FIXES, A System for Automatic Selection of Set-Ups and Design of Fixtures

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This paper reports on the development of a computer aided planning system for the selection of set-ups and the design of fixtures in part manufacturing. First, the bottlenecks in the present planning methods are indicated. A brief description is given of the CAP environment PARTR, in which FIXES is incorporated. The planning procedure of FIXES consists of two parts: the selection of set-ups and the design of a fixture for each set-up. The automatic selection of set-ups is based on the comparison of the tolerances of the relations between the different shape elements of the part. A tolerance factor has been developed to be able to compare the different tolerances. The system automatically selects the positioning faces and supports the selection of tools for positioning, clamping and supporting the part. A prototype implementation of FIXES is discussed.

KEYWORDS: jigs & fixtures, set-up, clamping, design, process planning, CAP, CAM

1. Introduction
Process Planning is one of the main bottlenecks in flexible manufacturing of parts in small batches. A large portion of the time and cost of work preparation is spent on the selection of set-ups and the design of fixtures. Also time-consuming and costly is the construction of a system which can automatically select set-ups and which provides an efficient tool for the design of fixtures.

The fixture process consists of both the selection of the set-ups required to machine a part according to the given specifications and the design of the different fixtures. With reference to present planning methods, the process planner is simultaneously engaged in the selection of machine tools, set-ups, machining methods, cutting tools and fixture components. His decisions are based on experience and are limited by the geometrical constraints stated in the part drawings and by the available equipment.

The most important bottlenecks in present fixture methods are:
- it takes much time to realize a fixture
- results largely depend on the capabilities of the process planner
- fixture knowledge is restricted to individuals persons
- the finally accomplished accuracy of a fixture is difficult to predict
- there is a lack of flexibility, resulting in (i) a new fixture for each problem and (ii) a large amount of fixture tools.

Present fixture knowledge is not available in an explicit form (e.g. as formalized procedures). This has hampered the development of adequate fixture methods and, in contrast with other planning functions, explains the lack of interest in carrying out research and education programs concerning fixtureing.

However, against the background of continuous developments in the field of CAD/CAM, there is an increasing need to use the computer for fixtureing as well. This requires an analysis of the present knowledge and the development of methods, which are based on this knowledge.

Important requirements for a computer aided fixtureing system are:
- it must be interfaced to other CAD/CAM functions
- it must be capable of storing solutions
- it must be able to generate alternative solutions on request
- it must be interfaced to other CAD/CAM functions

In order to develop such a fixtureing system, an analysis has been carried out of both the work preparation methods concerning fixtureing and the functions of fixtures. This has resulted in the definition of a system, which meets the above mentioned requirements.

2. The environment of FIXES
2.1. The process planning system PART
The use of a generative system for the selection of set-ups and the design of fixtures will only be efficient if it is integrated with the other process planning functions. At the moment a prototype of such an integrated process planning system, called PART, is under development in our laboratory (1). See fig. The PART system contains five main modules covering the machine tool selection (MTHS), the selection of set-ups and design (JF), the selection of machining methods (MM), the selection of cutting tools (TS) and the selection of cutting conditions (CC). The different modules are controlled by a so-called supervisor, which acts as an interface. A common database is required to achieve consistency of data and fast data exchange between the modules. Another important aspect is the use of a product modeler. The modeler can generate complete, exact and unambiguous 3-D part representations, which are directly accessible for automated information processing. Most of the applications, such as NC or CAPP, do not use for manufacturing applications, since e.g. the product representations cannot contain technological information (2,3,4,5). The PART system uses a boundary representation solid modeler (OPM) (1,2) with exact geometry representation and offering facilities to store technological information like tolerances and material specifications. The VE module is a user interface to the modeler and enables the user to interactively manipulate and visualize a product model. A common user interface emphasizes the integration of functions in the system. The FR module is described in the next paragraph. The FIXES system covers the JF and MM modules.

2.2. Product model and feature definition
Information exchange between the design and the manufacturing department is traditionally carried out by means of technical part drawings. To ensure the functionality of the part, the designer adds geometric specifications, such as tolerances, to the 2-D drawing. In order to manufacture the part, the process planner has to read and interpret this data. This twofold translation of information (to and from the drawing) can easily lead to misunderstandings and errors. The application of an adequate solid modeler in the design stage eliminates the 2-D drawing as a data bridge between the designer and the process planner.

The use of shape elements, so-called features, enables direct access of the data of the product model for planning purposes. A feature is a distinctive character of a part of a definite geometrical shape, which is either specific for a machining process and/or can be used for fixtureing or measuring purposes (2). Examples of features are a hole, a pocket, a slot, a (plane) face, etc. A face can be a feature, but also a part of a feature. The characteristics of a feature are described by feature parameters. The feature recognition module (FR) of the PART system is developed to enable access to the data of the product by the different PART modules; the FR module automatically searches a given product model and recognizes the different features and assigns values to the feature parameters (2.5.7). Each module of PART is designed to work with these features.

The geometrical requirements of a part are expressed as geometrical relations between the different features. The machining of a feature requires a particular orientation of the feature with regard to the machine tool axis: the feature orientation (F.O.). Each feature is provided with at least one default F.O. Some features can have more than one F.O. (e.g. a through-hole).
3. The FIXES system

3.1. The planning functions in FIXES

The machining process contains two important planning functions: (i) the selection of set-ups and (ii) the design of the fixtures.

The primary functions of a fixture are to position, to clamp and to support the part. The process of fixture selection starts with set-up selection and continues with the design of a fixture for each set-up. First, the system selects the features of the parts which have to be machined in one set-up. The selection depends on both the accuracy of the geometrical relations between the features and the required orientations of the part with regard to the machine tool axis. The design of a fixture starts with the selection of the positioning faces of the part. The selection depends on geometrical relations, in this case between existing features of the part and the features which will still have to be machined. Next, the clamping and supporting faces are selected, followed by the selection of the positioning, clamping and supporting tools. The tools are selected from a fixed tool set. Finally, output data is produced both for assembly of the fixtures and for use in the following planning processes.

3.2. The set-up selection

The features which have been extracted from the product model, represent the information necessary for positioning, machining and measuring the part. The features which have to be machined have to be arranged in groups (= set-ups). Each set-up requires a fixture. The number of fixtures has to be minimized because of cost and time involved in the realization of each fixture.

The machining of a feature results in a more or less accurate position of the machined feature with respect to the machine tool coordinate system. This position is lost if the part is dismounted from the machine tool and mounted again in a different fixture. The errors in the alignment of the fixture on the machine tool can be equal to or larger than the accuracy requirements of small-tolerance relations. As a result, the positional accuracy of a feature, which has already been machined in a previous set-up, can be insufficient to realize the required accuracy in the relations that feature and those which have to be machined in the present set-up. See fig. 2. So, closely related features have to be machined in one set-up, while less accurately related features can be machined in different set-ups. Therefore, the set-up selection has to be preceded by an evaluation of the tolerances concerning the different features. After that, the most accurate relations are selected and the corresponding features become primary candidates to be selected in one set-up. However, a set-up can contain only a limited number of different feature orientations (the maximum number depends on the machine tool configuration). So, only those candidate features are selected which feature orientations fit in the set-up. In this way, the selected set-ups result in minimum requirements for alignment of the different features.

3.3. Fixture design

Fixtures are based on a standard baseplate and separate positioning, clamping and supporting tools.

3.3.1. Positioning

Features which are dealt with in a given set-up, can have explicitly defined geometrical relations with features which have to be machined in a next set-up, resulting in existing features serving as a basis for the new set-up. In this way, existing features carry the most important relations with the features which still have to be machined, serve as reference features and have to be located at prescribed positions of the machine tool coordinate system. See fig. 3.

The faces which are actually used to position the part, are the so-called positioning faces. In most cases, reference features include the positioning faces. Only in those cases where the relative size of the reference features is small and/or the features are badly distributed, one has to look for separate positioning faces. See fig. 4.

The first stage in the positioning procedure is to find the best suited reference features. The extent to which the requirements of the relations between the existing features and the features which still have to be machined are met, depends on the accuracy with which the part can be positioned. The magnitude of position errors (both translation and rotation errors) are dependent on: (i) the positioning faces which have been selected and (ii) the realized geometric accuracy and mechanical stability of the fixture.

The translation errors resulting from inadequate part alignment can be compensated by the machine tool control system, which means that they need to be considered in the planning procedure. Contrary to this, rotation errors cannot be compensated, the required relation can be realized only when the corresponding features are machined in the present set-up. Therefore, the selection of the positioning faces for a given set-up is based on:

- a comparison of the accuracy of the relations between the already existing features and features which still have to be machined; this results in the selection of the reference faces
- the distance between the features which have to be machined and the reference faces
- the distance between the potential positioning faces
- the orientation and position of a potential positioning face relative to the remainder part of the workpiece
- the characteristics of the faces: size, type, roughness, shape tolerance, orientation and position with regard to the baseplate.

The first four items are of primary importance with respect to rotation errors in the position of the part. The last item is important with respect to the selection of the positioning tools.

3.3.2. Clamping

The clamping function is performed by locking the part to the supporting tools by means of one or more clamping tools. During the clamping process, the position of the part has to be determined by the positioning tools and must not be influenced by the clamping forces. See fig. 5. In this design stage of the fixture, the part is considered to be rigid (no deflections). First, the primary supporting faces are selected. Positioning faces are the first candidates to become primary supporting faces; these are selected depending on the size and the estimated load. Positioning faces which do not meet the requirements of sufficient strength will be assisted by additional supporting faces in the vicinity of the positioning faces. Subsequently, the clamping faces are as much as possible selected at locations opposite to the supporting faces.

3.3.3. Secondary support

Under normal conditions, a part will always deflect under the clamping and the machining load. If the estimated deflections of a part are larger than is allowed by the prescribed tolerances, then so-called secondary supporting components are required. The selection of secondary supporting faces is based on the available faces, the locations of maximum deflections and the deflection magnitudes.
3.3.4. Integration with the other planning functions

FIXES (the J & F module) is used in two phases of the planning process: (i) set-ups are selected after the selection of a machine tool and (ii) fixtures are designed after the selection of the machining methods and the cutting tools. This sequence results from the input requirements for both set-up selection and fixture design, as can be seen in the following table:

<table>
<thead>
<tr>
<th>Input to set-up selection</th>
<th>From fixture design</th>
<th>To set-up selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>the features of a given part</td>
<td>FR features with set-up parameters</td>
<td>SIM</td>
</tr>
<tr>
<td>the relations between the features per set-up</td>
<td>FR</td>
<td>ITM</td>
</tr>
<tr>
<td>the features in F.O.'s per set-up (number</td>
<td>FR</td>
<td>ITF</td>
</tr>
</tbody>
</table>
| The set-up selection process

4.1. Feature relations and the conversion of tolerances

The two main objectives of the set-up selection procedure are: (i) to reduce the number of critical tolerances in the geometrical relations between features on the parts to the number of set-ups, and (ii) to keep the number of set-ups as low as possible. The importance of the first objective is directly related to the positioning requirements of the part and each with which a fixture can be realized. The second objective is purely economic.

An important part of the selection procedure deals with the comparison of the significance of the different tolerances in the relations between the features. But, different types of tolerances cannot be compared.

For the procedure I: assign one single F.O. to each feature (procedure I), the machine tool configuration has been selected, so the limitations to the F.O.'s are known, (iii) the data belonging to the converted tolerance scheme and the T.F.'s have been calculated. (in) only those relations which contain features with different F.O.'s are taken into consideration.

The main procedure of set-up selection:
1. assign one single F.O. to each feature (procedure I)
2. select the set-ups (procedure II)
3. determine the sequence of set-ups (procedure III)

4.2. The procedures for set-up selection

As explained before, the selection of set-ups depends on: (i) the accuracy of the relations between the features, (ii) the F.O.'s of the features involved and (iii) the number and directions of the machine tool axes.

4. The information flow between J & F module and other PART modules

Table 1. Information flow between J & F module and other PART modules

<table>
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<td>NC</td>
</tr>
<tr>
<td>estimated machining forces</td>
<td>SIM</td>
<td>NC</td>
</tr>
<tr>
<td>plan of available fixture units</td>
<td>TS</td>
<td>NC</td>
</tr>
</tbody>
</table>

Fig. 7. The maximum admissible rotation within the tolerance field

During the set-up selection only a subset of feature relations is considered. This subset contains the relations between the features which have to be machined and in which the two features involved have a different F.O. The last requirement is needed, because related features with identical F.O.'s can be machined in one set-up and do not cause problems. Related features with different F.O.'s often have to be machined in different set-ups and can cause accuracy problems. The corresponding relations are the critical ones in the set-up selection procedure.

The procedure is based on the following assumptions: (i) all the features of the product model have been recognized and the parameter values have been assigned, (ii) the machine tool configuration has been selected, so the limitations to the F.O.'s are known, (iii) the data belonging to the converted tolerance scheme and the T.F.'s have been calculated. (in) only those relations which contain features with different F.O.'s are taken into consideration.

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The procedure is based on a machining center with a one axis turning table including a corner plate (3 usable directions), which implies that a set-up can contain at most 3 F.O.'s with the orientations in one plane. Some definitions:

- set-up base: the 3 first selected features, which form the basis of a set-up
- incomplete set-up: a set-up contains less F.O.'s than is admissible
- non-assigned features: the feature is not yet assigned to a set-up

The procedure to select the set-ups is as follows:

1. Select the set-up base
   - select the relation with the smallest T.F. The features contained in this relation determine two F.O.'s of the set-up base
2. Select the third F.O. of the set-up base
   - find the relation with the smallest T.F. from all other relations containing either the TOF or the REF of the set-up base relation. If the F.O. of the candidate third feature is fitting in the set-up and if this relation contains either the TOF or the REF then add the candidate third feature to the set-up base.
3. Attach the non-assigned features to a set-up

For positioning purposes a subset of all features is taken into account. Per set-up are considered:

(i) the features which have to be machined,
(ii) the already present features and (iii) the geometrical relations between the two kinds of features.

Just like in the set-up selection procedure, the tolerances of the relations are converted to tolerance factors. The smallest tolerance factors determine the maximum admissible rotation and translation errors of the parts during fixturing.

As explained before, rotation errors of the part cannot be compensated by the machine tools controller; therefore they must be under control during fixturing.

3.2. The automatic selection of the 3 positioning planes

Positioning of a part is based on the so-called 3-2-1-method to restrict the 6 degrees of freedom. The 3 positioning directions coinciding with the required 6 positioning faces constitute the normals of the 3 positioning planes: see fig. 9.

The selection of the 3-plane restricts 2 rotations and 1 translation of the part; the 2-plane restricts 1 rotation and 1 translation; and the 1-plane restricts 1 translation only. So, the F.O. of the REF connected with the relation which shows the two smallest rotation values in the converted tolerance scheme determines the orientation of the 3-plane. Subsequently, the orientation of the 2-plane is chosen by selecting the relation which shows only one rotation value in the remaining direction; finally the selection of the 1-plane is a trivial one.

3.3. The selection of the reference features

First, the reference features for positioning have to be determined. The first reference feature is selected by selecting the smallest T.F. The REF of this relation is not necessarily the same as the REF which defines the direction of the 3-plane or 2-plane, although in many cases it is. If the F.O. of the selected REF does not coincide with the orientation of one of the positioning planes (otherwise the feature cannot be used for positioning). The other reference features are also selected, based on T.F. and P.D. The selection is completed when at least one reference feature is found for each of the three positioning planes. In case of complex features (e.g. a deep pocket), it is theoretically possible that one feature can serve as a reference feature in each of the three principal directions; e.g. if the bottom face of the pocket is used as 3-plane and one of the sides as 2-plane and the other side as 1-plane, then the positioning procedure is completed. To recognize such cases, each reference feature has to be examined for possible use in more than one direction.

4.4. The selection of the positioning faces

The positioning faces are selected on the basis of the previous selected reference features. Among the 3 smallest, 6 positioning faces are required in order to position a part. A reference feature is the first candidate to provide one or more faces as positioning faces. The feature will be rejected if it does not meet the requirements of positioning faces; see 3.3.1. and fig. 4. If the feature can be split up into 3 separate faces with the same direction, it can on its own be used as a reference for a 3-plane. If not, one or two extra reference features are needed to create the 3-plane. The extra features are selected just like all the other reference features.

6. The implementation of FIXES

Since January 1983 the Laboratorium for Production Engineering is involved in the development of a computer aided fixturing (CAF) system. The first prototype, built for an industrial firm, was delivered in 1985 (12). This early prototype, called the CAF-system, represents an early version of a fixturing system, with a limited functionality. A technical drawing serves as the input of the CAF system. The data of the drawing are converted by hand into lists, which contain the relations between the faces. The selection of set-ups follows a similar approach as described in the FIXES system but without using the tolerance factor. The functionality of the design procedure is limited to the selection of positioning faces and positioning components. A limited set of modular positioning elements is available.

The system determines the orientation of the positioning components and finally integrates the components in the fixturing configuration. A part list and a coordinate list are generated automatically. Presently, the system is used in a job shop environment at Werkspoor Sneek b.v.

The FIXES project started in June 1985 (13). Since then, a more sophisticated method for both the selection of set-ups and positioning faces has been developed, based on an accurate comparison of tolerances (14). The implementation of the procedures for the selection of both the set-ups and the positioning faces is finished. Present work is directed towards the development of procedures for the selection of the clamping faces and tools for positioning and clamping.

7. Conclusions

During the last decade it has frequently been suggested, that despite the use of sophisticated CNC machine tools and computer aided NC-program generation, it would be impossible to achieve real flexible manufacturing conditions, because, after having solved the problems of automation of machining, tooling, loading and transport, the fixturing problem would still remain. In time and space. It has been demonstrated, that by systematic analysis of the activities of the planning department and by formalizing step by step the functions in the planning, fixturing does no longer need to be a bottleneck in computer aided process planning.

Acknowledgments

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