



A Computer-aided Workholding Planning Method and its Operation Using a New Automation-viable Fixture

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Abstract: A computer software based method for aiding and systematizing the procedure of fixture selection and allocation for workholding is proposed in this study. The method recognizes geometric features of parts from their CAD models and suggests fixture configurations that aide human operators to setup the fixture hardware based on supporting and locating fixture rules. It is further proposed that computerization of fixture planning should be combined with development of new, integrated holding devices that can be automatically configured and actuated, if the fixturing process is to be significantly automated. A recently proposed and developed device, called Dual-Dexterous-Vises, is applied as an example of such an integrated workholding system. The computer-aided workholding planning method was demonstrated by using traditional discrete fixturing elements and by applying the Dual-Dexterous-Vises system.

Keywords: Computer-aided Fixture Planning; Flexible Fixturing; Workholding; Flexible Machining System; Fixture; Clamping

Introduction

Motivation

The trend of economic development and industrial evolution has made "market niche" and "small lot size with diverse variety" a main stream in marketing and production. In this stream, quick turn-around product development and flexible production are necessary. Therefore, it is important for flexible workholding corresponding to such flexible manufacturing be developed to meet this need. It has been estimated that designing and fabricating fixtures can take up to 10-20% of the total cost of a manufacturing system [1]. In addition, and more importantly, the effectiveness and efficiency of fixtures can impact total manufacturing cost. It is well known to the machining business community that real cutting time (in-cut time) is only a fraction of the total time a work-piece spends on a machine tool [2]. A survey of performance of 183 machine shops of various types and sizes in the United States during

2007-2010 reported that average setup time was between 3.7 to 6.1 hours. Spindle utilization (in-cut time as a percentage of machine uptime) of a stand-alone machine is about 30-40%. If using a machining center with a multi-pallet shuttle of 6 to 8 stations, spindle utilization can go up to 60%, which is about the level of most machine shops [3, 4]. That is, most machines are actually not cutting for about 40% of uptime. And this is assuming that the operator already has a setup plan and knows exactly how to execute. Therefore, fixture improvement can help reducing time spent in loading, positioning, gauging and idling, and thereby increase spindle utilization.

Workholding in a machining process plan can be roughly divided into two stages: (1) the planning stage, which includes fixture selection (if using existing fixtures) or design (if special fixtures need to be fabricated), and fixture allocation (layout); and (2) the execution stage, which includes actual fixture fabrication (if any), setup, workholding setup, gauging and tool setting.

Any machining process plan may contain many cutting steps. Therefore, the planning stage actually



includes many sub-plans for each of the many steps. Each sub-plan contains different fixture selection/design and fixture allocations. Correspondingly, there are many sub-executions wherein each includes re-fixturing, re-gauging, and tool resetting. It is this nature of multiple steps and repetitive operations in both stages that associates the setup/fixturing process with significant operation costs.

The major cause of high cost in the planning stage is the need for skilled designer/operators and large amounts of time for fixture design and allocation. Currently, to the author's knowledge, fixture design and allocation is still mostly done through the experience and intuition of skillful machinists or tool designers. This is especially true for custom-made special fixtures, which could take weeks to make. Modular fixtures, when used for proper jobs can result in significant savings in lead time and cost. But careful planning and management are still important and necessary. Design and construction of a fixture system using modular elements still requires experienced workers. In some cases, custom-made fixtures must be used together with standardized flexible holding elements [5-7].

The major cause of high cost in the execution stage comes from the fact that many existing fixture elements are difficult to automate. The configuration of existing hardware was developed from a long tradition of manual operation. Fixture elements are generally discrete and their setups and adjustments through a complete machining process rely heavily on the dexterity of human hands. For convenience of discussion, six faces of a workpiece can be defined, as shown in Figure 1. To enable cutting on all six faces, the workpiece must be repetitively released from the fixture, reoriented, and re-fixtured to reveal the desired face to a cutting tool. After each re-fixturing, the exact position of the workpiece must be re-gauged, and the tool position must be reset, before the next cutting step can start. Traditional fixtures, such as vises or toe clamps, only

allow machining on one or two faces of a workpiece. In many cases, several fixture setups are required for a single workpiece in order to enable cutting on multiple faces.

Accordingly, improvements in both the planning stage and the execution stage are required if the fixturing process is to be automated, at least to a significant extent.

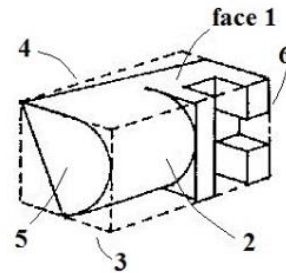


Figure 1. Six faces can be defined on any part.

Related Works

Research aiming at the improvement of fixture planning and design mainly apply computer algorithms to determine fixture configurations and assembly, based on an analysis of the geometry or features of a workpiece and on the rules of fixturing. Process information, such as the machining process plan, or other considerations such as positioning accuracy and holding forces may also be taken into consideration. For example, [8] describes an expert system for aiding flexible fixture design based on matching the 3-2-1 locating and clamping rule with the shape and size of a part. More recently, [9] describes a computer aided fixture design method based on modular principles using a database and knowledge base. Workpiece geometric features, process planning and machining information are considered. [10] describes an automatic computer aided fixture design system that uses manufacturing features extracted from part CAD models, such as holes, steps or pockets etc., and a set of rules to identify suitable locating methods. [11] proposes a model of modular fixture setup that considers cutting forces and tool approach directions. [12] describes a method for determining and evaluating fixturing methods based on multiple performance criteria including localization accuracy and the norm and dispersion of contact forces. [13] describes an automatic fixture planning approach that reduces workpiece outline into a simple polygon and then determines clamping positions.

As pointed out in the review article by [1], most existing approaches of fixture design are limited to modular fixtures and for simple polygonal workpieces. The lack of assembly sequence is also noted.

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With respect to hardware, in addition to modular fixtures consisting of discrete building blocks and elements, there have been research studies into, and niche products developed for, flexible fixturing. For example, rotary vises capable of changing workpiece orientation around one axis have been reported [14]. Flexible clamping systems have been developed based on conformable plungers acting as conformable clamping jaws. These have been combined with robotic arms so that the systems can "pick up" parts of irregular shapes at askew orientations [15]. Another type of conformable clamping device is the Clamping Sleeve, which clamps parts using a deformable sleeve jacket actuated by hydraulic pressure [16]. With respect to automated fixturing, many early works concentrated on direct automation of existing discrete fixture elements, such as using hydraulic actuated toe clamps and using robot arms to replace human workers [17]. These approaches are complex and costly. The spindle head of a milling machine has been used as an effective robot arm for fixture setup [18]. However, this approach has some limitations because the spindle head can only access the fixture from one direction.

In most of the hardware described above, the fixtures only allow machining from one direction relative to a workpiece in one setup.

Basic Concept

In order to improve fixture planning and execution, the ideal solution is to apply computer aids in the planning stage and to develop new modular fixtures that are more compatible to software planning and automatic actuation than conventional discrete fixture elements for the execution stage. Computer aid can help speed up fixture planning, but automation of fixturing cannot go very far without new hardware because of the discrete nature and the lack of dexterity of existing fixtures.

In this study, two separate but related approaches are proposed. First, a computer software based method is proposed to aid and systematize the procedure of fixture selection and allocation. This Computer-aided Workholding Planning Method recognizes geometric features of parts according to CAD models and suggests fixture configurations that aid human operators to set up fixture hardware. Second, a recently developed holding device, called the Dual-Dexterous-Vise (DDV), is proposed as an example of an integrated fixture system that is potentially suitable for coordinated and automated operations in conjunction with software planning, because the holding device has a structure capable of being configured and actuated automatically. Ultimately, by combining the software method with an integrated configurable holding device such as the

Dual-Dexterous-Vise, a workholding system that can be automatically configured by electronically controlled actuators will become possible.

The initial goal of this computer-aided method is to aid tool designers or machinists in fixture layout and setup. The ultimate goal is to automate fixturing processes and synchronize the fixturing operation with CNC cutting tools by using new integrated workholding systems such as the Dual-Dexterous-Vise.

Computer-aided Workholding Planning Method

The Computer-aided Workholding Planning Method is designed as a tool capable of selecting fixturing devices and generating fixture allocation (layout) according to input data of part geometry, cutting path, and other human defined constraints.

The basic approach of this method includes two major operations: surface recognition and holding planning. In the step of surface recognition, the geometry of the workpiece and the cutting path is analyzed and a list of surfaces available for holding without interfering with the cutting path is generated. In the holding planning stage, surfaces on the work piece are then selected from the list and fixturing operators are applied to them according to basic fixturing rules. Figure 2 shows a flow chart of this method.

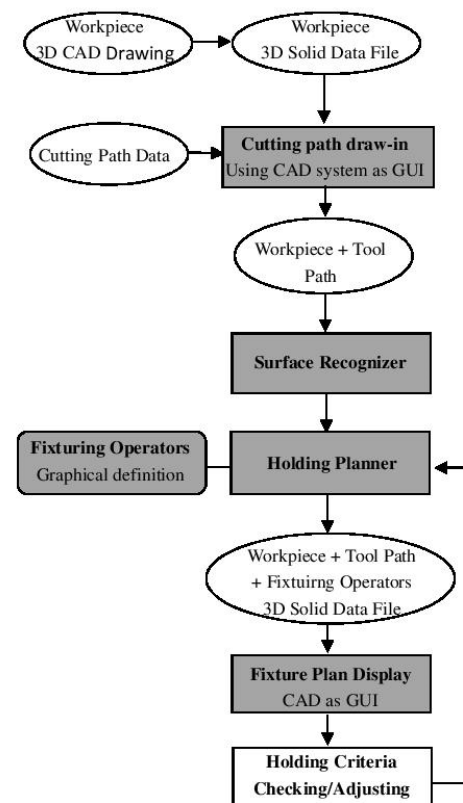


Figure 2. Flow chart of the Computer-aided Workholding Planning Method.



Table 1. Content of Surface category Table.

"Surface Category Table" contains the following information of a face, sequentially in each line in ASCII form,

Face_id	Surface_type	Size	Location	Normal	Asso_points	Note
Face_id	An integer starting from 0 to N for numbering each face					
Surface_type	"P" (prismatic or planar surface) or "C" (curved surface)					
Size	A number to index relative size of the face, using the area of the face					
Location	Center point of the face					
Normal	Outward pointing surface normal of the face					
Asso_points	Associated points, including all points pointed by all vertices used in the definition of the face					
Note	Additional notes or marks					

The procedure of the Computer-aided Workholding Planning Method is further explained in the following four basic steps:

- **Work Data Preparation:**

This step defines geometric data of a workpiece (body 1), a volume of tool path (body 2), and the machined body (body 3 = body 1- body 2).

The geometric data of the workpiece and the cutting path can be obtained from CAD and CAM data. The machining can be modeled by a Boolean operation (subtraction). A CAD system, or an equivalent 3D modeling system, is used as the graphical user interface (GUI).

- **Surface Recognition**

This step analyzes all faces of body 3 and makes a "Surface Category Table".

The Surface Recognizer analyzes the data of the workpiece and the cutting path and generates a list of surfaces available for holding without interference with the cutting path. Table 1 shows the content of the Surface Category Table, which includes information about the size, surface type, (planar or curved), center point, surface orientation (surface normal), and location of each "face" (surface) that can be identified in the data file of the geometry. This analysis is performed over body 3, while new faces created by the machining operation are marked, because those new faces may not be used for clamping. These are faces of body 3 that completely fall on the boundary of body 2 (tool path).

- **Holding Planning**

This step creates a holding plan for the geometry represented by the Surface Category Table. The Holding Planner selects surfaces from the list of faces in the Surface Category Table and applies fixturing operators to them according to basic fixturing rules.

In general, the well-known 3-2-1 locating and clamping rule is applied. According to the 3-2-1 rule, a part can be positioned by supports from three directions: at least three supporting points from a base direction, two supporting points from a side direction

perpendicular to the base direction, and one support from another side direction perpendicular to each of the previous two directions. This position can be secured by applying a clamping force to the part in a direction, preferably, opposite to the base direction, or clamping forces applied against the side supports. [19, 20] When using traditional, discrete holding elements such as locating pins and toe clamps, the 3-2-1 rule can be applied directly. When using a vise, assuming a workpiece is first correctly positioned against horizontal parallel gauges or a vertical plane, a generalized "vise rule" can be applied: a part can be positioned and secured by clamping forces from two opposite but coincident directions applied on suitable contact areas.

- **Fixture Display**

This step applies fixturing operators (devices of supporting, locating and clamping) onto specified surfaces in specified directions, with graphical display. The fixturing plan is displayed in a graphical user interface so that users can evaluate the plan and make necessary changes.

Dual-Dexterous-Vises

The Dual-Dexterous-Vise (DDV) is proposed as an example of an integrated fixture system that is potentially suitable for coordinated and automated operations in conjunction with software planning, because it has a structure capable of being configured and actuated automatically. The system features two held in one vise can be rotated to reveal its four faces to a cutting tool. Figure 3 illustrates the concept of a vise in the DDV system. It comprises a pair of jaw assemblies. Each jaw assembly includes a slide on a linear stage and a rotary jaw on the slide. The slide can move freely along and be locked onto the linear stage. The rotary jaw can rotate freely about a center line parallel to the linear stage, and can be locked in position. The two special vises arranged in perpendicular orientation. Each vise comprises rotary jaws such that a workpiece Jaw



assemblies are aligned in opposite directions along the same center line. The precise position of the slide on the stage is measured by a built-in scale on the stage. Similarly, the angular position of the rotary jaw is also accurately measured and located by a resolver, or alternatively by an indexer. When the workpiece is first setup and clamped on, initial gauging and tool setting can be performed. As a result, a workpiece being clamped between the pair of jaws can be rotated around the center line to reveal four faces to a cutting tool without the need of re-fixturing.

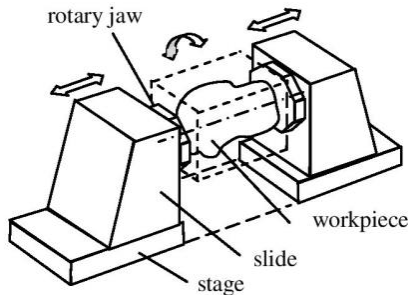


Figure 3. Basic concept of a single vise in the Dual-Dexterous-Vises system [21].

By combining two special vises described above, with their center lines perpendicular to each other, a highly dexterous "Dual-Vises" holding system can be configured, as illustrated in Figure 4. The first vise allows revealing four faces of a workpiece to a cutting tool, and enables rotation in the YZ plane. To reveal the remaining two faces, the second vise clamps the workpiece on its sides first, and then the first vise releases the workpiece and clears the space. The workpiece is thus transferred onto the second vise and can be rotated in the XZ plane. With the capability of changing orientation and transferring a workpiece between the two vises, the system is capable of holding a workpiece and revealing all of its six faces to a machining tool in one setting, that is, without the need of many steps of re-fixturing, re-gaging, and tool resetting during a machining process.

To ensure good gripping conformability, each rotary jaw contains a set of plungers and small hold-down clamps. The plungers, when released, can be pushed by compressed air pressure to conform to the shape of the surface of a workpiece. Once a shape is set, the plungers are mechanically locked in place, and the air supply can be disconnected. The small hold-down clamps can be applied to create clamping forces toward the center line, thereby increasing stiffness and stability. In some cases, an under-support mechanism may be added, either to provide a reference plan in the initial setup or to add holding stiffness. An under-support mechanism with plungers can serve this purpose. Figure 5 illustrates these design features.

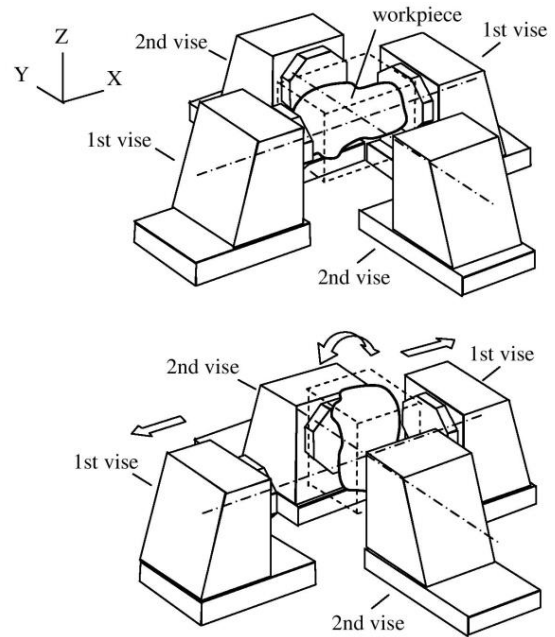


Figure 4. Basic concept of the Dual-Dexterous-Vises system; (Top) the first vise in action; (Bottom) "holding transfer" by actuating the second vise before releasing the first vise [21].

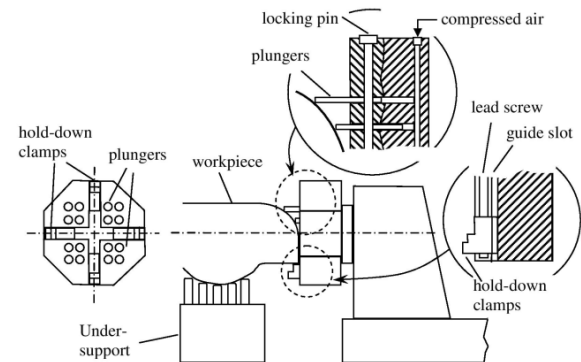


Figure 5. Basic concept of the jaws of the Dual-Dexterous-Vises system Conformable plungers and small hold-down clamps on the rotary jaws providing holding flexibility and conformability [21].

A study on preliminary design and actual machining tests of a DDV hardware prototype has been conducted and the details are reported in [21]. Figure 6 shows two pictures of the test prototype in operation.

Because of the DDV system's integral nature and the use of conformable plungers, it is easier to set up than other existing fixtures and setup time can be reduced. The DDV system also makes automation easy. For example, servo motors can be used to drive the rotary jaws; and hydraulic systems can be used to actuate slides and hold-down clamps. As a result, the holding system can be integrated into the complete system of CNC machining. A DDV system effectively adds two additional degrees of freedom to a machine tool. Using a CNC DDV system on a 3-axis machine tool can effectively provide 5-axis machining capability. The system has the potential of providing "done in one" capability to a 3-axis machine tool.

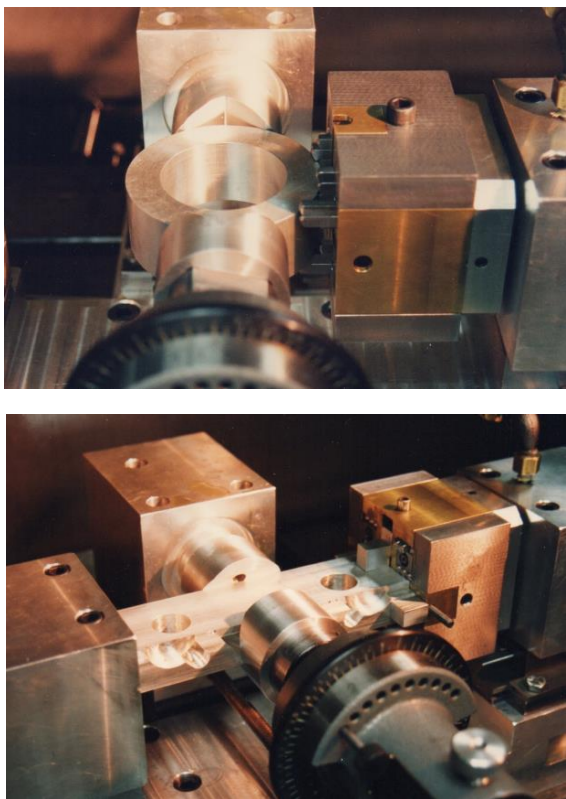


Figure 6. A test prototype of the Dual-Dexterous-Vises system demonstrating holding flexibility. Only one jaw has full features for demonstration purpose. (Top) Conformable plungers on the fully-functional jaw hold a part with curved surfaces with two other jaws. (Bottom) Small hold-down clamps hold a prismatic bar-shaped part with three other jaws.

Software Demonstration

The ACIS solid modeling engine, which uses the SAT files, is used as the operating standard for this project. ACIS has been incorporated into the AutoCAD since Release 13. ACIS defines a 3D solid through the collection of a number of basic surfaces, including planes and curved surfaces, and their intersections. All these basic surfaces are high precision, near-exact geometry. Therefore, the resulted solid is also near-exact, rather than comprising an approximation of limited polygon meshes, as in the case of other 3D solid data formats, such as the DXF format. In ACIS, a flat surface on a solid contains only one face and its edges are defined by intersections with other surfaces of the solid. As a result, each surface of the solid is clean and well-defined, which is most suitable for surface recognition and holding planning in this project. The solid modeling engine, called ACIS3DT (ACIS 3D Toolkit), contains a collection of commands and functions in C++ and Scheme, including functions that can be used for surface recognition. It contains solid modeling functions and a graphical output window.

A software prototype of the Surface Recognizer was developed using the ACIS3DT engine. Scheme functions for work data preparation and surface recognition were created so that the basic algorithm of the method can be demonstrated using ACIS3DT with Scheme language and graphical output. Two examples of fixture planning are presented here to demonstrate the software prototype and the planning algorithm. Figure 7 is a screen shot showing the three operation windows of the demo-software prototype: the graphical window showing the workpiece and the fixture elements, the ACIS3DT window showing response from code execution, and the WinScheme Editor window for a user to input operation commands.

The first example is the fixture planning of a simple milling operation on a part of simple geometry with discrete, regular fixturing devices, to illustrate the idea of the computer aided generation of fixture layout by analyzing blank and tool path, using the algorithms of Surface Recognition and Holding Planning described previously.

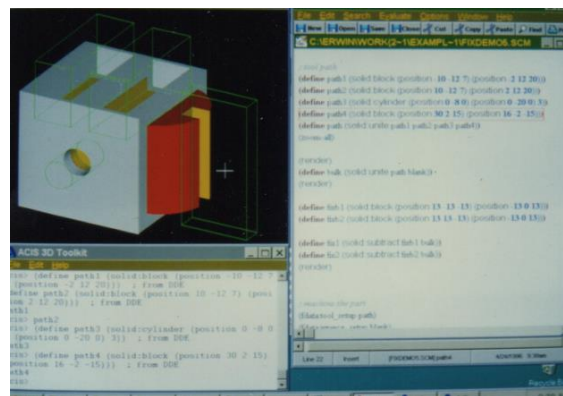


Figure 7. Screen shot of the Computer-aided Workholding Planning software prototype.

Figure 8 shows the graphical output generated during steps of the planning. Uncut surfaces are shown in red and surfaces to be created by machining are illustrated in yellow.

In step 1, Work Data Preparation, the workpiece data and the cutting path data were read in (Figure 8(a)). The milling operation basically makes a straight cut off. The machined body was defined by Boolean operation of subtraction (the machined body = the workpiece – the cutting path) (Figure 8(b)).

In step 2, the Surface Recognizer is applied to the machined body to obtain a Surface Category Table, as shown in Table 2. The surface types were obtained directly from the data structure of the SAT file of the machined body. The sizes, the locations and the surface normal vectors were calculated using the geometric data in the SAT file. The numbers marked in the figures indicate Face_ids of surfaces for easy reference.

In step 3, the Holding Planner was applied. This includes the following sub-steps:

First, the part orientation was set with (0 0 1) as “up” direction.

Then a base face was selected to be the surface for the 3 supporting points in the 3-2-1 locating rule. From the Surface Category Table a face of type “P” and with surface normal vector “(0 0 -1)” (opposite to the “up” direction), was found, which was face #4.

A face operator, representing a fixture device was then attached to face #4 (Figure 8(c)).

Next, a first side face was selected for the 2 locating points in the 3-2-1 rule. From the 3-2-1 rule, a face of type “P” and face normal perpendicular to the base face was needed. In the Surface Category Table, four faces were qualified: faces #0, #5, #6 and #7 (face #0 would be a cut face). Face #7 was selected because it had the largest size.

Next, a second side face was selected for the 1 locating point in the 3-2-1 rule. This was to find a face with type “P” and a face normal perpendicular to both the base face and the first side face. The only preferred choice was face #6, because face #3 is a curved face.

A face operator was then attached to face #7 (Figure 8(d)).

A pin locator was then attached to face #6 (Figure 8(e)).

The part was now located according to the 3-2-1 locating rule. A preferred face for clamping was then selected by finding a face of type “P” and a face normal “(0 0 1)”, which was opposite to the base face and therefore had the preferred clamping direction. Faces #1 and #2 had the right direction but face #1 would be a cut face. Face #2 was therefore selected.

A pad operator was attached to face #2 (Figure 8(f)).

In the above examples, multiple choices can be made by the user, which can result in different fixture

plans. For instance, Figure 8(g) shows an alternative fixture plan that could be generated, which is not preferred since the side fixture pad could interfere with the cutting. The user can modify the plan according to these results to obtain a better layout, such as the one in Figure 8(h).

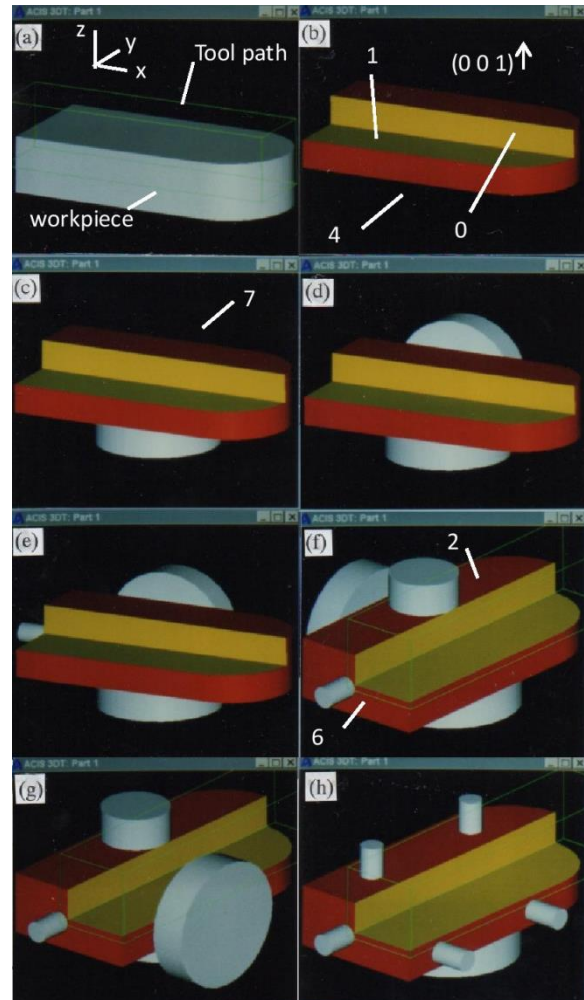


Figure 8. Example of fixture planning of a simple milling operation on a part of simple geometry with discrete, regular fixturing devices.

Table 2. Surface Category Table of the part of Figure 8.

Surface Category Table – for body f95e24

Face_id	Surface_type	Size	Location	Normal	Note
0	P	7800.000000	30, 0, 15	0, -1, 0	new
1	P	14827.433388	23.924797335772, -29.135183999066, 0	0, 0, 1	new
2	P	14827.433388	23.924797335772, 29.135183999066, 30	0, 0, 1	
3	C	0.000000			
4	P	29654.866776	23.924797335772, 0, -30	0, 0, -1	
5	P	6000.000000	0, -60, -15	0, -1, 0	
6	P	5400.000000	-100, 10, -5	-1, 0, 0	
7	P	12000.000000	0, 60, 0	0, 1, 0	

The second example is fixture planning applying the Dual-Dexterous-Vises system. This example involves machining on multiple faces. Figure 9(a) shows the workpiece to begin with and Figure 9(b) shows the machined part. Again, uncut surfaces are shown in red, and surfaces to be created by machining are illustrated in yellow. The process plan was predetermined. The holding planning algorithm was then executed according to the process plan. Figure 9 shows the result.

In step 1, Work Data Preparation, the workpiece data and the cutting path data were read in (Figure 9(a)). There were two milling operations on the top surface, one slot milling on the curved surface at the front end, and a hole sinking operation on the side. The machined body (finished part) was defined by Boolean operation of subtraction (the machined body = the workpiece – the cutting path) (Figure 9(b)).

In step 2, the Surface Recognizer was applied to the machined body to obtain a Surface Category Table, shown in Table 3. Take note that the finished part had 3 curved surfaces, face #5 corresponding to the inner ring surface inside the hole, faces #13 and #14 corresponding to the curved surface at the front end, which was cut into two separate curved faces. All other faces were planar faces.

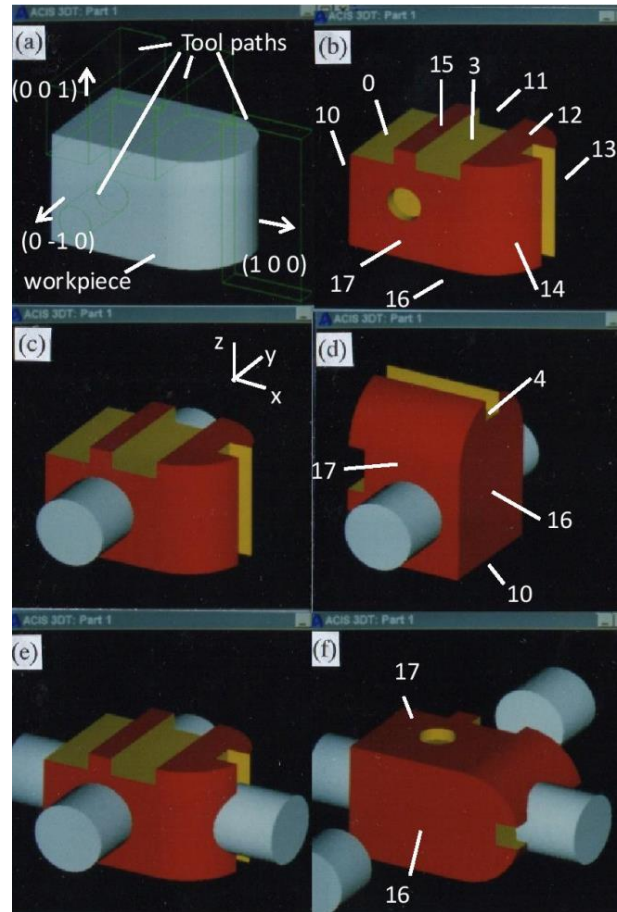


Figure 9 Example of fixture planning applying the Dual-Dexterous-Vises system.

Table 3. Surface Category Table of the part of Figure 9.

Surface Category Table – for body f95884					
Face_id	Surface_type	Size	Location	Normal	Note
0	P	160.000000	-6, 0, 7	0, 0, 1	new
1	P	60.000000	-2, 0, 8.5	-1, 0, 0	new
2	P	60.000000	10, 0, 8.5	-1, 0, 0	new
3	P	160.000000	6, 0, 7	0, 0, 1	new
4	P	60.000000	2, 0, 8.5	1, 0, 0	new
5	C				new
6	P	28.274334	0, -8, 0	0, -1, 0	new
7	P	75.959179	17.898979485566, -2, 0	0, 1, 0	new
8	P	80.000000	16, 0, 0	1, 0, 0	new
9	P	75.959179	17.898979485566, 2, 0	0, -1, 0	new
10	P	340.000000	-10, 0, -1.5	-1, 0, 0	
11	P	352.000000	0, 10, -1.1590909090909	0, 1, 0	
12	P	141.347923	13.829793343638, 0, 10	0, 0, 1	
13	C				
14	C				
15	P	80.000000	0, 0, 10	0, 0, 1	
16	P	541.347923	3.6110096263351, 0, -10	0, 0, -1	
17	P	323.725666	0, -10, -1.2603263896032	0, -1, 0	

In step 3, the Holding Planner was applied. Referring to Figure 9(a) and 9(b), the predetermined process plan is as follows,

Process step (1): Cutting from direction (0 0 1) of the workpiece to make the 2 wide slots;

Process step (2): Cutting from direction (1 0 0) of the workpiece to make the narrow slot;

Process step (3): Cutting from direction (0 -1 0) of the workpiece to make the hole.

Based on the process plan, the holding plan includes the following sub-steps:

(a) Determine holding directions for process step (1):

This was to find two opposite faces with their normal vectors perpendicular to the up direction (0 0 1). There were a few choices according to the data in the Surface Category Table, such as face #11 with face #17, face #4 with face #10 etc. Face #11 with face #17 was selected.

Face operators were then attached to face #11 and face #17 at their centers (Figure 9 (c)).

The two wide slots were then cut.

(b) Determine holding directions for process step (2):

This required a rotation of the workpiece to turn the curved end into the up direction (0 0 1). To perform this rotation, the vise clamping directions needed to be perpendicular to the direction of the curved end (1 0 0). There were several choices according to the data in the Surface Category Table, such as face #11 with face #17, face #6 with face #11, face #16 with face #0, face #16 with face #3 etc. Face #11 with face #17 was selected since the face operators had already been attached in the previous sub-step. For convenience, this pair of face operators clamping in the y-axis directions is called Vise A.

Next, the workpiece was rotated on Vise A about the y-axis by -90 degree, turning the (1 0 0) direction of the workpiece to the up direction. (Figure 9 (d))

The narrow slot on the curved end was then cut.

(c) Determine holding directions for process step (3):

This required the workpiece to rotate twice in order to turn face #17 to the up direction (0 0 1). There was more than one way to carry out these rotations. Further, the final clamping directions should correspond to two opposite faces with their surface normal directions perpendicular to the direction of face #17 (0 -1 0). In the Surface Category Table, there were several choices, such as face #16 with face #0, face #16 with face #3, and face #10 with face #4 etc.

Face #10 and face #4 (1 0 0) were selected as the final clamping faces. The part was first rotated on Vise A about the y-axis by 90 degree, to turn face #10 and face #4 to an orientation parallel to Vise B, which is along the x-axis.

Next, the part was transferred from Vise A to Vise B. First, Vise B face operators were attached to face # 10 and face #4 (Figure 9(e)). Then, Vise A was retracted. Finally, the part was rotated on Vise B by -90 degree to turn face #17 to the up direction (Figure 9(f)).

The last face was then cut.

Discussions

This work proposes a software approach that applies simple Boolean operations and surface recognition to provide computer aid in fixture planning and a hardware approach featuring non-conventional fixture hardware that is compatible with software planning and automatic actuation for easy fixturing executions. The software method considers both workpiece geometry and machined part geometry and distinguishes original surfaces and newly created surfaces in the 3D files. However, due to the variety and complexity of machining jobs in the real world, the software aims at providing aid to human operators, rather than providing fully automated fixture plans. Therefore, it is up to a human operator to select and determine, from the possibilities obtained from the software method, what the proper holding plans and details should be. Further, for jobs involving multiple steps, such as the example of Figure 9, a process plan needs to be determined either concurrently or in advance. In this regard, it should be further noted that process plans and workholding plans are both based on a premise of available fixturing hardware. Available fixturing hardware places a limit on possible process plans and workholding plans that can be applied in a machining job. An integrated fixture system, such as the DDV system, provides extended freedom in process and fixturing planning. For example, cutting from multiple directions can be done in one setup and holding on surfaces that are of irregular shape or are newly cut becomes possible. Yet it must also be emphasized that the DDV system is just one example. Other fixturing hardware creations and improvements are needed in order to cover more workpiece types and to reduce costs. In summary, a combined human-software-hardware approach may be the most reasonable approach toward the further automation of workholding processes.

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