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DEVELOPMENT OF A PROGRAMMABLE WORK-HOLDING FIXTURE FOR LASER WELDING OF SOLAR ABSORBER SHEETS

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Abstract: *Production of solar absorbers in significant quantities relies on laser welding of large, thin, aluminum sheets. Dealing with multiple product variants requires setup time minimization of the laser welding machine while preserving product quality. A mechatronic work-holding fixture was developed as a solution to this problem. The ultimate aim is to replace the manual setup method completely. The latter was documented first, accompanied by user requirements and resulting technical specifications including geometric limits and range of motion. The proposed design was developed and optimized using CAD simulation. In addition, a software interface was designed to allow fixture configuration based on just the necessary dimensions of solar absorber variants. Fixture tests proved achievement of desired precision and substantial reduction of setup duration.*

Key words: *work-holding, programmable fixture, microcontroller, laser welding, sheet metal*.

1. INTRODUCTION

The widespread use of CNC machine tools along with the introduction of information technologies in production plants have led to the shift from the model of mass production to that of mass customization. Today's manufacturing plants are driven to produce a significant number of smaller batches of different products or their variations using economically efficient methods while retaining high quality in order to remain competitive. Manufacturing flexibility is safeguarded not only be CNC machines and robots as material manipulators, but by programmable fixtures that can accommodate product variations [1].

Recent developments are evidenced in the large number of filed patents of various technologies of modular fixturing and fixturing automation usually tailored to a specific case of a part family and accompanying financial limitations. Meanwhile, there has been increasing interest in academic research towards reconfigurable fixturing technologies – more costly in general – incentivized by the advances in actuation and sensing technology [2, 3]. Among the four emerging design strategies for automatically reconfigurable fixtures of particular interest are those of *Cartesian Coordinate Concepts*, which, being the easiest to control and most compact, are widely used in assembly and machining stations [4–9].

This paper presents the development and validation of a mechatronic work-holding fixture for a laser welding station for large thin sheets. Related work is presented next in Section 2. The developed solution is intended as a single unit replacement to the multiple parts and tools used by the operators when manually adjusting the loading table. In Section 3, the Setup Planning is conducted by analyzing the previously manual fixturing method. In Section 4, the Fixture Planning and Fixture Configuration Design is presented and the proposed solution is finalized. In Sections 5, the assembly, testing, and performance evaluation of a prototype are presented, which constitute the Fixture Design Verification stage. The pertinent conclusions and further work suggestions are outlined in Section 6.

2. RELATED WORK

The reduction of the setup duration and the costs associated with both the setup itself as well as the design, manufacturing, and handling of individual fixtures and jigs constitute the main advantages of an automatically reconfigurable fixture system. Regardless of its type, a fixture has to fulfill three basic functions [3, 10, 11]. The first is the *locating* of the workpiece in a desired position and orientation using elements called *locators*. The second is the *holding* (fixating) of the workpiece with elements capable of exerting forces, called *clamps.* The third is *supporting* the workpiece by preventing elastic and plastic deformations by supporting elements, which might also contribute to the stability of the whole system.

For a fixture to meet the demands of a flexible manufacturing facility, additional specifications may be desired. Specifically, the reconfiguration times have to be low enough to be an effective replacement of conventional fixtures. At the same time, locating accuracy should be retained in every configuration. Of equal significance is the degree of adjustability, which, although dependent on the facility's needs, should be as high as possible. However, the fixture also has to allow for realignment and manipulation of the workpiece should corrections or intervention be required. These

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specifications can be achieved either manually or automatically. If mechatronic technology (sensors, actuators, control systems) are available, two additional capabilities are possible. Firstly, the clamps and supports can be reconfigured during the manufacturing process i.e. the fixture layout can be (re)optimized. And secondly, the clamping forces can be actively controlled to minimize the deformation in the part-fixture system due to the clamping forces [2].

Multiple attempts have been made to establish a taxonomy of the multiple fixturing technologies currently in use. In general, nine different concepts of fixtures can be distinguished [3, 11, 12] of which *Automatically Reconfigurable Systems* constitute a separate group. The other eight groups, mentioned for completeness, are *Modular Fixtures*, *Flexible Pallet Systems*, *Pin-Type Array*, *Sensor-Based Fixturing*, *Phase-Change*, *Base Plate Concepts*, and *Other Fixturing Concepts*. In particular, notable for some similarities pertaining to Automatically Reconfigurable Systems are the Modular Fixtures and the Pin-Type Array. The first are constructed using standard elements and *modular fixture elements* connected with universal connection methods such as "T-slots" and "holes" [9, 13, 14]. Their main disadvantages are their cost and in some cases sub-standard location accuracy pertaining to inaccuracy during the assembly of the fixture. The second concept is based on a bed of pins, and are also called "conformable" or "reconfigurable" in some publications. Via actuated or passive methods, the tip of each pin is positioned appropriately in the axial direction in order to support and locate the workpiece [15–17].

The group of Automatically Reconfigurable Fixtures, in its turn, can be further distinguished into four main concepts. The first are those that can be assembled or *reconfigured by means of robot systems*. A robot places the fixture elements on a base plate or magnetic chuck [9, 18–21], similarly to modular fixtures, with the fixture accuracy consequently depending on the positional accuracy of the robot. Of the *self-reconfigurable* concepts the first are those employing *dexterous grippers* to grasp and hold the workpiece [21, 22]. Often used in micro-machining, their positional accuracy and load bearing capacity for larger objects is comparatively worse. The remaining two concepts are those of *Parallel Kinematic Mechanisms* (PMKs) and *Cartesian Coordinate Concepts*. PKMs are mainly employed as assembly fixtures and involve one or more Stewart platforms as locating points for the workpiece [19, 20, 23–25]. Although they can provide better positional accuracy and stiffness than Cartesian concepts the latter are easier to control and more compact. Cartesian concepts involve components on a baseplate moving in independent directions to arrange the clamping and supporting elements accordingly [4–9].

The design process of a fixture for a specific product group or process has been categorized in four stages [3, 10, 11, 13]. Initially, during the *Setup Planning*, possibly in tandem with product design, the workpiece orientations, order of processes, and common reference points between product variations are established and the part-fixture setups determined. Following is the *Fixture Planning* during which locating points are selected from the designated reference geometry. During *Fixture Configuration Design* a kinematic restraint analysis is conducted to determine the validity of the locating scheme, a deformation analysis might be required to place additional supports, and lastly the suitable clamping locations are determined considering factors such as tolerance specifications, collision avoidance, and feasibility. During *Fixture Design Verification* the performance of the design is validated and analyzed.

In this work, the design and validation of a programmable/reconfigurable fixture that may be loosely classified into the Coordinate concept is presented.

3. MANUAL SETUP ANALYSIS

Solar absorbers are manufactured by welding copper tubing on aluminum absorber plates. The copper tubing consists of two header tubes running along two opposite edges, connected with multiple perpendicular riser tubes of smaller diameter. The dissimilar metal joining of copper and aluminum is achieved using a pulsed laser. The welding is performed along the length of each riser's line of contact with the panel. Two laser beams apply heat in pulses pointing symmetrically at a low angle on points along the line of contact. The two laser heads are suspended over the loaded table from a gantry system and are guided during welding by a "U-slot" wheel rolling on the riser. The panel is always loaded in the same orientation – its oblong side parallel to the table's oblong direction (Y) – and the risers can extend either along or across the panel; therefore, the laser heads' linear motion might be along either the *X* or the *Y* axis. This arrangement can be seen during operation in Fig. 1.

The machine possesses two loading tables; part loading on one table is performed while welding is taking place on the other. The manual loading procedure is performed by two operators by placing (locating) the absorber panel, locating the copper tubing over it and finally clamping them. An assortment of the necessary locators, clamps, and other fixturing components for the product variant at hand is selected and installed by the operators during the machine setup of the batch changeover.

The locators used for the tubing are hooks, see (A) in Fig. 2, and steel blocks, see (B) and (E) in Fig. 2. Locators used for the panel are an array of evenly spaced guides, see (C) and (G) in Fig. 2 and thin steel blocks, see (D) in Fig. 2. As regards clamping, custom made flexible "pivot hold-down clamps" are used, see F) in Fig. 2, so that the headers are not locally deformed by the clamping force.

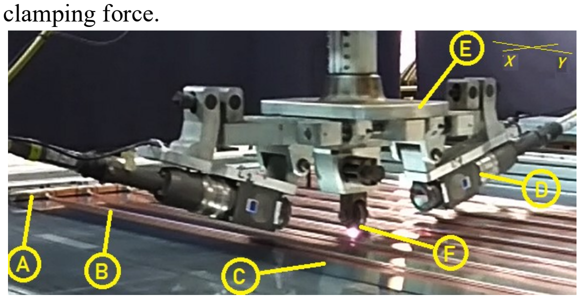


Fig. 1. Laser station (A – header tube, B – riser tube, C – thin sheet panel, D – laser head, E – gantry carriage, F – laser carriage wheel).

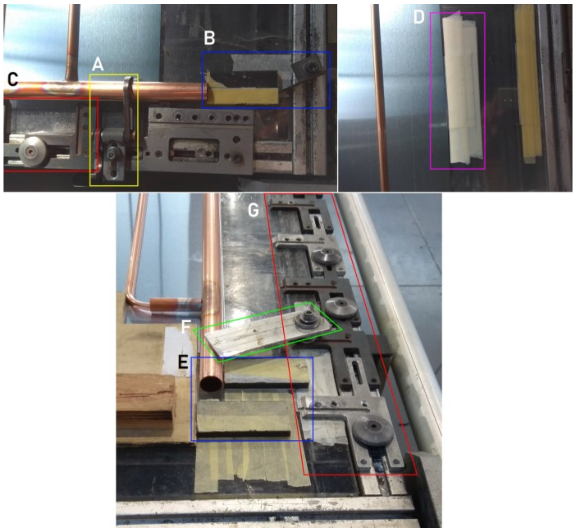


Fig. 2. Manual fixturing components (A – header hook locator, B & E – a header block locator supported by a fastened support element, C & G – one row of evenly spaced panel locators, D – a panel side's thin block locator affixed with adhesive tape, F – a custom pivot hold down clamp).

Clamping along the headers is necessary to ensure the retention of proper riser form during welding, which would otherwise be compromised by warping due to the intense local heating. The steel blocks are fixed on the table surface with adhesive tape and the hooks are screwed with fasteners in the table's "T-slot" extruded aluminum framing. Additionally, instead of the framing at one edge of the table, components can be placed on an installed "T-slot" aluminum bar – its ends fastened on the table's two long edges' framing.

Although the machine setup might differ from product to product, after recording the steps followed for every product variant and identifying the common underlying principles through *Hierarchical Task Decomposition*, a generalized setup procedure has been extracted. In a batch changeover, the machine setup can start once the operators have received the required product dimensions with the production command. The generalized manual setup procedure has been formulated as follows.

A. All the necessary fixture components and tools for their installation are gathered. These can include additional block locators for the tubing and panel, the header hooks, and clamps already present on the table, and in the case of absorber strips, instead of panel, the gauges of right length with which the panel guides' spacing is adjusted. The laser heads' wheel might also need to be replaced with another with a different "U-slot" radius.

B. Next, the present and additional components are arranged and adjusted on both tables.
   i. The additional bar – and its mounted components – is transferred, removed, or installed, so that by placing a panel on the table the tips of every row of panel guides are aligned with the panel's two short edges.
   ii. Afterwards block stops are added at the panel's two longest edges thereby completely framing the panel with locating components.
   iii. In the case of absorber strips instead of a single panel the panel guides' spacing needs to be adjusted. One by one, from left to right (from the operator's point of view), by inserting a properly sized gauge between two panel guides they are all fastened at their new positions so that they frame properly each fin's two ends when all of them are placed.
   iv. At this point, the copper tubing can be placed on top of the panel and manually positioned. After the risers are inspected and it is confirmed they are not skewed the block locators at the header exits are placed, one side at a time. The blocks are fixed using two-sided tape and further supported with components fastened at the table's aluminum framing.
   v. The four hook locators are arranged at each header's two ends, hooked, and subsequently fastened.
   vi. The hold-down clamps are placed at regular intervals along each header. Their height, and therefore the clamping force, is adjusted by adding or removing spacers.

In the case of a "horizontal" solar absorber (i.e. the headers run along the panel's two long edges) the above steps are executed as described but rotated by 90°.

C. Once both the tubing and the panel are securely held the laser program can be loaded (frequency, velocity, acceleration, etc.). The specific product's laser configuration file is stored at the station's computer. If a batch of the same product has been produced in the past the program is retrieved, otherwise a similar one is used and adjusted or a new one is created and stored for future use.

D. Subsequently the required offset for the laser heads to move safely down and weld along the first riser can be specified. The laser program is executed step by step from the beginning up until the laser heads are lowered on the first riser. The right offset value to center the "U-slot" wheel on the first riser is determined through trial and error.

It should be noted that not all the above-mentioned actions have to be performed in a strict order. The only essentially interdependent steps are the locating of the panel, the locating and clamping of the tubing, and the laser offset configuration. As long as locating and clamping are executed correctly (e.g. first locate the panel's short sides before the long sides, etc.) other tasks such as tool collection, laser program loading, removal of unused parts, or replacement of the laser wheel may be carried out concurrently.

4. WORK-HOLDING FIXTURE DESIGN

The mechatronic fixturing system should replace the manual fixturing process for all possible variants of the products, hence exhibiting reconfigurability. In particular, the following technical requirements were specified:

(a) Restriction of the panel's planar slip (in both X and Y directions).

(b) Proper location of each header relative to the panel and restriction of planar slip.

(c) Sufficient restriction of vertical motion (Z direction) of each header.

(d) Header-to-header distance at least 1200mm and/or header length at least 900mm.

In addition, the fixture is subject to the following constraints:

(a) It should not collide with station's parts or other components during table change.

(b) It should not collide with the laser heads during operation. (c) It should be possible to install on the currently used tables.

(d) Allow for easy and safe manual access should the need arise.

The proposed design can be seen in Fig. 3. It consists of two systems, i.e. one for the panel and one for the tubing. Four rotating locators are used for the panel, see item A in Fig. 3 and Fig. 4,*a*, namely two on an oblong and two on a short edge of the table. A Cartesian coordinate mechanism is employed for the tubing. Pivot hold-down clamps similar to the ones already used in manual setup are mounted along the table's two edges and the cartesian coordinate mechanism's aluminum bars, see item B in Fig. 3. All components are mounted on the table's aluminum frame, see item D in Fig. 3, arranged in the collision free space inside the bounding box according to the stated constraints.

The table's footprint is unaltered as no parts of the fixture protrude past its edges and the electrical wiring is channeled through the table frame's 'T-slot' tracks. The clamps and the panel locators can be unfastened and translated along the edges, although this is not a part of the setup procedure.

In total, 8 stepper motors are installed on the table, namely 4 for the cartesian coordinate mechanism's two bars, see items E and J in Fig. 3, and another 4 for the two pairs of panel locator elements, see item C in Fig. 3.

All the motors are the NEMA 17, with an angular step of 1.8°, rated voltage of 3.12 V, rated current of 2.5 A, holding torque of 480 mN·m, and detent torque of 27.5 mN·m.

Locating of the copper tubing is achieved with four moveable "corner-locators" which frame it, see item F in Fig. 3. Their positioning is achieved with the cartesian coordinate mechanism which consists of two perpendicular, planar moving bars (X and Y denoting motion in the respective directions) of extruded aluminum profile, see items G and K in Fig. 3. Each bar spans the whole width or length of the table and is driven at its ends via lead screws, see item H in Fig. 3, by two stepper motors at the corners of the table. The first of the corner-locators is fixed, whilst the second and third move along the *X* and *Y* directions following the motion of the respective bars, and the fourth functions as a connector at the intersection of the two bars moving accordingly along both *X* and *Y* directions. Thus, the "corner-locators" bounding frame for the copper tubing is formed by moving two perpendicular bars along the two cartesian directions.

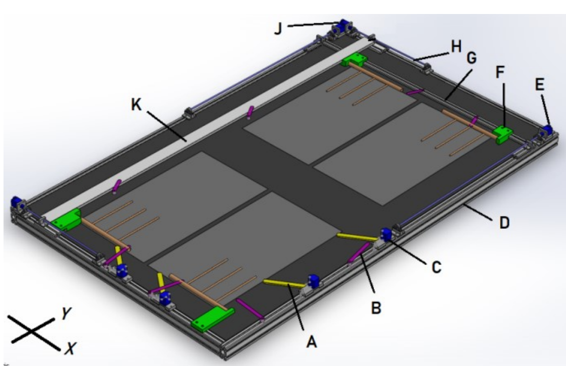


Fig. 3. Designed fixture (solar absorber is only partly shown for simplicity; A – panel locator, B – pivot hold-down clamp, C – panel locator motor, D – frame, E&J – cartesian mechanism motor, F – corner locator, G – cartesian mechanism X bar, H – lead screw mechanism for K, K – cartesian mechanism Y bar).

The stepper motors driving the bars are mounted on custom bases, see Fig. 4,*b*, which are fastened on the aluminum frame, see item D in Fig. 3. At their other end, the lead screws are supported by a bearing block mounted on another custom base on which a limit switch resides, see Fig. 4,*b*. The limit switches signal the bar end's farthest position which serves as reference position during "homing".

The use of lead screws offers two main advantages. The first is the significantly less space occupied compared to any planar link mechanism and the second is the huge detention force due to the high gear ratio, similar to a worm gear. The bars cannot be accidentally manually moved by applying force to them, as it is not possible to rotate the lead screws by such linear motion.

Furthermore, due to the use of stepper motors the absolute positioning of moving parts cannot be determined directly. Instead, at the start of every setup a homing procedure is performed as is customary in incremental positioning CNC systems.

Because the custom bases support the main driving components of the mechanism a strict enough geometric dimensioning and tolerancing was imperative for the surfaces in contact with the motors' faceplates. These tolerances were tight enough to avoid misalignment and bending of the lead screws.

In order to minimize wear due to friction at regions of relative motion between moving parts, POM sliders were used as seen in Fig. 4,*c*. Such regions are located

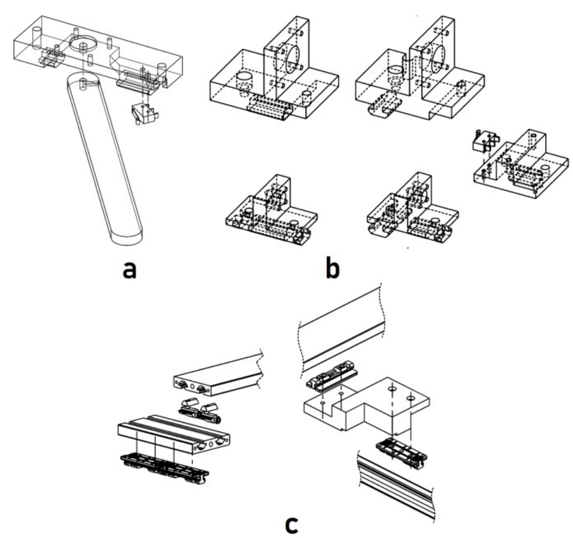


Fig. 4. Component details: *a* – rotating panel stop sub-assembly; *b* – custom bases for stepper motors, bearing blocks, limit switches; *c* – POM sliders between extruded profiles.

between the two bars and their connector, and between each bar's ends and the table's frame.

The exact positioning and dimensions were determined during detail design in CAD by ensuring collision avoidance with the station's other components and laser heads which were incorporated in the motion simulation for this purpose.

The table's wiring is connected automatically once it moves into place with the controller, stepper drivers and power supply, via an array of spring-loaded contacts and connectors, so called "pogo-pins". This was necessary due to the way tables are switched. The loaded table moves forward towards the welding station while the other – returning from welding to be unloaded and reloaded – rises from below to replace it.

A fixture configuration program with graphical user interface has been constructed to allow inputting the required product dimensions. These dimensions are shared among all product variants (Fig. 5,*a*).

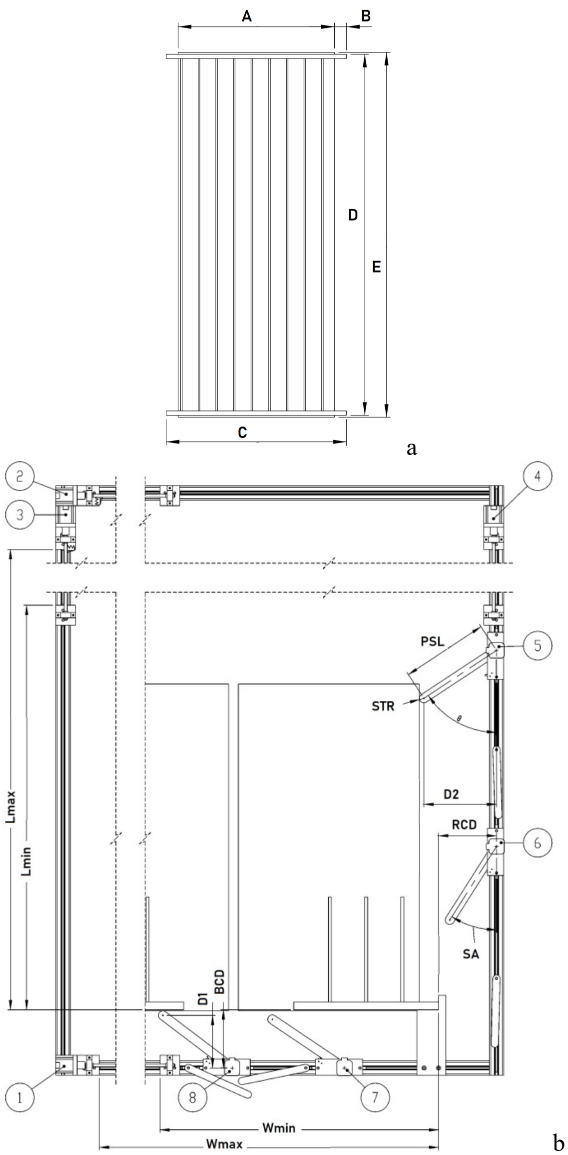


Fig. 5. *a* – Typical product dimensions needed to configure the fixture (A – panel width, B – header exit length, C – grid width, D – grid length, E – panel length); *b* – required geometrical properties of the fixture (motors numbered 1 to 8).

The program calculates the required rotation for every stepper motor to be actuated by a microcontroller through its driver. Thus, four independent components need to be positioned, namely the two cartesian motion bars, see items G and K in Fig. 3 and the two sets (pairs) of rotating panel locators, see item B in Fig. 3. They can be positioned simultaneously or serially, actuating each component's own stepper motor pair at a time, using a multiplexer. For the calculation of each motor's rotation the geometrical properties of the installed fixture, as shown in Fig. 5,*b*, are also required by the program. In addition, an offset for every motor can be specified to eliminate any possible systematic error observed by the operators. Lastly, the program checks the validity of the input values and computed angular displacement before configuring the fixture thus functioning as a soft protection against damage due to human error.

5. PROTOTYPING

In order to confirm that the final design meets the specifications and conforms to the restrictions set, validation testing was conducted. An assembly was built consisting of one of the four rotating panel locators and one of the two perpendicular moving bars. Both components essentially perform the same motion as their omitted counterparts. Hence, the bases were manufactured on a CNC milling center while parts such as the aluminum profiles, the stepper motors, as well as their drivers were bought off-the-shelf.

To test movements, first a program was written to control the stepping motors using an Arduino™ microcontroller. The corresponding flowchart is presented in Fig. 6.

The only information required to configure this program concerns the appropriate driver pins of the motor pairs along with corresponding limit switch pins.

This program is extensible for more motors as long as their pairs and pins are specified. No micro-stepping was used.

The assembly was installed on an aluminum profile frame of the same dimensions with the station table. The arrangement of the components can be seen in Fig. 7.

During the bar's motion testing it was first homed and then ordered to move to positions at various locations along the desired range. The bar successfully performed the required motion without the motors encountering substantial resistance or skipping steps.

The microprocessor's clock speed however constituted a limiting factor for the motors' return speed during homing. This was caused by the delay due to checking the state of the limit switches after each angular step. This issue can be alleviated by slightly compromising the fairly high positioning accuracy and performing the switch checks every two or three steps, therefore doubling or tripling the bar's speed.

The panel locator fin, see Fig. 7,*b*, was fastened on the base motor's "D-shaft" and was initially tested while sliding on one corner of the aluminum frame. The fin's motion was intermittent with occasional jittering, a consequence of the inadequate torque to overcome the sliding friction between the fin and the extruded profile. When placed upside down however, with the fin sliding on the motor base, the motion was as desired. Suboptimal

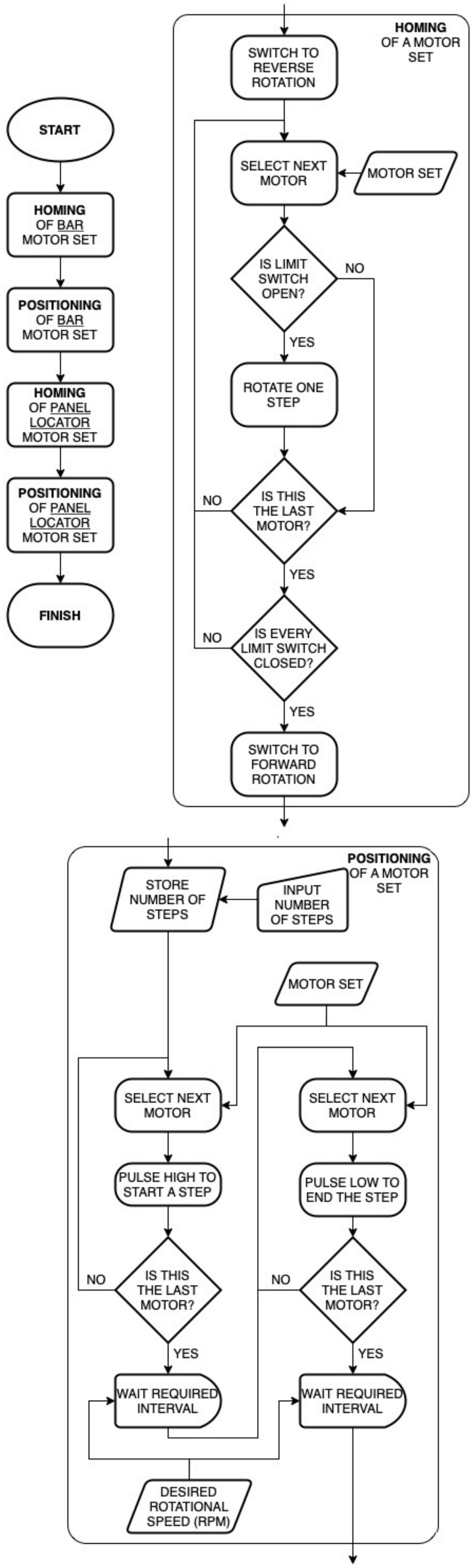
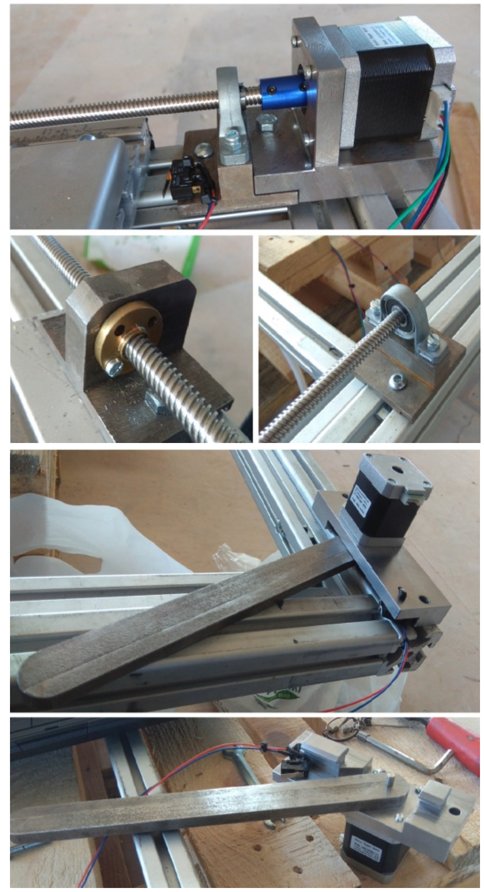


Fig. 6. Flowchart of the microcontroller program used during testing.



a

b

Fig. 7. Assembled components: *a* – the left end of the bar; *b* – the rotating panel locator.

frictional conditions in combination with the fin's weight were the main culprits in this case.

The time efficiency of this solution compared to the manual method was evaluated as follows. Only the horizontal and vertical product variations were considered for which this solution was designed. The manual setup procedure requires in every case the removal of previous components and their transferring and installation to new locations. Although this process varies significantly among product variations and even among products of the same family, the recorded times were never shorter than 5 min and, barring rare cases in which the operators might be occupied in irrelevant tasks, the longest required time never exceeded 10 min. On the other hand, the automatic procedure requires first the homing of every component and eventually their moving to the desired positions. It was assumed that the components were initially in the middle of their available position range, as would be an average of any possible starting scenario, and that they would have to be positioned at the farthest end of their range, i.e. an extreme case. Therefore, considering that the motor pairs are actuated in a sequence and that their rotational speeds are as stated above, it was calculated that the required homing and positioning durations are 1 min 54 sec and 3 min 46 sec respectively, yielding a total of 5 min 40 sec. The best-case scenario would be that in which a product with the largest possible dimensions is manufactured and

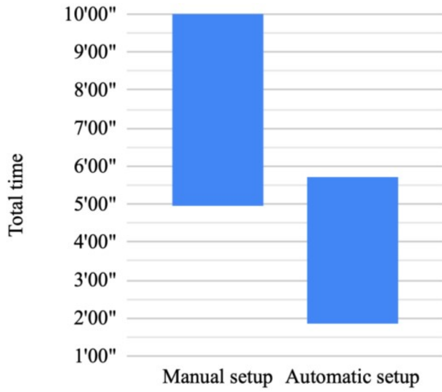


Fig. 8. Comparison between manual and automatic setup duration ranges.

therefore after the homing no further positioning would be needed, and the duration in this case would be only that of homing, i.e. 1 min 54 sec. A visual comparison between the manual and automatic setup duration is shown in Fig. 8.

Although the actual frequency of each product variation and an adequate set of measurements for their corresponding manual times are not available in order to conduct a test of statistical significance it can be observed that the automatic procedure is significantly faster even with conservative rotational speeds. Furthermore, additional time may be needed in manual setup when new fixturing components need to be added (e.g. transitioning from vertical to horizontal product type) or a human mistake might have to be corrected. It is important to note at this point that the manual setup method under consideration was performed by experienced operators.

6. CONCLUSIONS AND FURTHER WORK

After considering the prototyping and testing observations, it can be concluded that the complete arrangement of four panel locators can be used, since they function in the same manner, as well as the second perpendicular bar, the motion of which is independent of the first. As long as the connector component presents minimal friction resistance, with the use of the POM sliders, the stepper motors are capable of moving the two bars. All the components can be installed on the present station's tables with the space restrictions met, and the setup times as well as the possibility of human error are significantly reduced.

As far as the development process is concerned, it should be recognized that studying and documenting the manual setup procedure provided a much needed starting point for developing the concept of the automatic work-holding fixture as well as for implementing particular elements, such as rotating panel locators. It should also be mentioned that several alternative concepts and preliminary fixture designs were developed before the final one, which for reasons of economy of space have not been reported in this paper.

Overall, with the automatic setup not only is the possibility of human error eliminated and the positioning duration, precision, and accuracy guaranteed, but also the station does not require skilled or trained personnel, thus promoting workforce flexibility.

Regarding future improvements of the designed solution, several propositions can be made based on the testing observations. First, it is crucial that friction on every extruded aluminum profile face on which there is sliding be sufficiently reduced, e.g. by using PTFE sheets or POM. Lightening of the panel locator fin and lining it with PTFE will reduce both its moment of inertia and sliding friction component. Another possible solution would be the use of a stronger motor respecting space restrictions, i.e. retaining the same faceplate. A pertinent model of 650 mN·m instead of 480 mN·m torque does exist.

Secondly, would a controller with on-board memory running an operating system be employed, it could directly receive the product information as input, calculate the desired positions, and actuate the motors as well as be interconnected with other computers or a database. At present, the Arduino microcontroller was used as middleware, passively receiving the calculated desired steps from the station's computer and actuating the motor pairs in order while monitoring the limit switches.

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