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Development of Automated Fixture Planning Systems

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Fixturing is an important manufacturing activity. The computer-aided fixture design technique is being rapidly developed to reduce the lead time involved in manufacturing planning. An automated fixture configuration design system has been developed to select automatically modular fixture components and place them in position with satisfactory assembly relationships. In this paper, an automated fixturing planning system is presented in which fixturing surfaces and points are automatically determined based on workpiece geometry and operational information. Fixturing surface accessibility, feature accuracy, and fixturing stability are the main concerns in the fixture planning. The system development, the fixture planning decision procedure, and an implementation example are presented in the paper.

Keywords: Accuracy; Clamping; Fixture planning; Locating

1. Introduction

Fixturing is an important manufacturing activity in the production cycle. A computer-aided (or automated) fixture design (CAFD) technique has been developed as part of CAD/CAM integration [1]. The development of CAFD contributes to the reduction of manufacturing lead time, the optimisation of manufacturing operations, and the verification of manufacturing process designs [2]. CAFD plays an important role in flexible manufacturing systems (FMS) and computer-integrated manufacturing systems (CIMS) [3].

Figure 1 outlines the activities for fixture design in manufacturing systems which include three major aspects: set-up planning, fixture planning, and fixture configuration design [4]. The objective of set-up planning is to determine the number of set-ups, the position and orientation of the workpiece in each set-up, and also the machining surfaces in each set-up. Fixture planning determines the locating and clamping points on workpiece surfaces. The task of fixture configuration design is to select fixture components and place them into a final configuration to fulfil the functions of locating and clamping the workpiece. An automated modular fixture configuration design system has been developed in which, when fixturing surfaces and points are selected on the workpiece model, fixture units are automatically generated and placed into position with the assistance of fixture component assembly relationships [4,5]. This paper deals with fixture planning when the fixturing surfaces and positions on the workpiece are selected automatically.

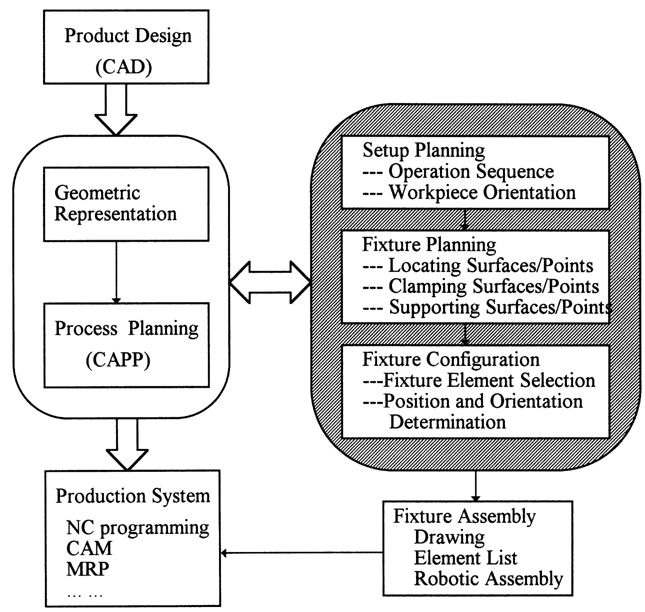

Fig. 1. Fixture design in manufacturing systems.

Previous papers on fixture design analysis have been published, but a comprehensive fixture planning system which can be used to generate fixture plans for industrial applications has not been developed. Previous work includes: a method for the automated determination of fixture location and clamping derived from a mathematical model [6]; an algorithm for the selection of locating and clamping positions which provide the maximum mechanical leverage [7]; kinematic analysis based fixture planning [8,9]; a fixturing grade and dependency grade based fixturability analysis [10]; automated selection of set-ups

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with consideration of tolerance factors of orientation errors in fixture design [11], and finally a geometric analysis based 2D fixture planning system [12]. In our previous research, fixturing features [13], fixturing accuracy [14,15], geometric constraints [16], and fixturing surface accessibility [17] have been studied. A framework has been developed for set-up planning and fixture design [18].

In this paper, an automated fixture planning system, Fix-Planning, is presented where fixturing surfaces and points are determined when the workpiece model and set-up planning information is input to the system.

2. Basic Requirements of Fixture Planning

In engineering practice, fixture planning is governed by a number of factors, including workpiece geometric information and tolerance; set-up planning information such as machining features, the machine tool and cutting tools to be used in each set-up; initial and resulting forms of the workpiece in each set-up; and available fixture components. To ensure that the fixture can hold the workpiece in an acceptable position so that the manufacturing process can be carried out according to the design specifications, the following conditions should be satisfied for a feasible fixture plan.

1. The degrees of freedom (DOF) of the workpiece are totally constrained when the workpiece is located.
2. Machining accuracy specifications can be ensured in the current set-up.
3. Fixture design is stable to resist any effects of external force and torque.
4. Fixturing surfaces and points can be accessed easily by available fixture components.
5. There is no interference between the workpiece and the fixture, and between the cutter tool and the fixture.

In this investigation, we focus on the first four requirements. Fixture planning is carried out based on the following considerations:

1. Although the workpiece geometry can be complex in industrial production, in most fixture designs, planar and cylindrical surfaces (internal and external) are used as the locating and clamping surfaces because of the ease of access and measurement of these features when the workpiece is fixed. In this investigation, planar and cylindrical surfaces are used in fixture planning.
2. Many CNC machines, especially machining centres, can be used to perform various operations within one set-up. In most cases, the cutting-tool axis of the machine tool is fixed. When considering fixturing stability, the locating surfaces are preferably those with normal directions opposite to, or perpendicular to, the cutting-tool axis. For clamping features, the normal directions should be in line with, or perpendicular to, the cutting-tool axis, because, in fixture design, clamping forces should be against locators.
3. For the surfaces to be machined, there should exist datum surfaces which serve as position and orientation references from which other dimensions and tolerances are measured. In fixture planning, surfaces with high accuracy grades should be selected preferentially as locating surfaces so that the inherited machining error is minimised and the required tolerances of the machining features are easily attained.
4. In fixture planning, more than one workpiece surface must be selected for the locating and clamping surfaces for restricting the DOF of the workpiece in a set-up. Therefore, besides the conditions for individual surfaces, the combination status of the available locating surfaces is also important for the accurate location of the workpiece.
5. Since the locators and clamps are in contact with the workpiece, the distribution of fixturing points plays a critical role in ensuring fixturing stability.
6. For a feasible fixture design, the fixturing surfaces must be accessible to the fixture components. The usable (effective) area of the fixturing surface should be large enough to accommodate the functional surfaces of the locators and clamps. Besides considering a fixturing surface, the accessibility of potential fixturing points on the surface is also important for the determination of the final fixturing point distribution.

3. Fixturing Surfaces

The concept of features has been widely used in design and manufacturing. A workpiece to be machined can be viewed as a combination of features such as planes, steps, pockets, slots, and holes. In a particular operation set-up, features used for fixturing the workpiece can be defined as fixturing features or fixturing surfaces. In practice, most fixturing features are planar and cylindrical surfaces. According to the fixturing functions, the fixturing surfaces can be classified into locating, clamping, and supporting features. Unlike design and manufacturing features, fixturing surfaces are orientation-dependent. They do not play the same role throughout the manufacturing processes. A set of surfaces may serve as fixturing surfaces in a set-up, but may not be used for fixturing or have different fixturing functions in another set-up.

The concept of fixturing features allows the fixturing requirements to be associated with the workpiece geometry. Feature information in a feature-based workpiece model can also be used directly for fixture design purposes. For manufacturing features, the information necessary for describing a fixturing feature contains geometric and non-geometric aspects. The former includes feature type, shape and dimensional parameters, and position and orientation of the workpiece. The latter includes the surface finish, accuracy level and relationships with machining features, and surface accessibility.

3.1 Discretisation of Fixturing Surfaces

In most fixture designs, the fixturing features, especially the locating surfaces, are planar and cylindrical surfaces. In order to evaluate fixturing surface accessibility and determine locating/clamping points on fixturing surfaces, a candidate fixturing surface is sampled into grid-arrayed discrete points with equal interval T. If T is small enough, the discrete sample points will be almost continuous.

In order to make the sampling algorithm generic, an outer-bounding rectangle on the surface is used as the sampling region. Since in most cases, the primary locating surface is perpendicular to the other locating surfaces, especially in modular fixture designs, the fixturing surfaces are considered as bottom-locating, top-clamping, side-locating, and side-clamping surfaces. For a bottom-locating/top-clamping surface with a normal Z (or $-Z$) direction, two edges of the outer-bounding rectangle must be parallel to the X-axis and two other edges parallel to the Y-axis. For a side-locating/clamping surface, there must be two edges parallel to the Z-axis, while the other two edges must be perpendicular to the first two edges. Figure 2 shows an example of sampled candidate fixturing surfaces with the outer-bounding rectangle. With the assumption that the Z-axis is normal to the surface in the surface local coordinate system, the points within the outer-bounding rectangle can be represented as:

$$x = X_{\min} + T \times u, \quad u = 1, 2, \ldots, N_u$$
$$y = Y_{\min} + T \times v, \quad v = 1, 2, \ldots, N_v \tag{1}$$

where N_u and N_v are the numbers of points in the X- and Y-directions, respectively, which are: $N_u = \text{int}\ [(X_{\max} - X_{\min})/T]$ and $N_v = \text{int}\ [Y_{\max} - Y_{\min})/T]$.

3.2 Fixturing Surface Accessibility

Fixturing surface accessibility is a measure of whether a candidate fixturing surface is accessible to a regular fixture component. Three major factors must be taken into account:

1. The geometry of the fixturing surface which involves the effective area and shape of the surface.
2. Possible obstruction of the workpiece geometry along the normal direction and/or around the geometric region of the fixturing surface.
3. The size and shape of the functional fixture components.

In practical situations, it is possible that a planar surface of the workpiece has a complex shape and has a full/partial obstruction along its normal direction and/or around its geometric region. It is thus required that the accessibility model should comprehensively reflect these facts so that a reasonably comparable accessibility value can be applied for every candidate fixturing surface.

The surface accessibility is defined as a statistical value based on the point accessibility (*PA*) of every valid sample point on the surface, where *PA* consists of two parts: the point self individual accessibility (*SIA*) and the point neighbour related accessibility (*NRA*). The *SIA* corresponds mainly to the isolated accessibility of the fixturing point, whereas the *NRA* reflects the extended accessibility of the fixturing point.

The *SIA* of a sample point is defined on the basis of three attribute tags. The tag s_1 is used to indicate whether the square test grid with its centre at the current sample point is inside, on, or outside the outer-loop of the fixturing surface. Three discrete values are assigned to represent its status, i.e. 0, 1, and 2, respectively.

If there exists obstructive workpiece geometry in the surface normal direction or surrounding the sample point, this affects the surface accessibility at the sample point. For example, as shown in Fig. 3(*a*), on a candidate bottom-locating surface of a workpiece, sample point p_1 is not accessible because of the obstructive geometry of the workpiece along the bottom-locating direction, and p_2 is not accessible either because of the obstructions surrounding it. To evaluate automatically whether an obstruction exists in the surface normal direction, a virtual volume is generated by extruding the square test grid to a solid entity in the surface normal direction. By employing a technique for detecting the interference between two solid entities, the obstruction can be identified, as shown in Fig. 3(*b*). The extruding method is a little different for the square

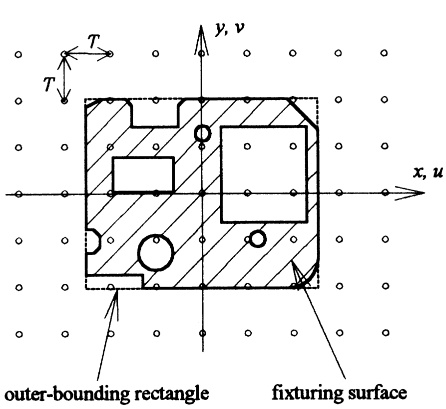

Fig. 2. Sampling of a candidate fixturing surface with an outer-bounding rectangle.

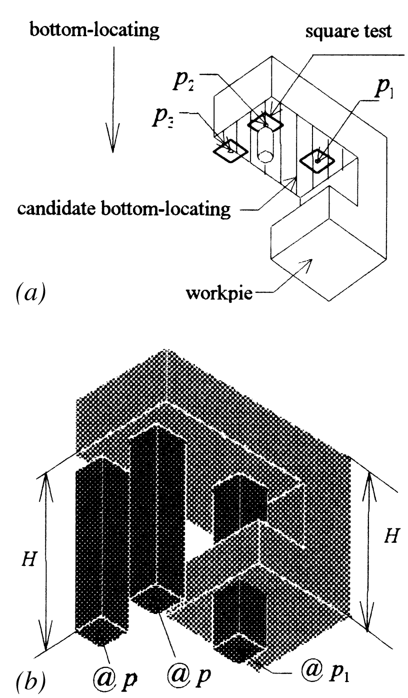

Fig. 3. Obstruction checking at virtual sample points on a bottom-locating surface. (@p_i means the extrusion is carried out at point p_i along its accessible direction.)

test grid on the side-locating/clamping surface, where the square test grid is first stretched along the bottom-locating direction, and then the stretched grid is extruded along the side-locating/clamping direction as illustrated in Fig. 4. The attribute tag s_2 is used for recording the result of obstruction checking at a sample point. When such an obstruction is detected, $s_2 = 1$, otherwise, $s_2 = 0$.

If the test grid at the sample point is found to be not obstructed, its individual accessibility is largely dependent on the contact area between the test surface and the fixture components, which is represented by the attribute tag s_3. The definition of s_3 is

$$s_3 = \frac{\text{Area}_1}{T^2}, \quad s_3 \in [0, 1] \tag{2}$$

where Area_I is the contact area and T is the edge length of the test grid.

On the basis of above three attribute tags, the *SIA* of a sample point $p_{u,v}$ can be given by a numerical value according to the following rules:

if s_1 = OutsideOuterLoop, $SIA = -1$ (inaccessible);
if $s_1 \neq$ OutsideOuterLoop AND s_2 = Obstructed, $SIA = -1$ (inaccessible);
if bottom-locating/top-clamping AND $S_1 \neq$ OutsideOuterLoop AND s_2 = NotObstructed, $SIA = s_3$;
if side-locating/clamping AND $s_1 \neq$ OutsideOuterLoop AND s_2 = NotObstructed, $SIA = 0.5^v s_3$;

where v reflects the height effect of the point in side locating/clamping.

The accessibility in the surrounding area of the sample point also affects the accessibility of the point. On a fixturing surface, the positional relationship between the current sample point and all the neighbouring sample points can be represented by a 3×3 map where P_c is the current sample point with a discrete position of (u, v), $P_1 \sim P_8$ are 8-neighbour sample points, and their locations are all labelled in Fig. 5. The *NRA* at sample point $p_{u,v}$ can be calculated using the equation:

$$NRA(u, v) = \frac{\sum_{k=1}^{8} F_k}{8} \tag{3}$$

where F_k is the related-access factor of kth neighbour, which can be determined based on the *SIA* as well as its measure (s_1, s_2, s_3).

For bottom-locating/top-clamping,

$$F'_k = \begin{cases} -1, & s_2(p_k) = 1 \\ 0, & s_1(p_k) = 2 \text{ and } s_2(p_k) = 0 \\ IA(p_k), & s_1(p_k) \neq 2 \text{ and } s_2(p_k) = 0 \end{cases} \tag{4}$$

$$F_k = \begin{cases} F'_k, & k = 1, 3, 5, 7 \\ F'_k, & k = 2, 4, 6, 8, F'_{k-1} \geq 0 \quad \text{and } F'_{k+1} \geq 0 \\ -1, & k = 2, 4, 6, 8, F'_{k-1} = -1 \quad \text{or } F'_{k+1} = -1 \end{cases} \tag{5}$$

For side-locating/clamping,

$$F'_k = \begin{cases} -1, & s_2(p_k) = 1, \; k = 1, 5, 6, 8 \\ -0.5, & s_2(p_k) = 1, \; k = 2, 3, 4 \\ 0, & s_1(p_k) = 2 \text{ and } s_2(p_k) = 0 \\ SIA(P_k), & s_1(p_k) \neq 2 \text{ and } s_2(p_k) = 0 \end{cases} \tag{6}$$

$$F_k = \begin{cases} F'_k, & k = 1, 3, 5, 6, 7, 8 \\ F'_k, & k = 2, 4, \quad F'_3 \geq 0 \\ -0.5, & k = 2, 4, \quad F'_3 = -0.5 \end{cases} \tag{7}$$

For a valid sample point, once the *SIA* and *NRA* are obtained, the *PA* can also be calculated according to the equation:

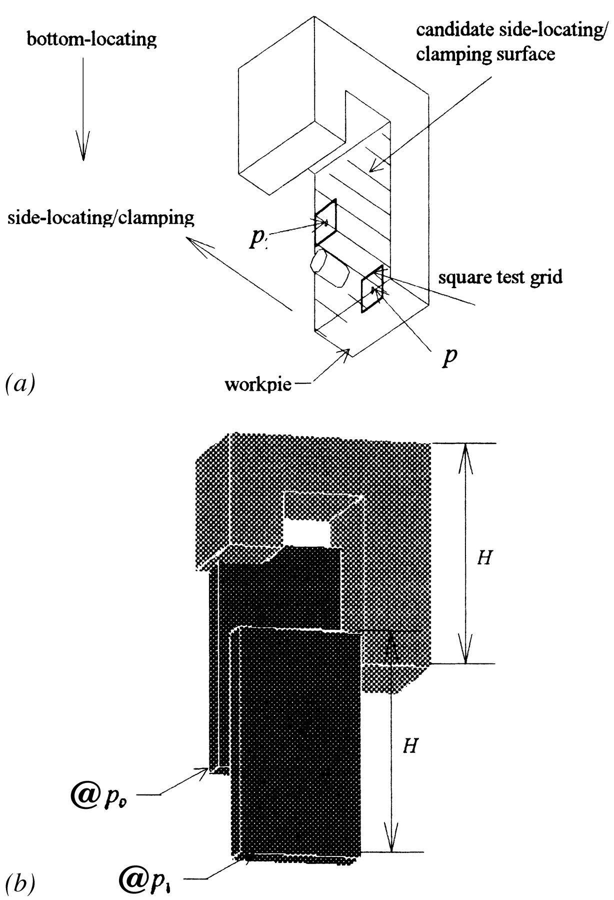

Fig. 4. Obstruction checking at sample points on a side-locating/ clamping surface.

P_4 ○ $(u-1, v+1)$	P_3 ○ $(u, v+1)$	P_2 ○ $(u+1, v+1)$
P_5 ○ $(u-1, v)$	P_c ○ (u, v)	P_1 ○ $(u+1, v)$
P_6 ○ $(u-1, v-1)$	P_7 ○ $(u, v-1)$	P_8 ○ $(u+1, v-1)$

Fig. 5. 3×3 position map of current point P_c and 8-neighbour sample points $P_1 \sim P_8$.

$$PA = SIA + NRA, \quad \text{if } PA < 0, \quad \text{then } PA = 0 \tag{8}$$

From the definitions of *SIA* and *NRA*, *SIA* is in the range of 0 ~ 1 and *NRA* is in the range of −1~1. Therefore, *PA* must be in the range of −1~2. When the value of *PA* is less than zero, the sample point is severely obstructed and is not a feasible fixturing point. The overall accessibility (*OA*) of the fixturing surface is defined as the sum of the *PA* values at all valid sample points, i.e.,

$$OA = \sum_{N_{\text{valid}}} PA_{u,v}, \quad \textit{sample point } p_{u,v} \textit{ is tested valid} \tag{9}$$

As *OA* is statistically measured by the overall effect of the accessibility of the sample points on the surface, the information about the effective area and shape complexity of the surface is represented in the model. Generally, the model satisfies the criterion that the surface with the larger *OA* is more accessible than the one with the smaller *OA*.

3.3 Generalised Accuracy of the Fixturing Features

One of the most important tasks for fixture planing is to guarantee that the tolerance requirements are met when the workpiece is machined. The accuracy of features can be characterised by their tolerance and surface finish, and the tolerance between features. Generally, the tolerance of features can be classified into two types: dimensional tolerance and geometric tolerance. The magnitude of the dimensional tolerance may express the relationship between two features on the workpiece. If there is a feature with a tight dimensional tolerance with respect to a machining feature, this implies that the feature may be used potentially as an operational datum, i.e. a locating surface in the set-up. Based on whether a datum feature is needed, the geometric tolerance can be further divided into form tolerance and positional/orientation tolerance. The form tolerance is associated only with the feature itself, which specifies the allowable geometric variation of individual features. The form tolerance, e.g. surface finish, of a feature affects the suitability of the feature to be the fixturing datum. The positional/orientation tolerance is of the same importance as the dimensional tolerance for fixture planning since it also represents a relationship between features. In order to evaluate the accuracy of a feature and use it efficiently in fixture planning, a generalised feature accuracy grade is applied in this investigation, which is defined as:

$$T_g = (w_1 T_d + w_2 T_p) * (w_3 T_f + w_4 T_r) \tag{10}$$

where T_d, T_p and T_f are the dimensional tolerance grade, positional tolerance grade and form tolerance grade, respectively; T_r is the tolerance grade equivalent to the surface finish of the feature. w_1, w_2, w_3, and w_4 are the weight factors. The multiple operation "*" represents a dominant relationship where a zero value can contribute to the final result, while the operation "+" represents a relatively weak relationship with preferences. T_d, T_p, T_f, and T_r can be obtained by applying the algorithms described in [11,18].

4. Development of Automated Fixture Planning Systems

An overview of the automated fixture planning system is shown in Fig. 6. The procedure for fixture planning can be divided into five stages, i.e. input, analysis, planning, verification, and output. The input data includes a workpiece CAD model containing the geometric and tolerance information of the features of the workpiece, and set-up planning information including the features to be machined and the machine tool type for the specific set-up. The data can be extracted either from a CAD database or entered interactively by the user in a CAD system.

Analysis involves the extraction of the candidate fixturing features with related accuracy information and an evaluation of the accessibility of the fixturing features. In this study, planar and cylindrical surfaces are considered for fixturing purposes.

The task of planning is to determine automatically the primary locating direction and to select the optimal locating/clamping surfaces and points in the current set-up. Algorithms are developed for the planning of the bottom (top) and side locating/clamping arrangements.

Accurate location is the major contributor in ensuring the machining accuracy of the workpiece. Once the locating/clamping scheme is determined, the fixture units corresponding to the fixturing points can be generated by using the fixture configuration design system (Fix-Des) developed previously [19]. A comprehensive program has been developed

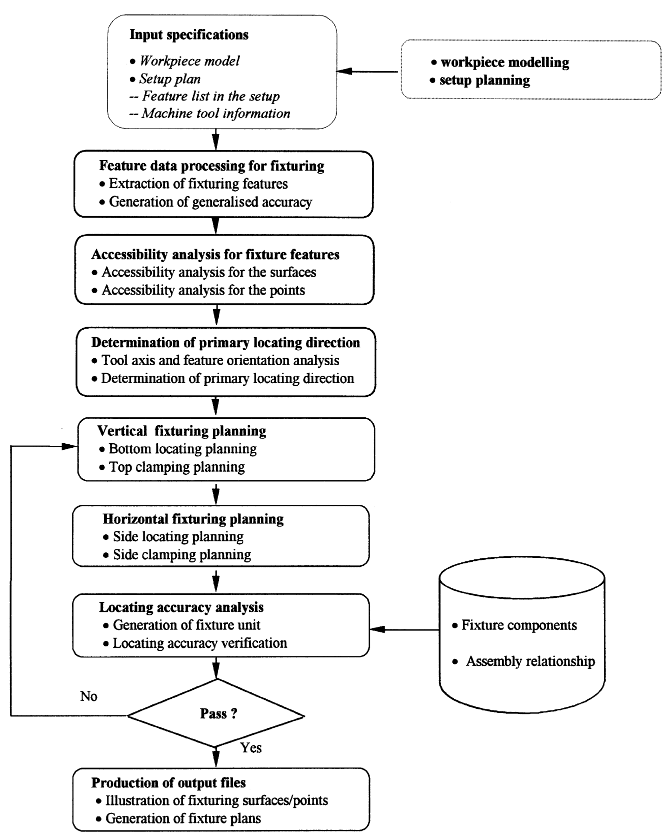

Fig. 6. The procedure of fixture planning.

to analyse the final fixture design in terms of the cumulative tolerances of fixture components and the effects on workpiece accuracy.

The output of the fixture planning is the fixturing surfaces/points in the format of a fixture plan which can be used in fixture configuration design. Although the fixture plan is generated based on some optimisation rules, alternative fixture plans are also provided for further optimisation or user confirmation.

4.1 Determination of Primary Locating Direction

In fixture design, there are usually three locating reference surfaces which determine the position and orientation of the workpiece. The primary locating surface is the major locating datum for determining the spatial position and orientation of the workpiece in the current set-up and constraining at least three DOF of the workpiece. The primary locating surface is perpendicular to the other locating surfaces, which is especially true when modular fixturing systems are used. In the general case, the primary locating surface could be a single plane or several planes in the same direction with the same or different heights. The normal direction of the primary locating surface, called the primary locating direction, needs to be determined first in fixture planning. It should be parallel or perpendicular to the cutting tool axis of the machine tool. Assume that the tool axis is $V_t = (V_x, V_y, V_z)$. The surfaces with normal directions parallel or perpendicular to the tool axis are extracted from the workpiece model. They are grouped as follows:

$$Sf_n = \{f_i(V_i, T_{gi}, A_i) \mid V_i \perp V_t \text{ or } V_i = -V_t, N_f > i > 0\}, \quad N_s > n > 1 \tag{11}$$

where Sf_n describes a group of surfaces with a normal direction in the primary locating direction; $f_i(V_i, T_{gi}, A_i)$ represents a feature with a normal vector V_i, a generalised accuracy grade T_{gi}, and a usable (effective) area A_i; N_f is the number of the features in the group; and N_s is the number of feature groups.

If the primary locating direction is selected as $Vl(Vl_x, Vl_y, Vl_z)$ and $Vl \in \{V_i\}$, the following index is used to identify Vl with a priority order:

$$In\_Vl = \max\{W_A * SA_n/\max SA + W_{T1} * ST_n/\max ST, \quad N_s > n > 1\} \tag{12}$$

where W_A and W_{T1} are the weight factors for surface area and accuracy, respectively. $SA_n = \sum_{j=1}^{Nf} A_j$, $ST_n = \sum_{j=1}^{Nf} T_{gj}$, $\max SA$ is the maximum area in the group, $\max ST$ is the maximum value of the generalised feature accuracy grade in the group. Once the In_Vl is obtained, the normal vector corresponding to the In_Vl is selected as the primary locating direction.

4.2 Planning for Bottom Locating and Top Clamping

The task of fixture planning in this stage is to determine the surfaces suitable for primary location and the distribution of the locating points on the surface, as well as the clamping surfaces and points corresponding to the primary location, as shown in Fig. 7.

The set of the candidate primary locating surface can be represented as:

$$LV = \{f_i(V_i, T_{gi}, C_i) \mid V_i = -Vl, \quad N_f > i > 0\} \tag{13}$$

where $f_j(V_i, T_{gi}, C_i)$ is a feature with a normal vector V_i, a generalised accuracy T_{gi}, and contours C_i characterised by lines and arcs, N_f is the number of features in the set.

When more than one plane is involved, the planes are projected along the primary locating direction to form a virtual plane surface which is represented by its boundary entities such as line segments and arcs. As the surface is sampled at discrete points, an outer-bounding region is generated in the virtual plane. As locating points cannot be very close to the outer edges of the workpiece, the size of the rectangular region is reduced by moving the boundary toward its centre with T. The projection of final locating points will be in this new region. However, since some points may be outside the surface boundary, a standard algorithm is employed for detecting whether a point is in the specific region.

In the primary locating direction, three points (or equivalent) must be selected to constrain three DOF. The three points can be used to construct a triangle and the centre of workpiece gravity should be located inside the triangle in order to guarantee locating stability. The optimal locating points are selected based on the following factors:

1. The area of the triangle should be as large as possible. It is calculated as:

$$TA = (S(S-l1)\ (S-l2)\ (S-l3)) \tag{14}$$

where $S = 0.5 * (l1 + l2 + l3)$, and $l1$, $l2$, $l3$ are the edge lengths of the triangle.

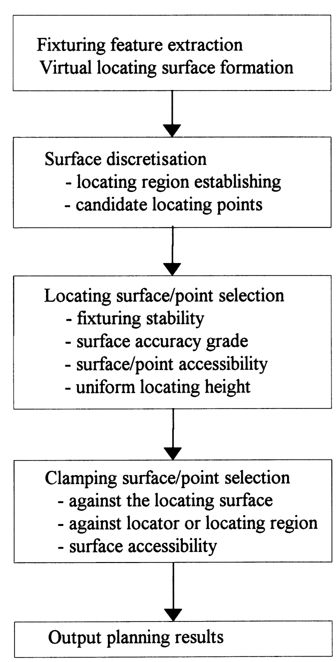

Fig. 7. A procedure of fixture planning in the vertical direction.

2. The distance from the centre of gravity of the workpiece to the three edges of the triangle should be as large as possible, It is calculated as:

$$TL = \sum_{i=1}^{3} Di \tag{15}$$

where Di is the distance from ith edge of the triangle to the workpiece centre of gravity.

3. The generalised accuracy of the planes in which locating points locate should be as high as possible (the tolerance value is as small as possible). It is calculated as:

$$TT = \sum_{i=1}^{3} T_{gi} \tag{16}$$

where T_{gi} is the generalised accuracy grade of the plane in which the locating point P_i locates.

4. The accessibility of the three locating points should be as large as possible. It is calculated as:

$$TC = \min\{Acc_i, Acc_j, Acc_k\} \tag{17}$$

where Acc_i, Acc_j, Acc_k are the accessibility values of the three locating points.

5. The locating height equalisation should be as uniform as possible. It is evaluated as:

$$TH = \begin{cases} 1, & \text{if } z_i \neq z_j \neq z_k \\ 2, & \text{if, } z_i = z_j \quad \text{or } z_i = z_k \quad \text{or } z_j = z_k \\ 3, & \text{if } z_i = z_j = z_k \end{cases} \tag{18}$$

When the values of the above factors are obtained, the following index is used to identify the optimal locating points, which has the maximum value:

$$\begin{aligned} In\_Pl = {} & W_S * (TA/\max TA + TL/\max TL) \\ & + W_{T2} * TT/\max TT + W_{C1} * TC_i + W_H * TH/3 \end{aligned} \tag{19}$$

where W_S, W_{T2} , W_{C1} and W_H are the weight factors for fixturing stability, accuracy, accessibility, and uniform height, respectively; and maxTA, maxTL, and maxTT are the normalisation factors for all candidate vertical locating planes.

Once the final locating points are determined, the locating surfaces corresponding to the three locating points are obtained. It should be noted that by using this procedure one or more planes may be selected as primary locating plane candidates.

Selection of the clamping type is related mainly to the direction of the machining force and the surfaces available for placing clamping devices. The top clamping surfaces are determined based on the following criteria:

1. The surface is opposite to the bottom locating surfaces.
2. The surface is the machining surface in the current set-up.
3. There is an overlap area if the surface is projected into the bottom locating triangle region.
4. The surface is easily accessible by the clamp (e.g. it has a high value of accessibility).

Once the clamping surface is determined, the optimal clamping point is selected so that the clamping force is in the direction against one of the bottom locators or inside the bottom locating triangle.

After the steps stated above, all the fixture plans available for bottom locating and top clamping are generated and recorded sequentially with priority determined by In_*P*l. Each fixture plan file contains fixturing information such as fixturing functions, locating/clamping surface IDs, and the coordinates of the locating/clamping points.

4.3 Side Locating/Clamping Planning

Fixture planning in horizontal directions includes side-locating and clamping planning. Side locating is to determine the non-primary locating surfaces and points. The most common method of side locating is the standard 3-2-1 locating principle. In this case, side locating planning selects two perpendicular planes as the secondary and tertiary locating surfaces where these planes contain two and one locating points, respectively. This locating scheme is preferred when designing a fixture configuration and controlling locating accuracy because of the independent constraints in different DOF. However, there are many cases where it is hard to find such mutually perpendicular locating planes in fixture design. For a more general situation, cylindrical surfaces and non-perpendicular planes may also serve as the locating surfaces and sometimes, the three side-locating points may be distributed on three different surfaces. In this study, general solutions are provided, including the standard 3-2-1 situation as the priority solution.

To select satisfactory side-locating surfaces, the normal direction, generalised accuracy grade, accessibility value, and the shape of the candidate surfaces are taken into account. The set of features which meets the side-locating requirements can be expressed as:

$$\begin{aligned} LH = \{ & f_i(V_i, T_{gi}, Acc_i, C_i) \mid V_i \perp Vl \text{ for planes, } V_i // Vl \\ & \text{for cylinders } N_f > \mathrm{i} > 0\} \end{aligned} \tag{20}$$

where $f_i(V_i, T_i, Acc_i, C_i)$ is a feature with a normal vector V_i, a generalised accuracy grade T_{gi}, an accessibility Acc_i, and contour C_i; N_f is the number of features in the set.

In order to constrain three DOF remaining from the primary locating, more than one surface is needed for side locating. As previously stated, besides the condition of individual surfaces, the combination status of the candidate locating surfaces is also an important factor affecting the locating of the workpiece. For the two kinds of locating features, there are many combinations which can be used in side locating. The following is a partial list of the combinations in the preferred order:

1. Two planes perpendicular to each other.
2. Two planes which are not perpendicular.
3. Three planes.
4. One plane and one cylindrical surfaces.
5. Two cylindrical surfaces.
6. One plane and two cylindrical surfaces, as shown in Fig. 8. Based on these types of combinations, feature groups can be constructed and expressed as:

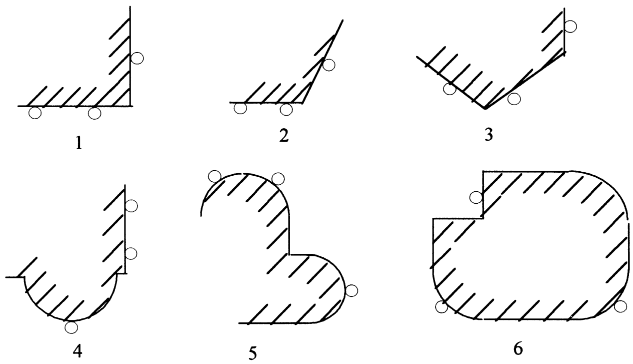

Fig. 8. The feature combination types. 1. Two perpendicular planes. 2. Two non-perpendicular and non-parallel planes. 3. Three non-perpendicular and non-parallel planes. 4. One plane and one cylindrical surface. 5. Two cylindrical surfaces. 6. One plane and two cylindrical surfaces.

$$LHC_m = \{f_i \mid i = 1, 2 \text{ or } 1, 2, 3, f_i \in LH\}, \quad m = 1, 2, \ldots, N_m \tag{21}$$

where f_i is a selected feature in the group and N_m is the number of feature groups.

Each feature group contains two or three features. The criteria used for evaluating the feature group includes:

1. *Feature combination status*. A weight factor, HF, is assigned to the different types of combination of locating surfaces, which is the most preferred if the feature group comprises two perpendicular planes and which is the least preferred if the feature group is comprised of three cylindrical surfaces;
2. *Generalised accuracy grade of the feature group*. The generalised feature accuracy grade is considered for all the surfaces in the group, $HT = \Sigma T_i$, where T_i is the generalised accuracy grade of the surface i in the feature group, and i = 1, 2, and 3.
3. *Accessibility value of the feature group*. Accessibility of each surface in the group is considered, $HC = \min\{Acc_i \mid i = 1, 2, \text{ or } 3\}$, where Acc_i, is the accessibility value of the feature in the candidate horizontal locating surface group.

The following index is used to identify the optimal locating surface group when the values of the above factors are obtained.

$$\text{In\_}Hl = HF + W_{T3} * HT_i/\max HT + W_{C2} * HC_i, \; N_s > i > 1 \tag{22}$$

where W_{T3} and W_{C2} are the weight factors for surface accuracy and accessibility, respectively, and maxHT is a normalisation factor of feature accuracy.

When the candidate locating surfaces are classified into groups, the locating height is determined. It is desired that all the side locators, as well as the clamps, are placed at an identical height, or the difference of the side-fixturing point heights is minimum.

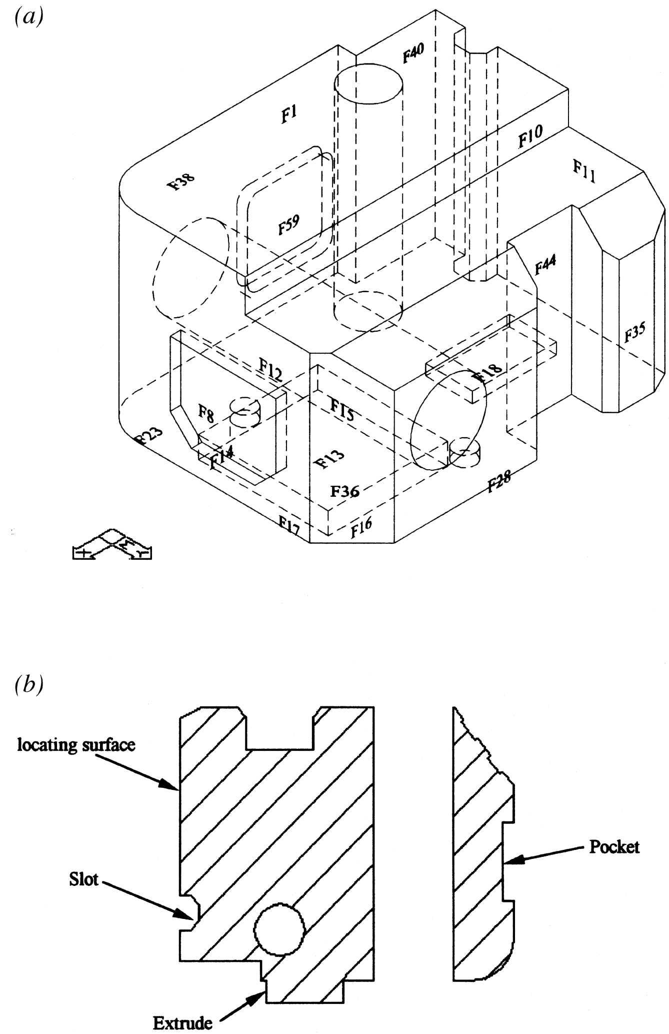

Fig. 9. Workpiece model and intersection plane for side locating.

Once the locating height is determined, the available locating region in the locating surfaces become 2D lines and arcs or circles. Those 2D locating “regions” can be extracted directly from the workpiece CAD model. Figure 9 shows an example of the cross section at the locating height. The positions of the locating points on the 2D line segments are determined, based on the different surface status and point accessibility. Two conditions must be satisfied for a feasible solution for side-locating planning [16]. The first one is that the normal directions of the locating surfaces cannot all be parallel, which is ensured in the feature grouping process. The second one is that the normal directions from the three locating points cannot meet at one point, which would give an uncertain location of the workpiece.

For fixturing stability, the side clamps should be applied to surfaces which are opposite to the locating surfaces. A complete solution has been developed for determining the side-clamping surfaces and feasible regions of the clamping points [20]. Figure 10 shows the planning procedure of side locating/clamping.

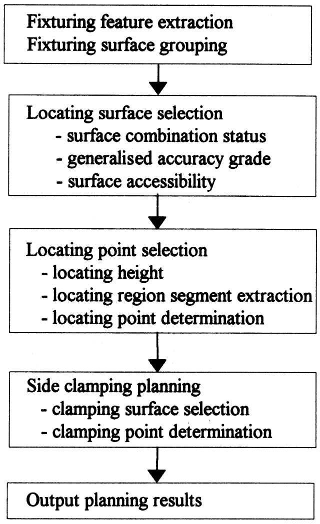

Fig. 10. A procedure of fixture planning in a horizontal direction.

5. Implementation Example and Conclusion

A fixture planning system, Fix-Planning, is developed, which is integrated with a CAD system and an automated fixture configuration system, Fix-Des. The CAD system is used as a platform to provide the system with the input information necessary for fixture planning, and Fix-Des is used for generating the fixture configuration design using the output from Fix-Planning. Figure 11 shows the main system menu showing eight functional modules. *SysSetup* is used to initialise the system before performing the planning tasks. An example of system initialisation is shown in Fig. 12 where the customised planning conditions are set-up, such as the clamping type, the minimum size of locators and the minimum placement height of locators in horizontal locations, and the priority sequence of the major factors which affect the vertical location. *File* is used to read the workpiece specification from the CAD database, and to store the fixture plans for fixture configuration design. *LocatingDir* is for determining the workpiece primary locating direction. *Accessibility* is for evaluating the accessi-

Fig. 11. Overview of the Fix-Planning system.

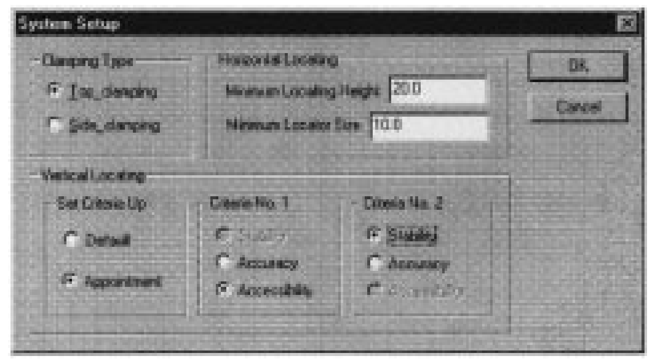

Fig. 12. An example of initialisation of the system.

Table 1. Results of accessibility analysis (BL – bottom-locating; SL – side-locating; SC – side-clamping; TC – top-clamping).

Face-id	Normal direction	Area	Function	Valid	*OA*
F1	$(0, -1, 0)$	6095.04	SL/SC	Yes	1.312395
F8	$(1, 0, 0)$	1900	SL/SC	No	N/A
F10	$(0, 1, 0)$	2322.58	SL/SC	No	N.A
F11	$(-1, 0, 0)$	6464.19	SL/SC	Yes	6.983632
F12	$(1, 0, 0)$	5126.26	SL/SC	Yes	4.819779
F13	$(0, 0, -1)$	3462.37	BL	Yes	0.875000
F14	$(0, 1, 0)$	563.77	SL/SC	No	N/A
F15	$(1, 0, 0)$	614.14	SL/SC	No	N/A
F16	$(0, -1, 0)$	563.77	SL/SC	No	N/A
F17	$(-1, 0, 0)$	614.14	SL/SC	No	N/A
F18	$(0, 0, -1)$	875.73	BL	No	N/A
F23	$(0, 0, -1)$	12342.47	BL	Yes	16.962994
F28	$(0, 1, 0)$	3109.46	SL/SC	Yes	4.090943
F35	$(0, 1, 0)$	1008.58	SL/SC	Yes	0.967515
F36	$(0.707, 0.707, 0)$	1996.16	SL/SC	Yes	1.743387
F38	$(0, 0, 1)$	9942.9	TC	Yes	19.599906
F40	$(0, -1, 0)$	3415.2	SL/SC	Yes	1.219500
F44	$(0, 1, 0)$	2322.58	SL/SC	Yes	0.579375
F59	$(0, -1, 0)$	1578.54	SL/SC	Yes	2.114299

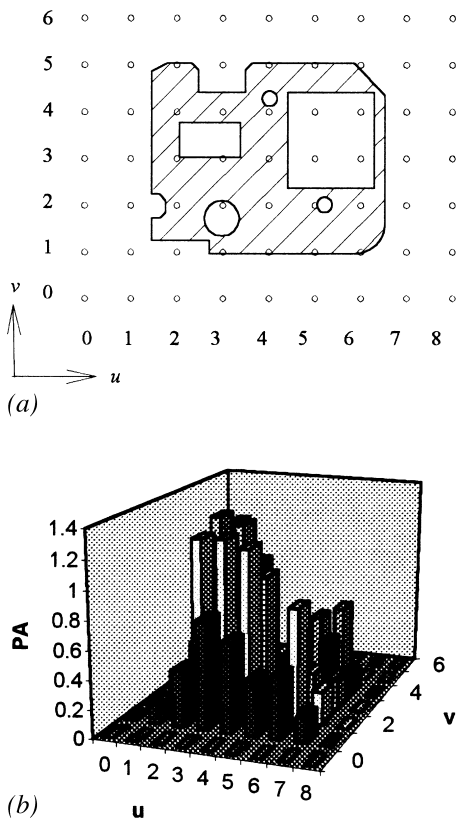

Fig. 13. *PA* values of sample points on a bottom-locating candidate surface F23. (*a*) The distribution of sample points on surface F23. (*b*) *PA* values of all sample points on F23.

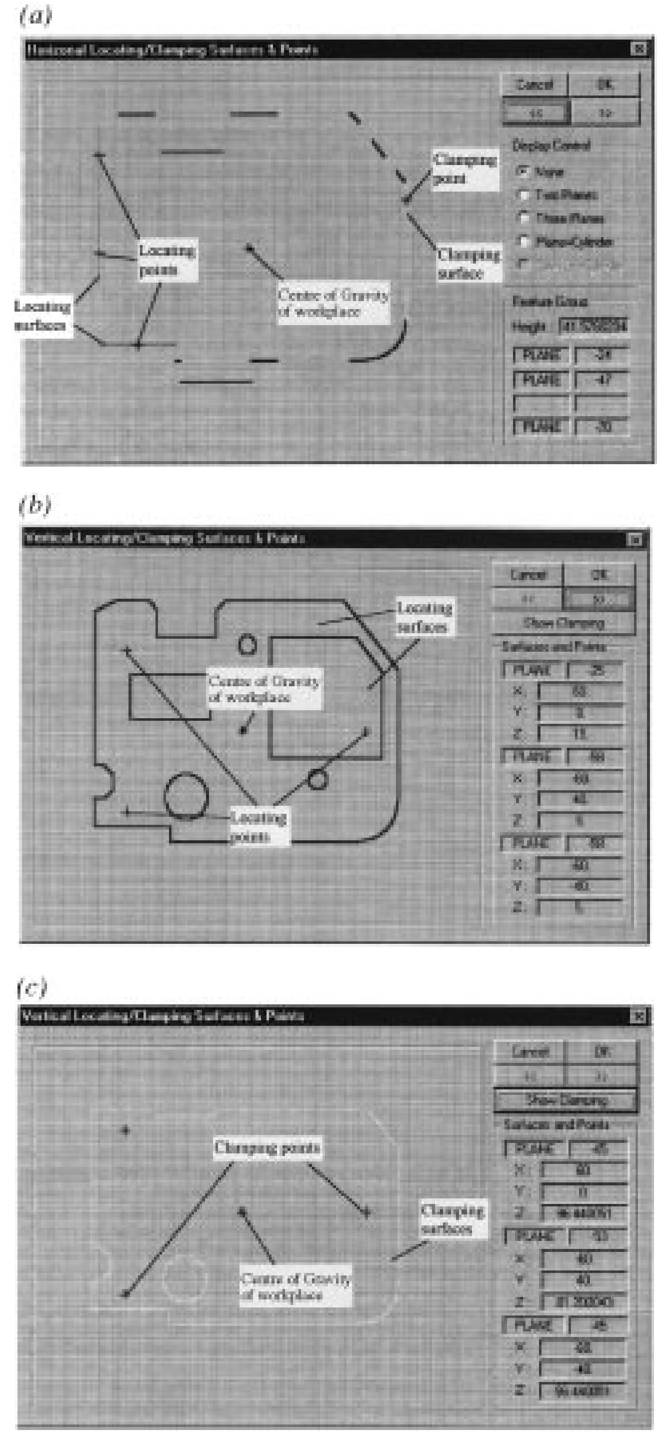

Fig. 14. (*a*) An example of horizontal locating/clamping. (*b*) An example of vertical locating. (*c*) An example of vertical clamping corresponding to vertical locating.

bility of fixturing features and points. The algorithms for side- and bottom(top)-locating/clamping are embedded in the modules *HorLocating*, *HorClamping*, *VerLocating* and *VerClamping*. When fixture planning is completed, the results are displayed with priority preference.

An example workpiece is shown in Fig. 9(*a*) where the step surface F46 is to be machined. Table 1 shows the results of the accessibility evaluation for candidate fixturing surfaces and Fig. 13 shows the point accessibility distribution of a candidate bottom-locating surface. The results of fixture planning in the horizontal and vertical directions are shown in Fig. 14. The results may not be unique. Alternative plans are also provided when necessary. Figure 15 shows the fixture configuration design.

As seen in the example, the fixturing surfaces and points are automatically selected based on the consideration of multiple factors including feature accuracy, fixturing stability, and fixturing surface accessibility. In the system, the workpiece geometric information is extracted directly from CAD models, set-up planning information is specified as input, and planar and cylindrical surfaces are considered as fixturing surfaces. Fixturing surface groups are established for vertical and horizontal planning. Alternative plans are provided for further optimisation and user confirmation. Fixturing points are also automatically determined, which is the output for fixturing configuration designs using the previously developed system, Fix-Des. Applications of the system will lead to a great reduction in manufacturing planning lead time and, therefore, enhance the capability of the manufacturing system to respond to changes in product design.

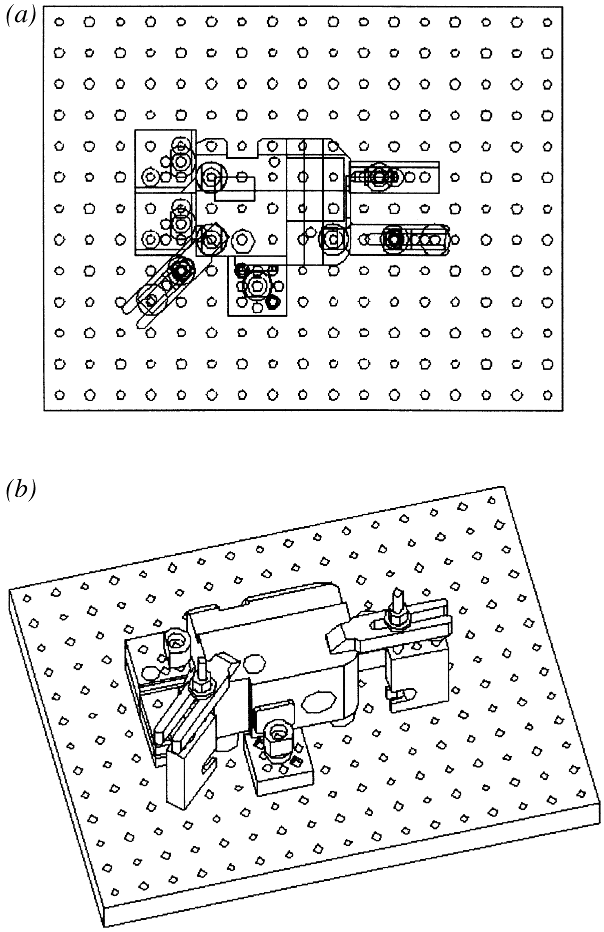

Fig. 15. The final result of fixture configuration design. (*a*) 2D top view. (*b*) 3D view after removing hidden lines.

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