to address the problem of efficient and fast correction of these defects in BiW. The project addresses the issue from four different perspectives where each perspective is formulated as a different work package (figure 1.b). These work packages focus on the solution of providing automated solution for in-line measurement of BiW, automatic corrective action decision through case based reasoning; and finally, flexible tooling development to facilitate the outcome of the first two work packages. Therefore, the development need for this project stems from the demand of efficient processes. Thus, it is important to acquire the ability to measure all features on all bodies and also possibility to correct faults accordingly. New robot based measurement systems [9,10,11] have the potential to measure many more of the required features in-line and within required cycle time. This also requires new ways of off line programming (OLP) in order to find the optimal path to minimize the cycle time. However, the question of making the correct decision regarding required rework is not addressed. If the necessary rework could be divided between manual and automated rework, the process would be more efficient; and unnecessary rework can be minimized. From tooling's perspective, today's fixtures being used in production are dedicated and welded. This causes changes in the system difficult to implement. Hence, AProC aims to describe the capabilities of new flexible tooling that facilitates the adoption of the product changes in a fast and effective way.

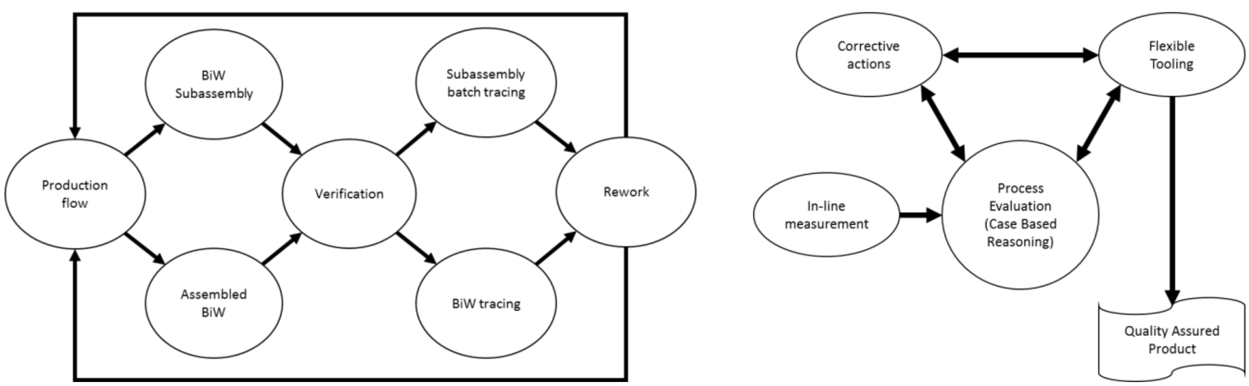

Fig. 1. *(a) Current rework process for BiW at VCC; (b)* AProC (Automated Process Control BiW)

AProC and agile production systems demand the fixturing techniques to satisfy their requirements; thus, the selection of the correct fixturing technique becomes vital. Therefore, aimed capabilities of respective fixturing technique must be flexible enough to handle in-process changes (shimming). In addition, the technique must also satisfy the demands of agile manufacturing such as cost effectiveness and low time consumption [12]. As a result, it is important to relate the current fixturing methods to the formulated requirements.

Today's fixturing technologies can be classified as modular, reconfigurable and affordable reconfigurable tooling. The final term, affordable reconfigurable tooling (ART), is the latest milestone developed and tested for aerospace applications in order to satisfy the requirements of agility [13]. Specifically, ART concept simply divides fixturing equipment into three levels where the first level corresponds to modular fixture frame. The second level describes a product interface that is comprised of a reconfigurable unit and pickups. The third level describes the workpiece. By manipulating the only the second-level units with an outer automation tool such as an industrial robot, ART aims to reach a maximum level of accuracy in a cost effective and fast way [14]. Previous applications of ART in aerospace industry indicate that ART concept is capable of reaching +/- 0.05 mm accuracy [15] – which can be used as an indicator of capacity for accuracy in automotive industry.

From tooling perspective, the primary objective of this project is to create and demonstrate flexibility that can facilitate the corrective actions. Thus, this paper aims to present the preliminary results on the development and building of flexible tooling concept where assembly and corrective actions of BiW subassembly can be implemented manually. The organization of the paper is as follows. In section 2, the paper focuses on the design of flexible tooling whereas in the third section building and reconfiguration strategies are explained. In the final section, the paper presents and discusses the results.

2. Design

There have been various methodologies created by various researchers to define the fixture development procedures. One commonly identified methodology suggests the procedure as steps of planning, design and verification [16,17,18]. As methodology's first stage states, the setup planning is done according to workpiece locating analysis and machining process. Therefore, the input from AProC related to the product plays a vital role in the first step of fixture design.

The product, GOR, is a subassembly of BiW that sets the framework for headlights and related components (figure 2.a). The GOR is comprised of nine sheet metal components –eight of which are symmetrical parts. The last component unifies these eight sheet metal units and complete the subassembly. The locating datums of these independent parts are created by Volvo Cars Corporation by using 3-2-1 principle [19]. The datum allocation for each part follows the same procedure where all the parts are first indexed to a certain point through two locating points in car coordinate frame. Then, they are clamped and fixated. Additionally, due to the elastic state of sheet metal certain amount of points are allocated to secure these parts in space. These datums are declaring the fixation axis in one positive or negative direction – which can be regarded as a locator rather than a clamping point (figure 2.b).

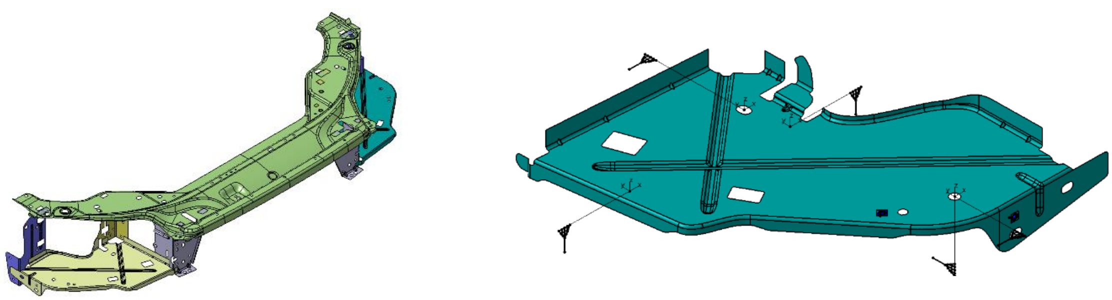

Fig. 2. (a) The GOR product in BiW; (b) datum points on a sheet metal component

The classification of the in-process shimming operations plays another important role in reaching a robust and capable flexible fixture. As stated earlier, the part variation causes the system to rework on the assemblies – which is later reflected to fixtures through a set of shimming operations. The span of these shimming operations collected at a database at VCC indicate that each datum point must be capable enough to move in all axes of car coordinate frame about +/- 0.5 mm. In practice, this shimming procedure is conducted as a set of translations. The current dedicated fixture is designed by using three different 5 mm thick plates fixated to a framework (figure 3). Then, an operator simply replaces the respective plate with a new one that has a different thickness to execute the corrective action. Hence, the shimming is implemented by steps through a mass produced tailor-made plates. As a result, the flexible fixture design can be aligned to the same capabilities of the current solution.

As the shimming requirements and allocation of datum points are analyzed, the next step is to define a design methodology. ART's main approach to the classification of a complete fixture unit is as framework, configurator and pickups [20]. Thus, this taxonomy can be used as the first stage to decide on the overall fixture components. The design procedure, on the other hand, can vary with respect to the product and procedure. For this project, the most appropriate procedure can start with pick-up design due to the fact that AProC relies on the in-process correction of independent locators. Later, the design of framework and configurators can be created to facilitate the locators and process in general.

Fig. 3. (a) 3D model of a shimming plates and fixture part; (b) Fixture application at Olofström plant of VCC

2.1. Pickups (Locators) and Clamps

In order to provide affordability, it is important to identify the cost drivers in a fixture application. Even though the use of tailor-made components is inevitable, ART suggests the idea of minimizing these components to minimum level; and instead, it recommends the use of standardized products to reduce the total cost [13].Thus, in this project tailor-made parts can be reduced to those that are going to interact with the GOR components.

From the analysis of product, the locator points are identified with two holes on each sheet metal. The span of these holes is comprising of three different sizes that are 8.1, 12.1, and 16.1 mm in diameter where the surface that the BiW components will lie on is also vital to be precision-machined. The important point here is to optimize the size of the surface so that the sheet metal can be located safely; and pickups remain affordable. Moreover, the locators should also provide a method to unload the GOR easily from the fixture without losing the current coordinate values.

As a result of these requirements, a design that consists of four different components was formulated to provide flexibility without comprising on the capabilities. The first component is a cylindrical tailor-made part that the GOR components will lie on. The second manufactured part is a sleeve alike unit that locates a GOR component through its holes. The remaining components of the pickup are standardized units namely a bushing and dowel pin. These components' main function is to enable a transition fit so that the GOR can be easily unloaded after spot welding without losing the current coordinates on the pins. These standardized parts also reduce the cost on the first cylindrical unit by eliminating the tolerance demands on tailor-made components. The assembly and constituting parts of the locators can be seen in figure 4.

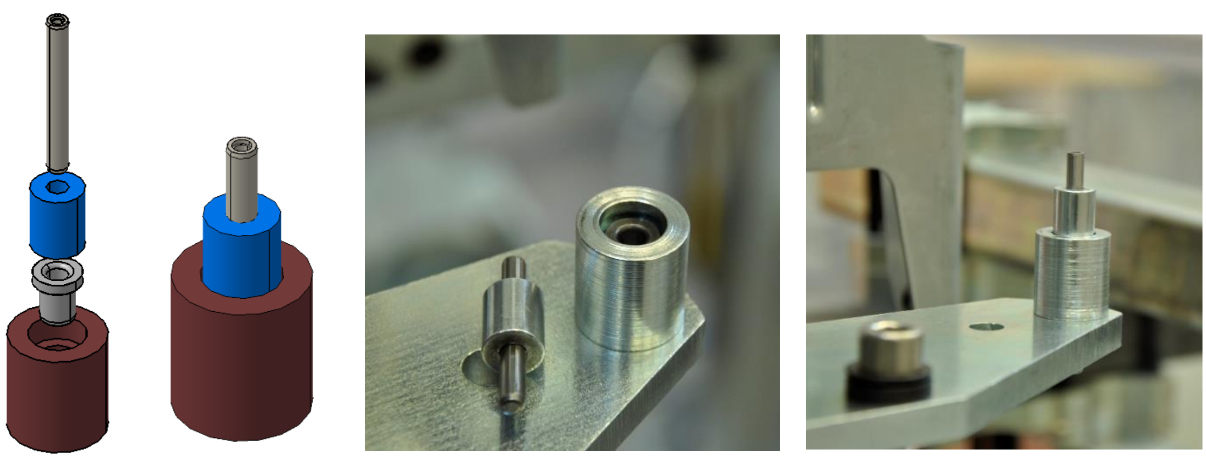

Fig. 4. Locator assembly of a cylindrical guiding unit, bushing, sleeve and a dowel pin

Another important point is to associate the design to the shimming capabilities. As stated earlier, the shimming operations are conducted for locators and clamps in positive and negative directions of X, Y, and Z-axes within the range of +/- 0.5 mm. The corrective actions on X and Y-axes require the complete assembly of the pickup to float on a separate unit since the design does not allow the shimming of bushing within the cylinder-shaped part. Therefore, they can be transferred to configurators where the pickup assembly can freely float on a surface. Similarly, shimming in Z-axis can be achieved through a set of shims that is commercially available for affordable prizes. These washers can be simply installed between the configuration unit and the locator. Hence, the shimming can be done by adding or removing shims to provide different lengths.

Clamping is also considered to be one of the challenging tasks in a fixturing application as providing a sufficient clamping force plays a major role in robust fixation of the workpiece. Furthermore, the clamping units must also be compatible with corrective actions similar to the locators. It is also expected from these units to be affordable and comply with the framework of ART where easy and fast configuration is essential. Therefore, it is possible to conclude over the notion that a standardized product with reconfiguration capabilities would be affordable enough and a sufficient choice for AProC. One particular standardized product that fits these requirements – clamping force of which is approximated to be around 1700 N – is GN820-M-230. Additionally, the respective clamp's shimming capabilities are provided by a flat knurled screw (i.e. DIN653 or WN61) as the holding base. As a result, shimming in Z-axis can be done by adjusting the height of the screw where shimming in X- and Y-axes are compensated by the surface area.

2.2. Framework

Traditionally, assembly fixtures comprise of a welded steel beam framework where the beams are in the circumference of the product(s) to be assembled. In order to access the product(s), its components are attached on pickups. Then, the pickups are extended to reach the steel beam framework via flags. In some cases, pickups can also be attached directly on the steel beam framework or use flags to reach the framework. Thus, a flag can sometimes be up to a meter in length. Since the location of the pickup will define the accuracy of the assembled product, they have to be calibrated very accurately. In a conventional fixture, the accuracy of a pickup is given by the accuracy of the flags and steel beam framework; hence, the framework itself is required to be accurately built. Welding a steel beam framework is indeed difficult to get to high accuracy.

Accuracy in the framework beam structure is achieved by dividing the framework into substructures where the pads are machined in a large NC machine. These machined surfaces are providing accurate positions of beams as the sub structures are assembled in the fixture build-up. The insertion surfaces of the flags are also machined to make sure they are not losing accuracy in the build-up. This traditional way of building fixture is very costly and time consuming.

One way to solve these time- and cost drivers is to use shim boxes. A shim box is a method to avoid machining pads in the steel beam framework, and instead adjust the pads simply by screws. This is a common approach to set accurate locations of flags in the fixture build-up. The purpose of a shim box is, in most cases, to get accurate surfaces to place the pick-ups on. The final X, Y and Z location of the pick-up is in many cases set by using shim elements. Such element typically constitute a plate or a washer. In the end we have a system with accurate surfaces via the Shim boxes and accurate positions via shim elements.

The approach in the project is to use a solution that completely eliminates the welding of steel beam frameworks. This solution is a patented steel beam joining system called BoxJoint. On the market today there exists many modular beam joining systems, but for assembly fixtures they are aluminum in most of the cases. BoxJoint gives the same capability as an aluminum based beam joining system, but allow steel beams instead of aluminum beams. One of the project requirements was to use a steel based framework, but it was required to be non-welded in order to enable changing the framework design when needed. Another key advantage using BoxJoint was the fact that it has very few requirements on the beams to be used in the system. These are that the material thickness was enough to allow its clamping pressure and that the beams were warm rolled as to have a lower radius on the corner with respect to cold rolled beams.

The concept of BoxJoint is to clamp the beams instead of welding them together. One beam-joint has two plates that are clamped together with four screws and four nuts. One such box are then connected to another box that clamps another beam; hence, we reach a box joint. The BoxJoint system uses screws in the range of M16, M10 and M5. Every range has only a few number of box plates (figure 5). The way boxes are combined create a very large number of joint applications. The box plates are fabricated from a high strength steel (750 MPa). Since BoxJoint uses a classic "mechano" build-up approach with no welding needed, it enables an easy and quick setup methodology which requires a very minimum amount of training.

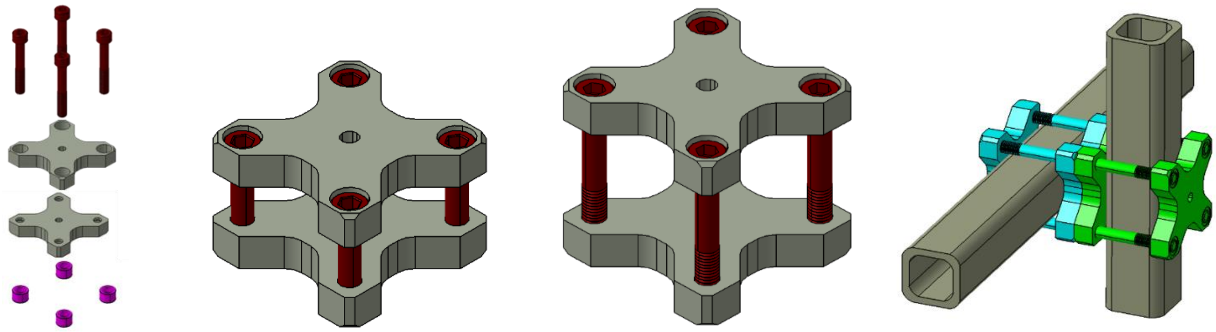

Fig. 5(a) BoxJoint components; (b) Box of size 25 mm; (c) Box of size 50 mm; (d)Two beams assembled with BoxJoint

2.3. Flexapod Units (Configurators)

One very important property in BoxJoint is to understand the reason that it is not an accurate system. Low accuracy in the framework is key to enable simple and quick fixture build-up as there is no sole reason to have accurate beams in a fixture. It is the pickups that are required to be accurately located. Therefore a unit called flexapod is used as either flags and/or pickups for flexapods have the same purpose as shim-boxes. However, the difference between shim boxes and flexapods is that a flexapod handles all degrees-of-freedom inside one unit. Specifically, theses flexapods control not only x, y, and Z, but also the roll, pitch and yaw in the configuration of a flag or pickup. The BoxJoint system has standard flexapod units inside its range of components. These standard units are however more purposed to be used to configure a 6 degree-of-freedom flag location in space. Due to the lack of space in the application of this research, these BoxJoint Flexapod units could not be used. Therefore, a new and more compact flexapod pickup unit was developed.

Basically, the new flexapod unit consists of a plate with fairly good surface quality – installed to BoxJoint by four bolts with spherical washers, and grub screws. In order to analyze how the flexapod unit is operating, it is essential to break the plate into sub-areas where each section fulfils a different role (figure 6.a). The first area's purpose, then, is to provide the function of configuration and connection to the BoxJoint plates. The area is consisting of four oversized holes for plate-specific bolts with spherical washers and three threaded holes for grub screws. Explicitly, these oversized holes provide the connection with the BoxJoint plates whereas the grub screws negate the error built up from BoxJoint structure. Thus, in order to arrange the correct orientation of the flexapod the unit is first connected freely to the BoxJoint plate through the bolts. Then, by changing the distance between the respective lengths of the grub screws the flexapod unit can be configured to the desired orientation and position (figure 6.b).

The second areal function of the flexapod is to provide a surface for the locators to float on so that the locators can be configured and shimmed easily. The connection between the flexapod and the locator can be done through a screw and washer connection. Thus, the allowance for shimming operations is automatically limited to the diameter of the hole when the diameter of the screw is deducted. Lastly, the third section provides an extra space for auxiliary functions such as clamp attachment or measurement system integration.

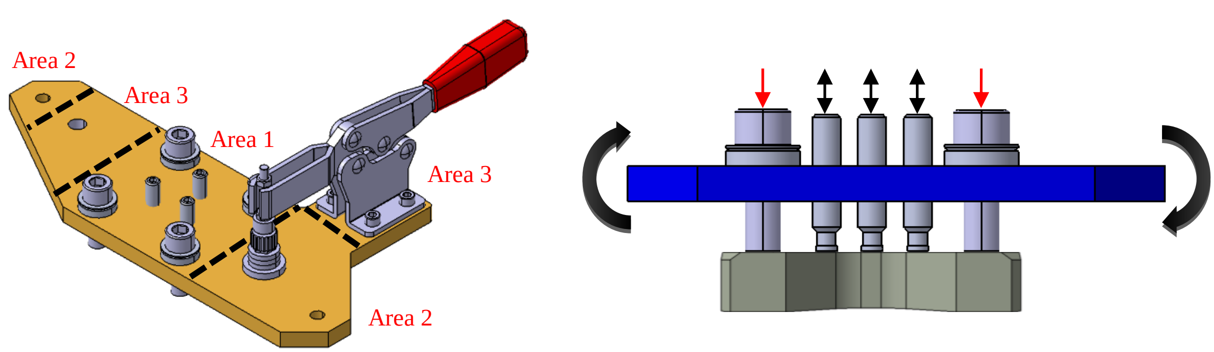

Fig. 6(a) Assembly of flexapod unit showing functional areas; (b) Configuration of a flexapod with a BoxJoint plate

3. Fixture assembly and reconfiguration

Design and appointment of features are primarily significant for fixture design; yet, it is also essential to create a working method for ART applications when it comes to building and reconfiguration. This is particularly important since fast set-up and adaptability of a fixture is considered to be as vital as the holding capabilities. Therefore, this section will first describe the initial building strategy employed; and later, it will disclose the reconfiguration technique to minimize the tolerance chain of errors in beams, configurators and pickups.

The framework as stated in section 1 is centered on the notion of having an inaccurate system so that the cost of machined surfaces can be negated. However, this does not mean that the accuracy in framework should be neglected completely. When building a fixture, it is known that errors keep building up in a chain as the system is integrated with parts assembled to each other [14]. Therefore, identifying major contributors to errors and aligning them as accurate as possible would make the configurators remain in a capability zone. Hence, locators can be ensured to the desired position and orientation.

The identification of the critical points in the framework can be done by considering two aspects. These are the planar accuracy of beams and positional proximity of the plates. Thus, the beams setting the base for the configurator plates should be arranged without spending too much effort and time. Moreover, the plates to which flexapods will be attached should be only considered for positional accuracy as plates are directly aligned to a beam. In figure 7, a section of the AProC fixture is exemplified to demonstrate the arrangement of a base beam and a configurator plate. The beam is one of the longest in the fixture and sets the base for four flexapods. The surface of the beam highlighted with green represents the accuracy zone in XY-plane whereas the red surface shows in YZ-plane. The plate connecting the flexapod is swiftly aligned to a positional accuracy in the surfaces that are not in contact with the beam. The flexapod unit, as described in section 2, follows the same methodology where the locator surface requires to be very accurate through the grub screws. The positional accuracy of a flexapod is arranged by measuring the locator interaction holes. As a result, the locators can be easily attached and arranged to the datum points by using a measurement system.

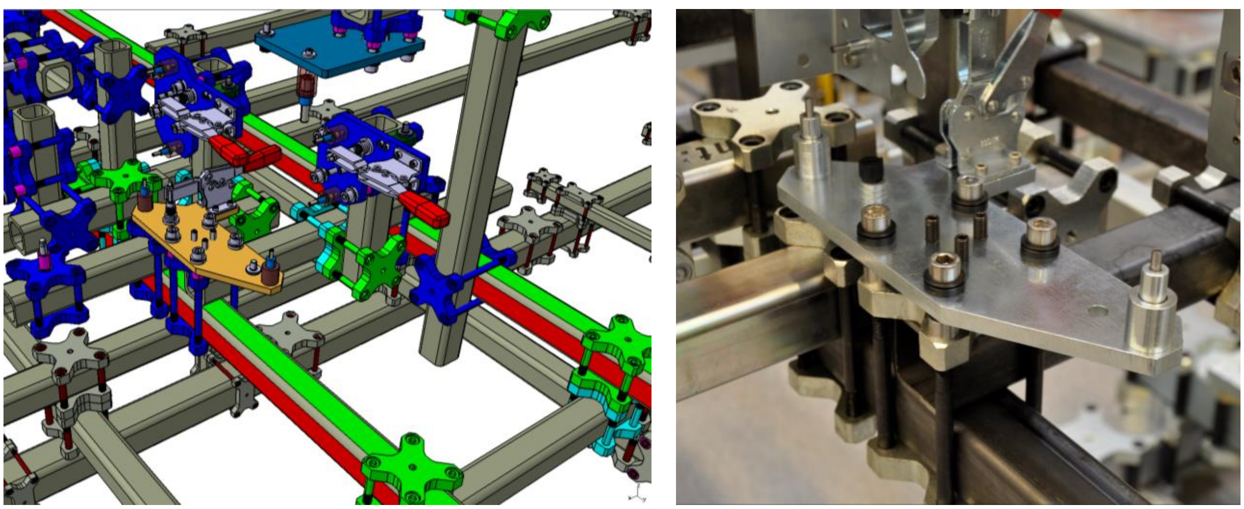

Fig. 7(a) Base beam in framework where green surface represents XY and the red YZ-plane; (b) Configurator plate

4. Results and discussion

The current fixturing equipment at Olofström relies on dedicated tooling where the components are either welded and/or tailor-made with respect to a group of products. Additionally, the shimming capabilities are provided by a set of custom-made plates working as modular interfaces to the locators. These circumstances, indeed, make the fixturing equipment to be quite robust and effective. Furthermore, the strength and other demands on a fixture are directly offered by these tailor-made components. Moreover, the modular parts of the fixture are entirely designed to be very time-saving in building and reconfiguration. On the other hand, nature of the tailor-made components cause products to be bounded to a certain group of features where the same nature also limits the quality of the assemblies as the understanding towards the shimming requirements deepens. Consequently, the current fixturing technique becomes a cost-driver and capability limiting factor even though it provides the necessary strength and requirements satisfactorily.

The idea of shimming flexibility is, in the test rig, approximately limited to +/- 0.5 mm in X- and Y- axes with respect to the diameter of interface holes. However, this flexibility can be easily expanded to the process requirements by increasing the respective diameters. It is also important to emphasize the point that the framework of the flexapods might reduce the quality as the plates are not machined for a higher surface quality. Therefore, as the use of a non-machined surface raises, higher shimming capabilities can cause the locators deflect from the anticipated tolerance zone. This was particularly observed as the surface of the framework is measured to vary roughly +/- 0.1 mm on the axis perpendicular to the plane – which might affect tolerance variation greatly. One way to cope with this problem is to machine the framework surface to a certain tolerance – which creates a trade-off between the quality and cost especially when the flexapod is relatively big.

Another important result about flexibility can be drawn with regards to time; particularly for building, reconfiguration and shimming. ART concept provides lesser design and lead times; and building the fixture happens directly at the plant site. The measured amount of time for the framework's initial assembly was around 16 hours whereas the reconfiguration time of the key components in the framework required 5 hours. The configuration and assembly of each flexapod takes a trained person to spend 1 hour – which can be seen as the change over time of each component in case a different product needs to be introduced.

The time spent on the locator positioning requires a separate emphasis. Since the design capabilities do not provide a continuously-controlled motion due to floating on a surface, the positioning of each locator might consume relatively more amount of time with respect to tailor-made parts. What was measured throughout the locator positioning is that each locator takes almost 15 minutes to reconfigure. This might be a major concern as the number of locators increase, the time required for positioning will be more accordingly. In order to avoid this time consumption, it is important to design the locators with an interface to a measurement system that will ease the measurement procedure. This particular point can also be reflected on shimming capabilities where reaching a correct locator position will repeat the same procedure as in initial assembly. However, when compared to existing tooling at VCC the shimming and locator positioning takes approximately 1-2 minutes due to the use of standard plates in all directions.

Even though the paper presents a set of results on flexibility, they are still immature in terms of integration to a highly-automated production line. Therefore, one possibility that can completely disclose the competence and weakness of flexible tooling concept is to devise a capability test on the developed fixture. These capability tests will evaluate the rig from process and operator perspectives by applying the same shimming operations currently used at VCC. These tests, from fixturing perspective, will be conducted with the aid of an in-process measurement system where the shimmed GOR will be installed to an already-built control fixture. Through the measurement of certain points on the GOR, the resulting data will be communicated to the case-based reasoning system for another set of shimming suggestions. This way, it will be verified that all the work packages are functioning as they are aimed to. Moreover, with each measurement the case-based reasoning system will enrich and start to produce better results. From operator’s perspective, the aim will be to evaluate what the division between manual and automated work should be. This division will be decided by measuring the time for each test scenario and comparing them to the appointed values at VCC. Preliminarily, if the time required for shimming any component of the GOR in any axes of car coordinate frame surpasses the production line requirements, then the corresponding flexapod will be considered for automation.

Despite the lack of capability tests, the test rig clearly shows that the ART concept is capable of providing tools required not only for changeovers but also for in-process shimming operations. Since the focus of ART is on affordability, the fixture also provides cost-effective solutions compared to dedicated tooling technologies. However, the manual work requirement and ambiguity of whether the fixture can withstand the process forces robustly remain as the weakest points. Therefore, an important conclusion in the light of these learnings can be that flexible tooling must be further investigated for the integration of flexible automation tools and assisting technologies. Hence, ART concept with flexible automation is expected to provide flexibility, strength to handle process forces, affordability and less time consumption – which will eventually function better than the dedicated tooling solutions.

5. Conclusion

This paper presented the preliminary results on a development of flexible tooling concept for car manufacturing cells in collaboration with Volvo Cars Corporation. The fixture developed was aimed to show that affordable flexibility can facilitate not only the product changes but also in-line process adjustments. Because of the manual labor intensive nature, the fixture is not possible to integrate to a highly automated production line at its current state. However, the fixture clearly showed that the affordable reconfigurable tooling can set the basis for future fixturing where flexibility meets the automation. Thus, in order for flexible fixturing to compete with current dedicated tooling technologies flexibility concept must be implemented with affordable flexible automation tools along with key-enabling mechanical solutions. These solutions must provide the features of dedicated tooling such as high stiffness and the ability to withstand process forces. In addition, the emerging automated flexible tooling should remain cost-effective and time-saving. Consequently, the demands of today's agile manufacturing can be further satisfied with these features on flexible tooling.

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