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Fixture Planning for Multi-Workpiece Setup for Make-to-Order Industry

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Abstract: An alternative method to reduce setup time is to simultaneously carry out fixture planning for several parts in one setup planning. This is possible due to the size of parts which are relatively small to the size of the machine work bed, typically found in a make-to-order industry. This research proposed a fixture planning method for multi-workpiece setup. The fixture planning method comprised two stages: 1) multi-workpiece layout and 2) 3-2-1 pin location. An example of multiple workpiece setup is illustrated in this paper to point out the method's applicability. Future research activity will integrate the proposed collaborative human-robot assembly design system method.

Keywords: Fixture planning, modular fixture, 3-2-1 pin location.

Introduction

Make-To-Order (MTO) industry is a strategy to respond to customers by manufacturing parts based on their specifications. The nature of the MTO industry is to manufacture a wide variety of products, usually in small volumes. It is reported that 90% of the lead time relates to nonvalue-added activities [1], one of which is fixture design. A fixture is to hold and position the workpiece correctly during machining (e.g., milling, drilling). Its length of time can take 7 to 20 weeks to design, setup, and validate a fixture when human experience is utilized [2]. Its cost can account for 10% to 20% of the total manufacturing cost [3]. Its design is also required in a robot assembly process [4]. The fixture performs as a positioning and holding mechanism for the robot to assemble. Thus, it is essential to lean the fixture design activity.

One fixturing strategy to handle various products, short lead time, and well-controlled cost is to utilize modular fixture [5]. The advantage of modular fixture is derived by configuring standard holding devices and components. As shown in Figure 1, a typical modular fixture consists of a baseplate, locating unit, clamp supporting unit, and a clamp. The workpiece is set on the baseplate, positioned by dowel pin locators, and held by the clamp mechanism. Two types of baseplate are available as standard: T-slot and dowel-pin baseplate. In positioning the workpiece, T-slot baseplate is more flexible, while dowel-pin baseplate is more rigid. The pin holes are in patterns depending on the baseplate specification, which consists of the distance between the holes and the diameter of the pinhole.

This research investigated three MTO industries as case studies. The investigation revealed that up to 60% of workpieces have a dimension range less than 30% of the baseplate size. Therefore, utilization space for fixturing a workpiece is often spacious. This condition is typically found in industry manufacturing mechanical parts of various prismatic shapes [6]. Considering this deficiency, an alternative fixturing strategy to lean the fixture process is to conduct a multi-workpiece setup in a single process. The challenge to setup multi-workpieces for MTO products is that the workpieces have different shapes and dimensions enabling wide alternative combinations of possible setup.

Modular fixture design consists of four phases: 1) setup planning, 2) fixture planning, 3) unit design, and 4) verification [7][8]. Setup planning defines the number of setups required to process the whole part. A setup consists of machine operations where the workpiece is held at a specific position and orientation. Then, fixture planning is a detailed plan to locate which workpiece surfaces and fixture unit will establish a contact point. The number and position of contact points must eliminate the workpiece's six degrees of freedom during machining. A common approach to establishing the contact points is the 3-2-1 locating principle [9]. The 3-2-1 contact points will eliminate five degrees, as shown in Figure 2. Three pins are indicated as pin A, B, and C.

Two pins are indicated as pin D and E. The remaining pin is indicated as pin F. A clamping unit eliminates the remaining freedom. After that, the third phase is to select the modular fixture unit available at the site or catalog. In a fixture unit, all components are connected one to another where only one is in contact directly with the fixture base, and one or more are in contact with the workpiece serving as the locator, clamp, or support [10].Finally, the verification phase is to ensure the fixture design satisfies the fixturing requirements [11].

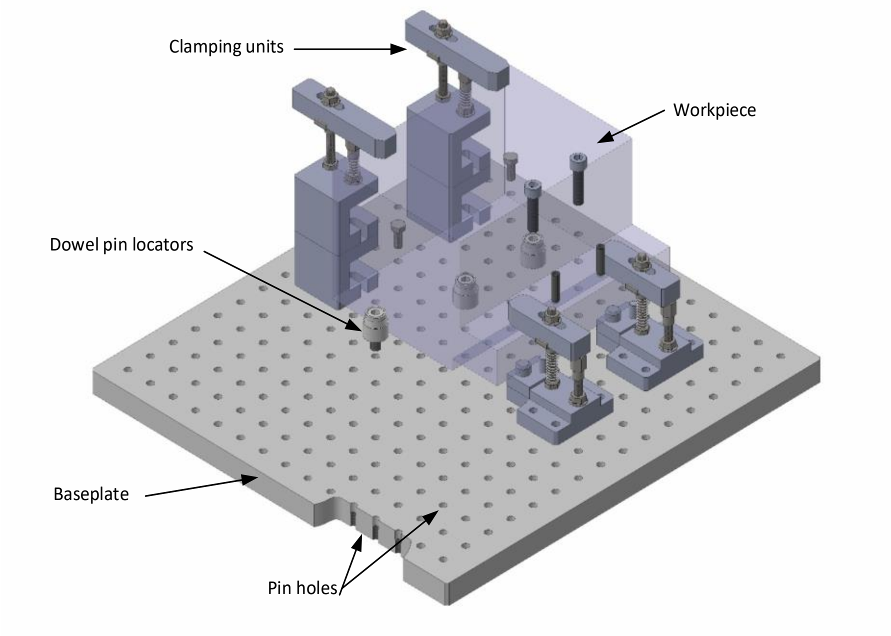

Figure 1. Example of a typical modular fixture

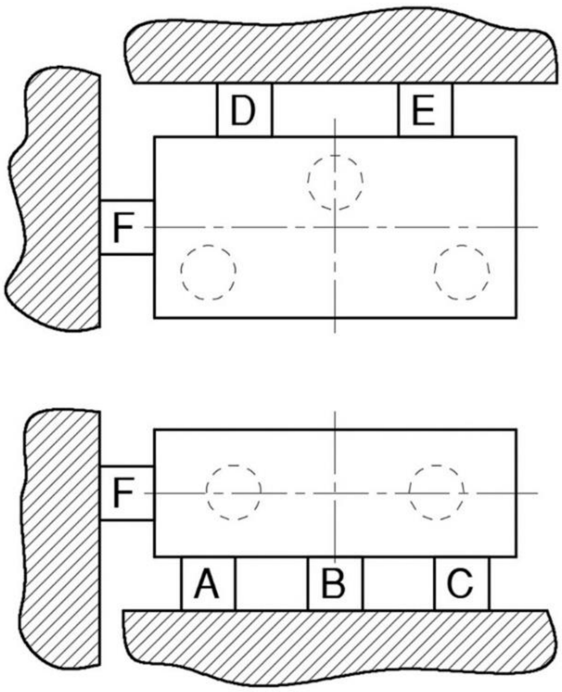

Figure 2. The 3-2-1 principle

Research and development of computer-aided fixture design (CAFD) has been conducted to enable a lean fixture design process [12]. This research focused on the fixture planning phase for small workpieces, allowing multi-workpieces on a single baseplate. A method was proposed to define the contacting point for the dowel-pin baseplate. The following section will discuss the related research within the four phases of fixture design and the proposed method for fixture planning. The third section will illustrate the application of fixture planning and conclude with remarks and future works.

Methods

This research followed the fixture design phase [13]. The first phase was setup planning, which can be conducted using an algorithmic, heuristic, or simulation method to synthesize and analyze the setup plan. This planning was proposed by Sakurai by identifying the cutting direction table as the primary setup classification and then analyzing the locating face, clamping force, and estimation of deformation and adjustments to define fixture configuration [14]. Besides Sakurai, Hajimiri proposed a series of procedures to define and classify setup planning by identifying the control face, control factor, and machining priority [15]. The procedure was an iterative process for all machining features of the product. Nelaturi proposed a heuristic search approach to evaluate alternative force/form closure configuration [16]. The selected configuration was further mapped to a library of reconfigurable fixturing units. Kumar developed an interactive and semi-automated fixture design system [17], which provides a user interface for selecting faces, points, and elements to define the fixturing points. Sarma proposed a unified graph-theory approach to represent the entire fixturing space plan [18]. An algorithm further processed the graph to select access faces to minimize the number of setups and tool changes.

Another common approach for setup planning was to utilize machining features and apply a specific algorithm to reduce the number of setups [19]. Wakhare applied an expert system approach to identify the number of setups by grouping machining features having the same tool approach direction [20]. Haghigi applied a simulation approach to enumerate alternative groups of setups within a certain objective function, for example, tolerance zones [21]. This research utilized predefined process panning alternatives to group machining features for each setup. The predefined process was classified based on the type of machine (i.e. horizontal/vertical spindle) to cluster the tool approach direction [22]. The Computer Aided Manufacturing (CAM) output consists of the number of setup and machining features in each setup.

The second phase was fixture planning, which consisted of two main steps: a) multi-workpiece fixture layout and b) 3-2-1 pin location. The 3-2-1 locating principle is suitable for dimensionally stable parts [23]. Thus, this is also suitable and in line with the case study being conducted. These two steps of fixture planning were the focus of this research and would be described in the following sub-section. The third phase was unit design, which has been developed by searching similarities and combinations of standard fixture components in a predefined database [24]. The fourth phase was verification whose process currently developed in this research was limited to collision checks between the fixture and tool path during machining [25].

The related works mentioned above are proposed for single-workpiece fixture planning. Naeem proposed a fixture planning methodology for multi-workpieces but for high-volume production [26]. In other words, several workpieces having the same shape are fixtured in a single setup. This research focused on the MTO industry where each workpiece has a variety of shapes and is produced in a low volume. Therefore, this research aimed to propose a fixture planning method for multi-workpieces for the MTO industry. Several workpieces having different shapes are setup in a single fixture.

Multi-workpiece Fixture Layout

This research developed a multi-workpiece fixture model by modifying the single-part layout model proposed in [27]. Meanwhile, in a single-workpiece fixture planning, the model usually focuses on defining the best pin location to hold the workpiece. In line with this, the proposed model added additional constraints enabling multiple workpieces to be placed and rotated at any position considering the boundary of the baseplate and no workpieces overlapped. Its objective was to minimize the tool travel between multi-workpieces by all possible part translations and rotations. The model assumed a rectangular locator to identify the border of the workpiece.

The mixed integer non-linear programming model is developed in the following notations:

i : number of workpieces
w : number of locators
$px_{i,w}$: X coordinate of border w of workpiece i
$py_{i,w}$: Y coordinate of border w of workpiece i
g : number of horizontal pin holes of the baseplate
h : number of vertical pin holes of the baseplate
a_i : horizontal distance between two locators of workpiece i
b_i : vertical distance between two locators of workpiece i
jr : spacing between pin holes of the baseplate

cl : minimum spacing between the workpieces
$x_{i,w}$: X coordinate of locator w of the workpiece i
$y_{i,w}$: Y coordinate of locator w of the workpiece i
nr_i : right translation of the workpiece i
nl_i : left translation of the workpiece i
nu_i : up translation of the workpiece i
nd_i : down translation of the workpiece i
z_{ij} : disjunctive binary value of the workpiece i and j
M : big number

The mathematical model is presented as follows:

$$\text{Min } Z = \sum_i \sum_w \left|x'_{i,w} - x'_{i+1,w}\right| + \left|y'_{i,w} - y'_{i+1,w}\right| \tag{1}$$

Subject to:

$$x_{i,w} = px_{i,w} \;\; \forall\, i, w \tag{2}$$

$$y_{i,w} = py_{i,w} \;\; \forall\, i, w \tag{3}$$

$$x'_{i,w} = \sum_w x_{i,w} * \cos(\theta_i * \tfrac{\pi}{2}) - \sum_w y_{i,w} * \sin(\theta_i * \tfrac{\pi}{2}) + nr_i - nl_i \;\; \forall\, i, w \tag{4}$$

$$y'_{i,w} = \sum_w x_{i,w} * \sin(\theta_i * \tfrac{\pi}{2}) - \sum_w y_{i,w} * \cos(\theta_i * \tfrac{\pi}{2}) + nu_i - nd_i \; \forall\, i, w \tag{5}$$

$$0 \le \theta_i \le 4 \quad \forall\, i, w \tag{6}$$

$$1 \le x'_{i,w} \le g \;\; \forall\, i, w \tag{7}$$

$$1 \le y'_{i,w} \le h \;\; \forall\, i, w \tag{8}$$

$$\left|x'_{i,w} - x'_{i+1,w}\right| + M * z_{i,i+1} \ge \frac{1}{2}\left(\frac{a_i + a_{i+1}}{jr}\right) + \frac{cl}{jr} \quad \forall\, i, w \tag{9}$$

$$\left|y'_{i,w} - y'_{i+1,w}\right| + M * (1 - z_{i,i+1}) \ge \frac{1}{2}\left(\frac{b_i + b_{i+1}}{jr}\right) + \frac{cl}{jr} \quad \forall\, i, w \tag{10}$$

$$z_{i,j} \in \{0,1\} \tag{11}$$

$$x_{i,w}, y_{i,w}, x'_{i,w}, y'_{i,w}, nr_i, nl_i, nu_i, nd_i, \theta_i \in \mathbb{Z} \tag{12}$$

The objective function of the method was to minimize the toolpath travel between workpieces, while the equation was to minimize the distance between the boundaries of all workpieces. Equations 2 and 3 define the boundary of each workpiece. The boundary assumes any shape of workpiece be translated into a rectangular boundary. Equations 4, 5, and 6 enable the model to rotate the workpiece position to find any combination that minimizes the objective function. Equations 7 and 8 ensure the pin location within the size of the baseplate. Equations 9, 10 and 11 are disjunctive constraints that ensure each workpiece does not overlap in both X axis and Y axis.

3-2-1 pin Location

This research applied the 3-2-1 pin location concept to eliminate the six degrees of freedom. Toha proposed an optimal method to define this location [28]. The procedure is based on a non-linear model. Thus, the result is applicable for an infinite pin location and not feasible for any fixed pin location fixture, such as a dowel-pin modular fixture, as focused on this research. Nudu proposed an algorithm to eliminate this location by iterating each pin, giving the least friction force [29]. Among the location candidates, the final pin location is fine-tuned to the nearest pinhole location. This research proposed a CAD-based approach to define the 3-2-1 location. The baseplate provided the 3-pin locations. The remaining 2-1 pin locations were presented by manipulating the orthogonal projection of the workpiece. This research defined several terms to locate the pin location candidate. Base View (BV) is the front view of the workpiece, which usually contains the most visible geometry information of the workpiece. Matching View (MV) is the orthogonal projection of BV. Usually, the right or left view of the workpiece is selected. Locator View (LV) is the top projection to identify the 2-1 pin location. The next step was to generate the three cells in the BV. A phantom line is generated from any intersecting solid lines, as shown in Figure 3. Two phantom lines are generated by the intersection of solid lines and three cells on BV.

The proposed 2-1 pin location is depicted in Figure 4. A cross line (CL) is projected from the centroid of each cell. The CL of the outer cell crossing any solid line in LV is set as the 2-pin location. The CL of the inner cell crossing any solid line in LV is set as the 1-pin clamp location.

The 2-1 pin location candidates are further fine-tuned to the nearest dowel-pin location by enumerating all alternative feasible holes.

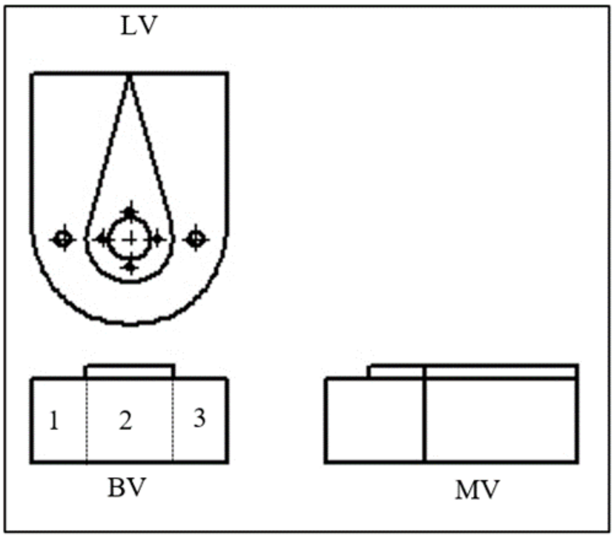

Figure 3. Generating cell on Base View (BV)

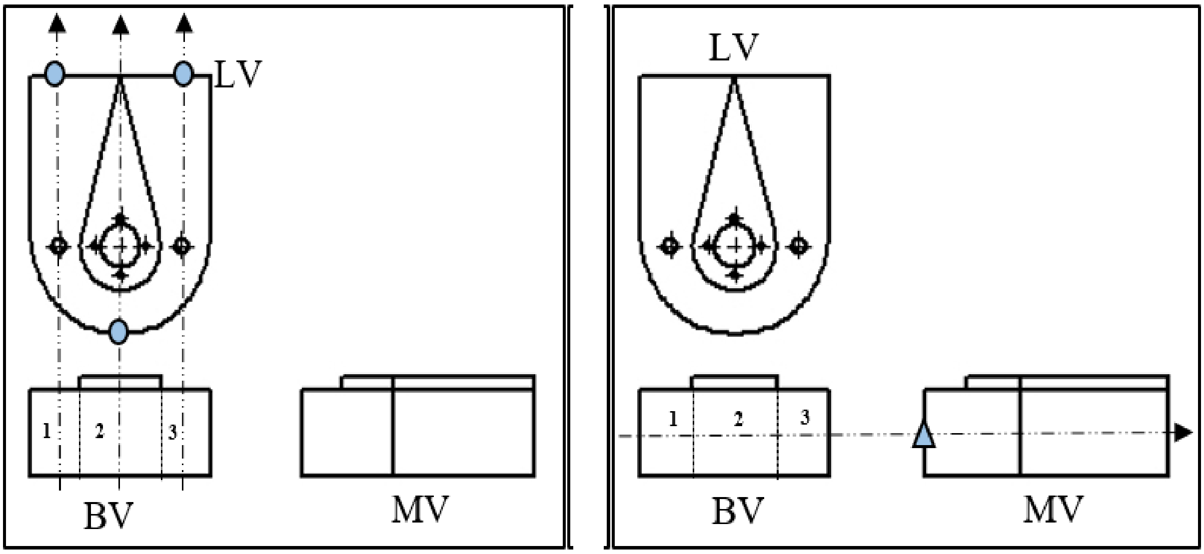

Figure 4. Generating Cross Line for 2-1 pin location candidate

Results and Discussions

Numerical Examples

An example of four different workpieces is illustrated for fixture planning to give a clear overview of the proposed method. The workpieces represent industrial components having different kinds of shapes and features. The components are: a. packing carb, b. filter cleaner, c. bearing hanger, and d. oil pump gear. The X and Y coordinates of the boundary of each part are listed in Table 1.

Table 1. X-Y coordinate border of each part

px_i	W				py_i	W			
	1	2	3	4		1	2	3	4
1	1	1	5	5	1	1	6	1	6
2	1	1	5	5	2	1	3	1	3
3	1	1	5	5	3	1	4	1	4
4	1	1	5	5	4	1	5	1	5

The multi-workpiece fixture layout model is executed in Lingo optimization software. The output of the model is the boundary location of each workpiece (mark in blue color) as depicted in Figure 5. Four workpieces are positioned in a single baseplate.

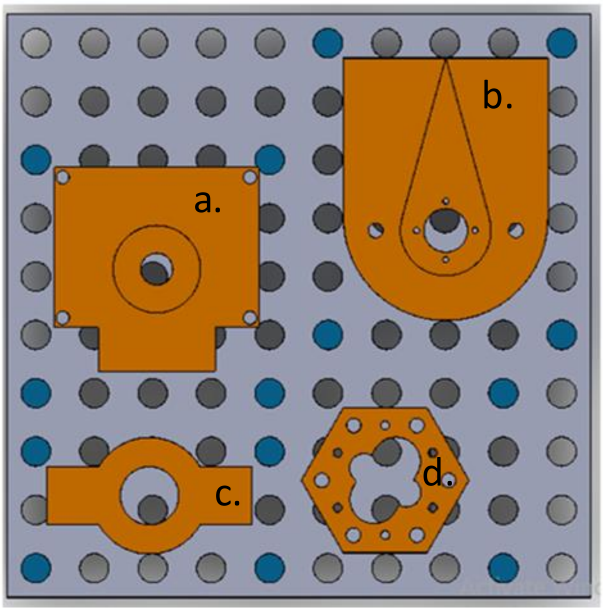

Figure 5. Multi-workpiece layout result (a. packing carb, b. filter cleaner, c. bearing hanger, and d. oil pump gear)

The next step was to identify the 2-1 pin locations by generating the orthogonal view of each workpiece. If 2-1 pin locations are not coaxial with the available pinhole, the pin location is further fine-tuned by an iterative process. The process evaluates feasible neighboring pin locations. Usually, there will be some alternatives of 3-pin location. The final pin location nearest the proposed 2-1 pin location will be selected. The result of the final 2-1 pin location is shown in Table 2 and depicted in Figure 6. The blue circles are the border of each workpiece, and the red ones are the 2-1 pin location.

Table 2. 2-1 pin location

i	Pin locator *x* (2-1)			Pin Locator *y* (2-1)		
	1	2	3	1	2	3
1	7	8	9	10	5	10
2	2	3	4	1	3	1
3	6	7	8	3	1	3
4	2	3	4	8	4	8

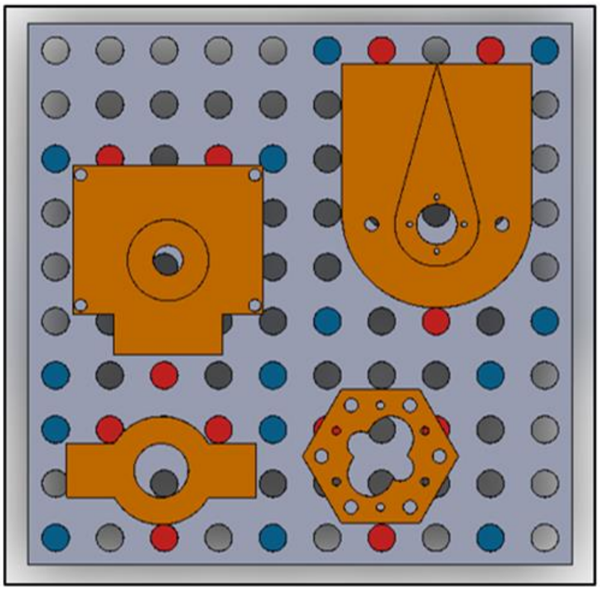

Figure 6. Final multi-workpiece fixture layout

As shown in Figure 6, the proposed fixture planning method depicts an applicable solution. All workpieces are positioned and located within the boundary of a single baseplate. There were limitations to the proposed method, one of which was that not all pin locations were practically located. Regarding the workpiece on the lower right corner, the 2-pin locations were mating at the center of the hole, thus needing a manual shifting or locating unit to accommodate such location. Another weakness had been identified for a workpiece that did not resemble a rectangular shape. (e.g., L-shaped component). The current model could solve such a shape but has more void spaces. The solution would have fewer workpieces being setup on a single baseplate.

The proposed method for multi-workpiece setup has been discussed with partners from the MTO industries. They agreed that a multi-workpiece setup of different shapes has the potential to shorten the setup process. The multi-workpiece is conducted as an external setup. Thus, loading and unloading of multi-workpiece is only conducted once for all workpieces being mounted on the base plate. They also agreed that the objective function for multi-layout is prioritized for minimizing the total travel of cutting tools during the machining process. The total travel is minimized due to two factors: a) the objective function of fixture layout model minimizes to total distance between workpieces, and b) possibility of reducing number of tool change process if workpieces utilized the same cutting as defined during the CAM process.

Conclusions

This research proposed a two-stage fixture planning method for fixturing multi-workpiece setup. The first stage was to define the position of each workpiece on a single baseplate as a result of a mixed integer non-linear model. The second stage was to identify a 2-1 pin location by utilizing the orthogonal projection of the workpiece. Examples have been given by revealing the applicability of the proposed method. The advantage of the proposed methods is providing a systematic method for fixture planning multi-workpieces for various shapes of workpieces found in the MTO industry. Multi-workpiece fixture planning has the potential benefits of reducing setup time and reducing the number of tool changes. Its limitations were related to the assumption of rectangular parts. Small voids could be found in a few cases.

The fixture planning is part of ongoing research in developing a computer-aided assembly design for a collaborative environment between human and robot. This research result will provide work elements of an assembly activity, reference points, and the location of the workpiece to automate robot movement.

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