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The SwarmItFix Pilot

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Abstract

The paper presents the integration and experiments with a pilot cell including a traditional machine tool and an innovative robot-swarm cooperative conformable support for aircraft body panels. The pilot was installed and tested in the premises of the aircraft manufacturer Piaggio Aerospace in Italy. An original approach to the support of the panels is realized: robots with soft heads operate from below the panel; they move upward the panel where manufacturing is performed, removing the sagging under gravity and returning it to its nominal geometry; the spindle of a milling machine performs the machining from above.

Keywords: Flexible Automation; Manufacturing; Reconfigurable Fixtures; Multi-Agent systems

1. Introduction

Sheet metal components form the backbone of current day automotive and aircraft manufacturing sector. They belong to a fundamental form, where various metal working operations can result in a variety of geometrical shapes. Sheet metals are also ubiquitous in modern aviation industry where they act as the primary candidates for aircraft structures held together by rivets and fasteners. With the advent of mass customization and need for faster time–to-market using automation, the demand to introduce new flexible technology for the fixturing systems in the transport industry arises. The aircraft industry consumes sheet metal of wide dimensions next only to the shipping industry. The technology for handling these flexible metal sheets are yet the traditional moulds for fixturing the skin of the aircraft panels. The existing methods are considered to be very robust but in its entirety is parts-specific. SwarmItFix, the system being discussed in this article, is a robotic system conceived for providing an alternative solution to the traditional mould fixture technology [1]. Flexible fixture systems (FFS) are generally classified [2]

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into Modular flexible fixture systems (MFFS), Single structure flexible fixture systems (SSFFSS) and Robotic Fixtureless Assembly (RFAs). The MFFS and SSFFSS contribute towards easier re-tooling using modular kits and adaptive clamping respectively and the RFAs use robotic manipulators with specialized grippers. The SwarmItFix is a specialized version of the RFAs, where the existing RFAs consist of mostly non-mobile robots or robots confined to a smaller workspace whereas the concept proposed here introduces a mobile manipulator. The solution developed has taken into account the shortcomings of the previous generation of systems and also in particular the current application it seeks to tackle, i.e. fixturing large sheet metals and providing adequate support over time with the concept of reconfigurability. The reconfigurable mobile fixture was developed in the European Framework Program FP7, project 214678 NMP2 SL, where each mobile fixture is considered as a robot which supports the sheet metal by traversing a fixed bench when machining operations are performed over the workpieces hence preventing sagging of the workpiece.

2. SwarmItFix Multi-Robot System

SwarmItFix is a complex mixture of intertwined mechanical systems, smart materials, control systems and software. The innovative fixture is considered modular with reference to its physical characteristics and action planning. The current prototype as shown in Fig. 1 consists of two robots, mounted on a stationary bench with pneumatic and electric supply, and passive supports to fixture the thin sheet metal components.

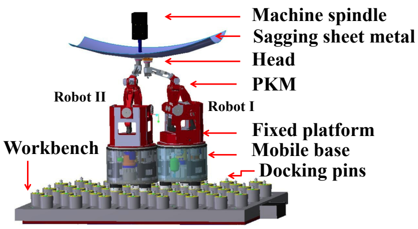


Fig. 1: Virtual assembly of prototype: SwarmItFix

2.1. Physical Architecture and measurable parameters

The robots comprise of a head, a parallel kinematic machine and a mobile base. The following sections describe the design implementation with respect to the needs of the flexible fixture system.

2.1.1. Head

Head is the element which makes contact with the sheet metal. Initial design proposed a cup shape design [3] with pseudo phase change material, and later a more mature equilateral triangle shaped design with phase change magneto–rheological (MR) fluid [4] was implemented (Fig. 2). The MR fluid has a low off-state viscosity and fast response time which is ideal for quick adaptation to the contour of the workpiece.

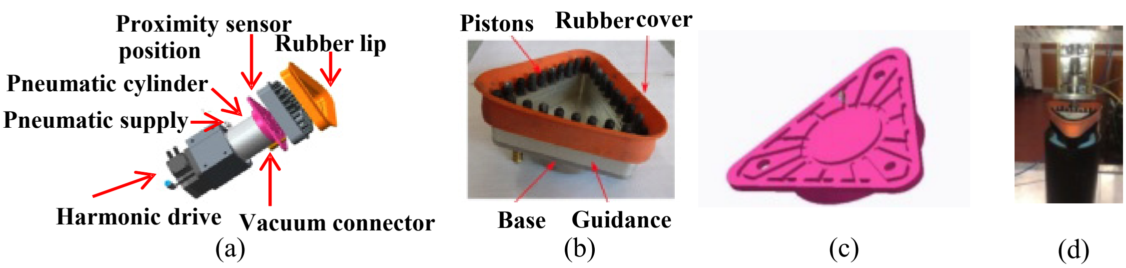


Fig. 2: (a) Head CAD Model; (b) Head sub-assembly; (c) MRF central container; (d) Final prototype on testing

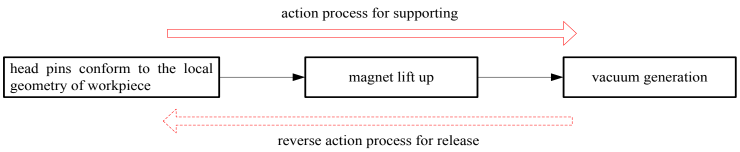


Fig. 3: Head Working Principle

These pistons are placed inside a chamber containing MR fluid. The viscosity of this MR fluid is increased by positioning a neodymium permanent magnet close to the chamber. Highly viscous fluid stalls the pistons in their current position, thus positioning the head with respect to the workpiece. The working principle is shown in Fig. 3. A soft rubber lip as shown in Fig. 2(b) encloses these pistons to generate vacuum and avoid rough surface marks due to direct contact. The triangular head is made of T 300 series stainless steel. The material was chosen to guarantee the effect of magnetic field on the MR fluid. Channels are provided in the head to lead the MR fluid from a central collecting chamber (Fig. 2(c)) to the piston chamber. The upper part of the chamber is made of Aluminium Al-6082 to prevent the work-piece from getting magnetized by the permanent magnet. Experimental tests revealed absolute accuracy at the supporting point close to 2100 µm, and local deformation caused by head due to its corresponding adhesion system to be lower than 100 µm in all directions under no load condition.

2.1.2. Parallel Kinematic Machine

Three manipulator structures are compared as shown in Fig. 4, based on their ability to attain an accurate pose of the head and to support the sheet during the machining operations while the fixed platform which supports the PKM, attached to the mobile base, is docked to the bench. The manipulator structures are shown in Fig. 4 (a): (a), the head is positioned by means of three cooperating links to the PKM in a classic PKM configuration; (b) connects the head to the PKM through a serial link to form a hybrid architecture (in this configuration the head workspace is wider but the stiffness is lower than in configuration (a)); (c) shows 2 heads connected to two joints of the manipulator through a branched kinematic chain.

After having compared the performances of the competing structures, the Exechon PKM X 150 was selected and suitably modified. Exechon parallel manipulator X 150 (Fig. 4) was modified to create a hybrid architecture, where a 3-DOF RRR spherical wrist is combined with the standard 3- DOF X 150 tripod version. The hybrid mechanism provides additional orientation capability required for this specific application. A detailed analysis on the kinematics, mobility and singularities of the PKM were reported in [5,6]. A complete analytical solution has been developed [5], replacing the traditional approximation based on numerical methods to obtain the specific pose of the end-effector (MRF head). In addition to the kinematic model, stiffness modeling of the PKM using reciprocal screw theory and virtual work was developed [7] to study the stiffness map within the workspace of the manipulator. These studies [7] provide a good insight into the feasibility of the PKM to withstand the loads generated during machining operations.

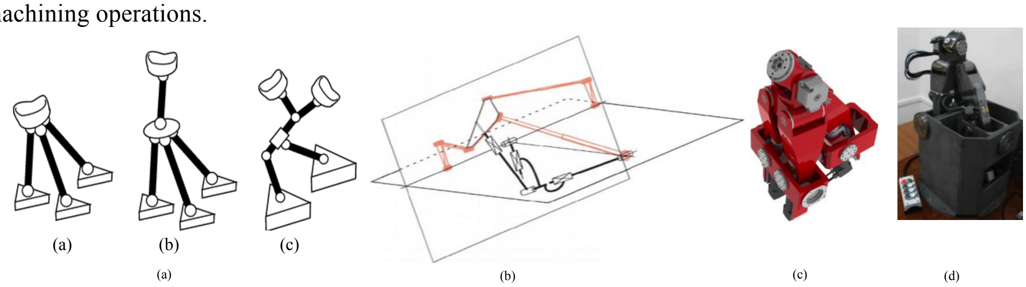
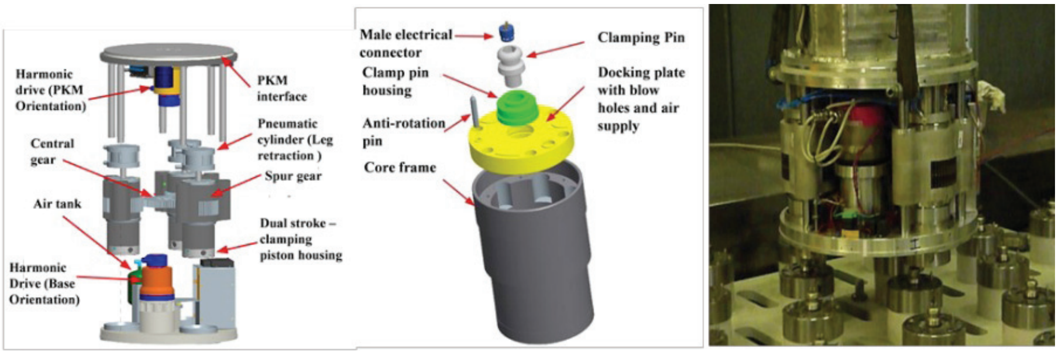


Fig. 4: a) Manipulator structures (b) Adopted PKM kinematics sketch [5] (c) PKM Virtual Model (d) PKM physical prototype



(a) (b) (c)

Fig. 5: a) Components of mobile base [8] (b) Exploded view of docking pin (c) Physical prototype of mobile base and bench

2.1.3. Mobile base and bench

The PKM is mounted on a mobile base that is able to move on the bench and to lock to it at the position needed to suitably support the workpiece. A novel locomotion method [8], where robots swing around stationary pivot pins on the bench, was invented and patented [9] in the current project. The bench is made of steel with 52 docking pin modules. The mobile base consists of three legs placed at the vertices of an equilateral triangle. For movement of the robot, rotations of 60° are performed around one of the legs while the other two legs are disengaged and lifted from the docking pins. A pneumatic cylinder with a stroke of 45 mm which can be traversed in 0.5 seconds lifts the legs from the bench. Electric and pneumatic supply is available to the robot through the docking pins. This forms a cable free environment and hence contributes to a Plug and Play type robot system. A central harmonic gear drive and a spur gear mechanism (Fig. 5a) are used to transfer the motion from the actuator system to rotary motion of the legs around the docking pins. Rotation is around only one leg, the clamping force between the leg and the pin has to be greater than 10 kN. The docking pin (Fig. 5b) components provide the necessary holding force of 75kN and draw in force of 18kN [10] with accuracy close to 0.005 mm. The pin design also permits engaging the robot even if it tilts by an angle or with eccentricity. The base contributes for the high positioning accuracy of the robot without the need for an external sensor network and complex control system. The bench also employs a device to blow the swarf generated during machining before the leg engages, hence maintaining a dust-free environment for the docking pins. The physical prototype manufactured is displayed in Fig. 5c.

2.2. Control Architecture

The architecture of the designed system was conceived using the concept of an embodied agent. This concept stems from the general definition of an agent [11] and the physical grounding hypothesis [12]. Subsequently it was formalized by providing an adequate symbolic notation for the description of its structure and activities, e.g. [13]. Each agent has its unique control subsystem and zero or more real effectors and real receptors as well as virtual effectors and virtual receptors. Real effectors and real receptors are hardware devices influencing the environment and acquiring information from it, respectively. Virtual effectors are responsible for representation of the real effectors to the control subsystem in such a way that it is easy to express the task at hand. Virtual receptors aggregate the data gathered by the real receptors. The control subsystem obtains data from the virtual receptors and commands the virtual effectors in such a way that the task is executed. The activities of each of the mentioned subsystems is described in terms of finite state machines switching behaviors, which follow one general pattern parameterized by specific transition functions. Control subsystems of different agents can communicate with each other, thus multi-agents systems can be created.

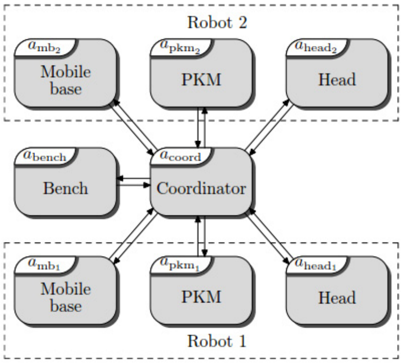


Fig. 6: Logical structure of the multi-robot fixture system

The SwarmItFIX fixture is an example of a multi-effector, multi-agent, multi-robot system. The decomposition of the system was guided by the task that had to be accomplished and the fact that the devices constituting the system were developed separately, thus separate testing was required. Hence each robot consists of three effectors: mobile base controlled by the agent a_{mb}, manipulator controlled by the agent a_{pkm} and the head controlled by the agent a_{head}. Fig. 6. Logical structure of the multi-robot fixture system shows the logical structure of the system. Each of those agents, besides its control subsystem, has one virtual effector controlling the corresponding real effector (i.e. either the head or the PKM or the mobile base). The plan of motions [14,15] is delivered by the operator to the system coordinator a_{coord}. It controls both the agent governing the activities of the bench a_{bench} and as many triplets of agents a_{mb} , a_{pkm} and a_{head} as there are robots in the system.

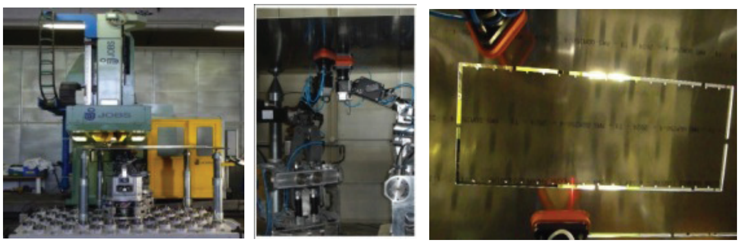
Reconfigurable fixture is programmed by supplying CAD definition of the work piece and the CAM data describing the machining process to the off-line planner [16,17]. Out of this data the planner generates the positions of the robots and the locations of the supporting heads. The off-line planner is invoked only once per work piece type. It decomposes the CNC-tool trajectory into segments. The path planning problem is converted into a discrete constraints satisfaction problem [11]. A classic CSP is defined by means of domains of variables and a set of constraints. A solution to CSP is every assignment of values to all problem variables fulfilling the constraints.

The off-line path planner consists of a supervisor that exercises overall control over path and time plan creation. Three hierarchically arranged modules execute three stages of path planning corresponding to the actions of the three parts of the each robot (head, mobile base and PKM). Each one of them uses incremental search within the corresponding domain (a depth-first strategy with backtracking), to find head locations, mobile base translocations, and PKM trajectories, respectively. The path planner explores physical and geometrical constraints. Hence, the plan, if produced, satisfies all known constraints, although it may not necessarily be an optimal one. The triangular heads have to be located in such a way that they are not too far from each other and the border of the work piece. They need to be relocated fast enough so that the machining tool does not damage them or the work piece does not become too flimsy in the vicinity of machining. Motions of PKMs are preferred over motions of mobile bases, but if the head location runs beyond the PKM workspace the mobile bases have to be translocated. While performing base translocations, PKMs have to be folded to avoid collision between each other and the work piece. All those factors are expressed as the above mentioned constraints.

The coordinator a_{coord} on the basis of the downloaded plan effectively controls the behaviors of the supporting robots in both drilling and milling operations. The plan contains commands for all the agents of all robots present in the system: $a_{\text{mb}i}$, $a_{\text{pkm}i}$, $a_{\text{head}i}$, where i is the designator of a particular robot, as well as the bench agent a_{bench}. The agent ambi lifts the robot and rotates it, subsequently locking onto the bench pins. The agent $a_{\text{pkm}i}$ extends or withdraws the PKM, thus moving the head. The agent $a_{\text{head}i}$ either solidifies the head or makes it soft and uses vacuum to attach the head to the work piece. The agent a_{bench} operates the valves delivering the high pressure air through the pins and turns on/off the electric power delivered to the robots through the pins. It is also responsible for blowing off the chips from the bench.

3. Implementation of the Pilot

The pilot prototype was setup at the Piaggio Aero Industries SPA (Fig. 7), Finale Liguria [18]. Most of the test experiments were performed on the P180 airplane parts. The SwarmItFix bench was installed under the 5-axis Jobs CNC vertical machine center for the entire period of the testing phase and was not subject to any relocation. An overbench to hold fixtures was installed above the SwarmItFix bench with the aid of the docking pins, this was to ensure the normal shift operation of the plant without altering the test environment. The pilot prototype encompassed: a fully functional workbench with integrated pneumatic and electric supply, two functional robots consisting of a mobile base, Exechon parallel manipulator and an MRF head, 4 passive supports with adaptable head and vacuum cups to constrain and position the workpiece.



(a) (b) (c)

Fig. 7: (a) Final setup at Piaggio Finale; (b) Fixturing of sheet metal by the robots; (c) Trial of drilling and milling demonstration

3.1. Selection of Prototypical parts

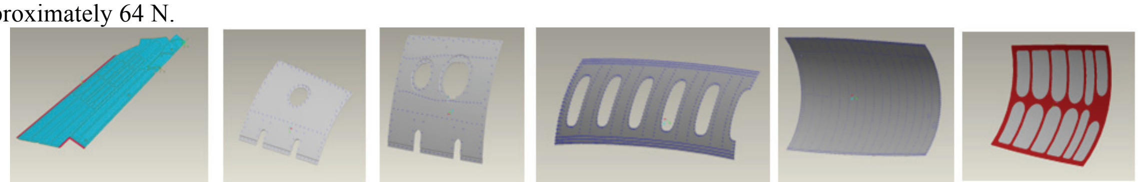
Six different candidates were examined for the selection of the appropriate prototype sample for testing the effectiveness of the pilot flexible fixturing system SwarmItFix; Vertical fin panels, Left sub-wing fuselage, Right sub-wing panel, Skin assembly window, Lower skin, Skin assembly upper cabin (Fig. 8). These candidates were representative of aircraft body panels manufactured

The vertical fin panels are installed at the end of the aircraft body for providing stability for the aircraft by controlling the yaw. The maximum cutting force applied during contouring is about 30 N.

The left and right sub-wing fuselage panels have almost the same features where they have symmetric geometry and equal number of openings and pockets. The rectangular profile makes contouring easy. Fixturing space is reduced due to the presence of an oval opening in the center. The milling cutting force is in the order of 36 N. The quantities of holes in these parts are quite high.

Skin assembly window is a symmetric part with comparatively high stiffness, reducing the effort of fixturing. The large openings located along the panel limits the fixturing space available. The milling cutting force is in the order of 100 N.

Lower skin geometry is almost rectangular simplifying the process of contouring. They also have simple manufacturing processes but have very low stiffness making fixturing relatively hard. Maximum milling force is approximately 64 N.



(a) (b) (c) (d) (e) (f)

Fig. 8: (a) Vertical fin panel; (b) Left sub-wing fuselage; (c) Right sub-wing panel; (d) Skin assembly window; (e) Lower kin; (f) Skin assembly upper cabin (Courtesy: Piaggio Aero)

Table 1. Stock sheet properties of prototypical parts

Properties	Vertical fin	Left sub-wing fuselage	Right sub-wing panel	Skin assembly window	Lower skin	Skin assembly upper cabin
Material	Al 2024-T3	Al 2024-T62	Al 2024-T62	Al 2024-T42	Al 2024-T42	Al 2024-T42
Overall rough size	2800 mm x 1100 mm	600 mm x 700 mm	600 mm x 700mm	3500 mm x 600 mm	3500 mm x 1200 mm	1500mm x 2800mm
Original thickness	3mm	4 mm	4mm	2.3 mm	1.27mm	2.03 mm
Manufacturing processes FRONT	Chemical etching Contouring Holing	Chemical etching Contouring Holing Opening of windows	Chemical etching Contouring Holing Opening of windows	Chemical etching Contouring Opening of windows Holing	Chemical etching Milling Contouring	Chemical etching Contouring
Manufacturing processes REAR	Chemical etching	Chemical etching	Chemical etching	Chemical etching	None	None
Stiffness estimate	Compliant, large deflections when shaken	Comparatively very stiff	Comparatively very stiff	Comparatively stiff due to curvature and dimensions	Compliant, large deflections when shaken	Compliant, large deflections when shaken
Max curvatures	0.0003 mm $^{-1}$	0.0011 mm $^{-1}$	0.0011 mm $^{-1}$	0.0011 mm $^{-1}$	0.0011 mm $^{-1}$	0.00117 mm $^{-1}$

Finally the skin assembly upper cabin, this part is not subject to CNC machine operations. The part has no holes and only pockets, which are obtained by chemical etching process. The stock sheet metal details of all the candidate materials are as shown in Table 1.

3.2. Selection of Prototypical parts

All the 6 prototypical parts are compared based on the overall dimension, shape, manufacturing process, fixturing requirements and geometric curvatures. Two parts emerge ideal for the analysis purpose: the vertical fin panel and left side sub-wing fuselage panel. The characteristics of the comparison are as follows:

1. Overall dimensions are different for the two parts.
   - Vertical fin panel : 2800 mm × 1100 mm
   - Left side sub-wing fuselage: 600 mm × 700 mm

2. Variance in shapes is high among the two choices
   - Vertical fin panel : Irregular shape and contour
   - Left side sub-wing fuselage: Regular shape alike a rectangle with central opening

3. Manufacturing processes involved are typical to the common process involved in aircraft and automobile manufacturing
   - Vertical fin panel: Chemical etching, contouring
   - Left side sub-wing fuselage: Chemical etching, contouring, holing and opening of windows

4. Geometric curvatures of the vertical fin panel is the least among the candidate parts and the left side sub-wing fuselage has a higher curvature, although the skin assembly upper cabin has a slightly bigger average curvature but the overall dimension is much smaller for the left side sub-wing part.
   - Vertical fin panel: 0.0003 mm^{-1}
   - Left side sub-wing fuselage: 0.0011 mm^{-1}

The reference parts were chosen to conduct all analyses during the development phase of the project. During the testing at Piaggio Aero, test workpiece similar to the analysis geometry was chosen, a subwing fuselage panel and lower skin panel (**Errore. L'origine riferimento non è stata trovata.**). Three different experiments including through-all milling (windowing), blind – plunge milling (pocketing) and drilling were performed with a five-axis CNC machine to prove the effectiveness of the proposed concept. The corresponding tools used were a HSS mill with 10 mm diameter (windowing) and Sandvik plunge mill CoroMill 316 20 mm diameter (pocketing). The measurement parameters for the tests include: deviation of the machined trajectory from the nominal trajectory in mm. Sheet metal of 1.2 mm thickness is considered as in the test workpieces. A Micro – Epsilon OPTO NCDT 1402-200 laser displacement sensor is used with a class 2 laser, powered by 24 VDC, 13 μm of resolution, 180µm of linearity and a measuring rate of up to 1.5 kHz. The laser sensor is connected to a laptop using a data acquisition card. A mechanical interface was designed to support the laser sensor with close proximity to the cutting tool in the CNC. The test results are as described in the following sections.

4. Pilot Test

Detailed test results have been reported in [18]. The orthogonal stiffness of the fixture is observed to be higher than 1 N/µm which is higher compared to the modern day Modular Flexible fixture system (MFFS). The setup time to reconfigure the new part is lesser than 5 minutes which contribute to the state of art in fixture. Adaptable robot head as discussed above can be repositioned by robot in 60 seconds and also has the capability to extend from planar fixturing to orienting in 3D space for complex work-profiles. All these suggest that SwarmItFix, while presenting innovative characteristics of adaptability also satisfies aircraft manufacturing standards. A brief summary is provided below also with the trial results displaying the effectiveness of the system.

4.1. Drilling

Drilling is the foremost important operation in sheet metal fabrication. Especially in aircraft manufacturing, rivets, bolts and other fasteners provide high structural integrity. Fixtures play a great role to maintain the centering of the holes, damping of bending vibration, and provide positioning accuracy of the fixture tangential to the workpiece drill operation.

A test sheet metal of dimension 800 × 600 × 1.2 mm was used for the experiments. For repeatability 50 trials were performed on same dimension sheet metals where 100 equally spaced 5 mm holes were drilled. A maximum position error of 0.11 mm was observed with average error around 0.08 mm. The deviation from the allowed position error was just 0.01 mm for the worst case condition and on average the accuracy was well within the tolerance limit of 0.10 mm.

4.2. Pocketing

For the pocketing operation, 50 experimental trials were performed on sheet metal of dimension, 500 × 500 × 1.2 mm to machine a 0.8 mm square pocket of 100 × 100 mm. The pocketing operation is generally carried out by chemical etching in the normal procedure. For experimentation the operation is carried out by the 5-axis CNC machine. The pocketing operation was followed by laser measurement of the contour. As mentioned earlier the laser sensor is mounted on the 5-axis CNC tool handle, where the scanning is made along two directions; one along the feed direction and the other perpendicular to it. Three scans are made in each direction representing a strip, where the strip starts and ends in the opposite edges of the pocket. Each strip was subjected to two trials. If there were deviations of more than 10% in the readings, an additional trial was conducted. The peak-valley distance is measured as the test parameter. Experiments indicate peak-valley distance of 0.09 mm along feed direction and 0.12 mm along the direction orthogonal to the feed direction. Chemical etching process provides higher accuracy, but SwarmItFix supports High Speed Machining (HSM) process, which is more environmental friendly compared to chemical etching based pocketing.

4.3. Windowing

Windowing: through- all milling of dimension 200 × 200 mm is performed on an 800 × 600 × 1.2 mm sheet metal. Laser measurement of the window contour is performed providing insight of the parallelism of the opposite edges of the contour and the error between the machined contour and the nominal profile.

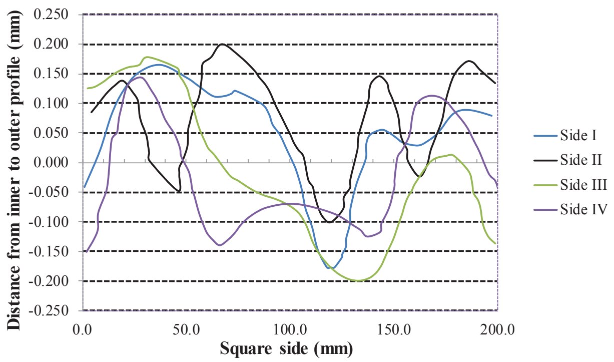


Fig. 9: Through - all milling results

As reported in [18], the distance observed (Fig. 9) between the two limiting profiles is 0.4 mm. The deviation is close to the acceptance criteria.

4.4. Further Achievements

The realized PKM was exploited by the Exechon partner in a high efficient multiple spindle drilling (Fig. 10) and assembly system giving a significant contribution to a technology that allows multiple spindles to operate at the same time over a limited area. This technology was chosen by an aeronautical manufacturer for its flexibility and compatibility. The patented locomotion of the base has also been proposed to be used as an industrial Material Handling Agent [19].

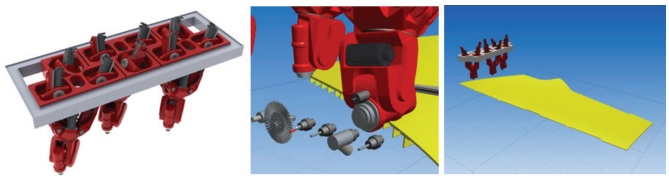


Fig. 10: Multiple spindle PKM (Courtesy: Exechon)

5. Conclusion and Future Work

The article discusses a novel flexible concept of manufacturing fixture systems. A short presentation of the evolution of the design of the hardware and control part is provided in a chronological order. The implementation of the SwarmItFix pilot and the test results are provided giving an insight into the feasibility of the proposed system in a real world manufacturing application. The SwarmItFix is further proposed to be implemented in a much wider application of robotized hemming and for generalized material handling systems. Future work will explore the application of the system in a much wider domain in the manufacturing sectors. Further the authors aim to improve the ability of the pilot fixture to interface and cooperate with other manufacturing resources.

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