Knowledge in the Domain of Feature-Based Fixturing Planning*

Chen-yu WANG** and Ichiro INASAKI**

This paper focuses on the development of domain knowledge in feature-based fixturing planning. A knowledge base can be classified into compiled, qualitative, and quantitative knowledge. The knowledge is expressed in the form of rules to aid the assessment of machining sequences. One example is the utilization of the combination factor for feature primitives. The assessment of the combination factor precludes less optimal machining sequences for machining operations. Four sub-domains, viz., predicate logic, frames, production rules, and procedural programs represent the domain knowledge in fixturing planning. Production rules are the most essential type of knowledge for fixturing planning process. They are a collection of fixturing rules and axioms. The inference mechanism based on the 3-2-1 fixturing method can refer to the production rules and suggest fixturing configurations from a feature-based workpiece data model.

Key Words: Fixturing Planning, Knowledge Base, Expert System, Process Planning, Machining Sequence, Feature-Based Data Model

1. Introduction

Fixturing planning is one of the most challenging process planning tasks. A study shows that in small batch production, the cost of the fixture can easily be more than 30% of the total cost of the manufacture of a product. On average, the time needed for the design of the fixture is approximately 25% of the total process planning time⁽¹⁾. The imperfection of fixturing planning in terms of cost and time has drawn various researchers and engineers to determine ways to improve its overall performance⁽²⁾. It is generally perceived that the difficulty in speeding up the fixturing planning process lies on the fact that the process requires a broad range of human knowledge, or on-the-job experience, rather than rigid steps of computational optimization.

Advances in feature technology have enabled a partially automated fixturing planning process. By utilizing the feature technology, workpiece model is represented by means of form features that carry far more helpful information on the workpiece that could

aid the process planning task^{(3),(4)}. However, feature-based workpiece representation is not the sole solution to overcome the current obstacles in fixturing planning process. Still, a feasible automated fixturing planning system requires the application of knowledge-based expert system. Several researchers have presented the work on various knowledge bases for use with process planning task⁽⁵⁾⁻⁽⁷⁾. Nevertheless, few have achieved satisfactory result as for the shop floor practice. It has been identified that one of the underlying causes is the absence of formalized fixturing knowledge⁽⁸⁾.

This paper starts with the introduction of the feature-based data model and continues on the architectural overview of the knowledge base. A schematic of the fixturing system, currently under development, is shown in Fig. 1. Based on the structure, the assessment of machining sequence for feature-based data model and the development of knowledge representation for fixturing planning would be elaborated in the later paragraphs followed by the inference structure proposed to utilize the fixturing knowledge base. The paper will also touch upon the setup of a fixel database for use with the system. Fixel is the acronym for fixture elements, such as locators, clamps, and supports. Lastly, a conclusion on the proposed system and further work to migrate the

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** Keio University, IA & A Laboratory, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan. E-mail: wang@ina.sd.keio.ac.jp

Fig. 1 Feature-based workpiece fixturing system

knowledge base to computer programs are explained.

2. Feature-Based Data Model

One of the key components of the fixturing system is the feature-based data model. The feature-based data model provides more robust information about the workpiece than traditional IGES (Initial Graphics Exchange Specification) based data model. In fact, there have been various research activities to study the feasibility and application of the feature technology⁽⁹⁾. Due to the complexity involved in the process of designing a fixture, standard IGES representation no longer serves the sufficient purpose for process planning tasks because it carries merely the collection of geometrical entities that comprise the workpiece. On the other hand, the feature-based representation of a data model consists of more comprehensive descriptions about the workpiece. In addition to the geometrical composition of the workpiece, the design functions can also be incorporated into the data model.

A formal description language is adopted to represent a knowledge based data model that can allow greater seamless integration of computer-aided design (CAD), computer-aided process planning (CAPP), and computer-aided fixturing planning (CAFP). The knowledge based data model is compliant with the information modeling language EXPRESS (ISO 10303-11), which is part of the STEP standard (Standard for the exchange of product model data, ISO 10303)^{(10),(11)}. The workpiece description that is used for the exchange of actual workpiece data is generated by a feature-based CAD system. The CAD system utilizes a so-called EXPRESS-Object-Library, where object templates are structurally defined, to comprehend the design knowledge regarding the workpiece. Consequently, the created objects are referred as "features" that incorporate the

data model with information about its geometric features, quality features, supplemental geometry objects, fixturing features, machining process objects, fixturing processing objects, process plans, and fixturing plans⁽¹²⁾.

The immediate advantage of the feature-based data model representation is that different types of feature can be defined to suit various process planning tasks. At the design stage, form features, or feature primitives, are used to represent a designer's intended functions. During process planning, fixturing features could be applied to represent the workpiece to exhibit its functional elements to be concerned for fixture configurations. Down at the manufacturing stream, machining features are adapted to deal with material removal from the workpiece. The information-rich feature-based data model could greatly assist the knowledge-driven machining sequencing and fixturing planning tasks.

3. Knowledge Base for Fixturing Planning

The structure of the knowledge base is consistent with the framework of the planning system itself. Very often, the process of gathering, organizing, and compiling the knowledge does not end with the development of the system. The types of knowledge involved in the design of fixtures are implemented in the form of a knowledge base to provide systematic reference and update. They are collected to form a search space for knowledge acquisition. The structure of the knowledge base can be decomposed into three categories, compiled knowledge, qualitative knowledge, and quantitative knowledge⁽¹³⁾. Compiled knowledge includes the physical properties of the workpiece as well as inventory statistics of modular fixturing elements. Dimensions, tolerance, and mechanical properties of a workpiece are a form of compiled knowledge. Qualitative knowledge is an essential category of the knowledge base. It contains rules of thumb, heuristics, or common senses from skilled workers and is often the primary basis for decisions in the fixturing planning process. Production rules are examples of qualitative knowledge. These rules are difficult to be quantified and significantly dictate the final design of the fixture. For example, four locators are sometimes used to secure a workpiece's datum surface although three locators could sufficiently serve same purpose. Despite the redundancy of the extra locator, designers argue that such practice benefits from the increased stability of the fixture enclosure when four-point locating mechanism is put to use. Quantitative knowledge contains numerical specification data and values which can be used for automatic computations of pertinent

Fig. 2 Architecture of the knowledge base

characteristics of the fixture. It facilitates the implied qualitative knowledge in optimizing a fixture configuration. In other words, while production rules are able to provide the result as where the fixels should be placed to secure a workpiece, mathematical functions, such as the calculation of center of gravity of the workpiece with respect to the fixture, can be employed to fine-tune the fixturing positions on the workpiece. Other integral components to handle the search space are the search facility and the search process. They facilitate the process of knowledge acquisition by means of inference and explanation. Figure 2 shows the architecture of a knowledge base. While a search space comprehends the knowledge in the domain of fixturing, the search facility is deemed to be the "intelligence" for decision-making process in knowledge acquisition.

4. Assessment of Machining Sequences

In fixturing planning, machining sequence determines the order of machining operations to be performed on the workpiece. For a feature-based workpiece model, the determination of machining sequence utilizes the feature attributes associated with the workpiece. From the viewpoint of feature-based data modeling, the machining sequence is the steps of creation of each individual form feature. The desired final shape of a workpiece is achieved gradually by combining, or superimposing, individual feature primitives. Thus, by evaluating the combining feasibility of features, the order of machining for each form feature can be determined. The combination factor (CF) measures the degree of conformity between feature primitives. The combination factor is assessed according to the quantitative knowledge acquired for machining sequence. The knowledge consists of rules in the form of "IF <evidence> THEN <hypothesis> CF"⁽¹³⁾. The hypothesis will increase the degree of the combination factor given that the same

Fig. 3 Coplanar relationship for a workpiece

evidence is observed. The combination factor can also be interpreted as the certainty factor. It measures and defines the "importance" of a hypothesis with a weighted value relative to the fixture design process. The determination of the combination factor is rather subjective since human reasoning in the design process often possesses different viewpoints on to what level a condition is satisfied and granted. Therefore, the purpose of quantifying the combination factor is to propose a consistent framework that the fixturing rules can be valued in accordance.

To illustrate the facilitation of combination factor, consider the example workpiece shown in Fig. 3. Here, the example workpiece is comprised of six feature primitives. The arrows indicate the direction of association between feature primitives. The numerical values enclosed in the circles and parentheses are the numbers of coplanar surfaces and imaginary surfaces one feature possessed with another, respectively. We define coplanar surfaces as surfaces, of different feature primitives, that share the same 2-D plane within the geometric boundary of the workpiece. For example, in Fig. 3 the top surface of the Open_Step is positioned on the same 2-D plane as the top surface of the Stock material. Both top surfaces are said to be coplanar surfaces. The coplanar surfaces are the new surfaces to be created on the workpiece after the particular feature primitive is machined. The imaginary surfaces are the shared surfaces of the particular feature primitive and its associated one.

The coplanar relationship between feature primitives serves as a knowledge rule that can be considered as the evidence to obtain the combination factor. That is based on the reasoning that the more shared surfaces of feature primitives, the more closely they are related in the machining sequence. When there exists a coplanar relationship between two feature primitives, which indicates the two are "connected"

Fig. 4 Feature selection for machining sequence

volumetrically. Thus, the selection criteria determine which portion of the volume, or the feature primitive, is to be removed by machining operation first. In the case when one coplanar surface is parallel to the datum surface, that is, one feature is “stacked” on the top of the other, a general practice will be to machine the feature primitive that is closer to the machine tool. By doing so, the depth of cut for other feature primitive could be shortened to minimize tool deflection that leads to machining inaccuracy. For instance, in Fig. 4(a) the coplanar relationship between the Through_Hole and Open_Step features suggest that the Through_Hole to be drilled either before or after the Open_Step is created. Nevertheless, the rule would further suggest the Open_Step to be machined first for the two reasons: it requires lesser depth of drilling for the making of Through_Hole at later stage and it minimizes burrs around the Through_Hole. The first reason also explains the preference in having the top Open_Step machined before the feature located at the bottom, as illustrated in Fig. 4(b). Under the circumstance when the feature primitives of a workpiece are equally represented such as the Through_Hole feature primitives shown in Fig. 4(c), the machining order will depend on the type of machine and the location of its tool. In general, the order will be determined according to the shortest possible moving path of the machine tool. Overall, although the assessment does not necessarily simplify the machining operation to a great extent, the process is perceived as common practice on the shop floor.

Figure 5 shows the assessment of the combination factor for the example workpiece given in Fig. 3. Using the syntax of the knowledge rule, the assessment takes the form of “IF coplanar=yes THEN CF=no. of coplanar surfaces.” The assessment table shown in Fig. 5 lists all the combination factors for each pair of feature primitives that comprise the

Fig. 5 Assessment of combination factor

Fig. 6 Domain knowledge in fixturing

example workpiece. The assessment is a process of elimination. In the initial stage, Graph 1 in Fig. 5 shows all the possible machining sequences of the feature primitives. After the assessment of the coplanar relationship, some sequences are eliminated (dotted lines) due to their “zero” value of combination factor. The remaining possible sequences are represented by solid-line connections in Graph 2. As a result, the number of possible machining sequences is reduced to simpler combinations as shown in Graph 3. It is apparent that the assessment of combination factor does not yield a single feasible machining sequence. However, this is only the result of one assessment rule. Additional rules such as machining processes and workshop rules can help assess the machining sequences in a more concise way and thus, result in sequences that can be considered as the most feasible solutions^{(14),(15)}.

5. Knowledge Representation

An expert system contains the expert’s knowledge that is represented in a specific domain. In this case, it is the domain knowledge in fixturing. As illustrated in Fig. 6, we have identified four

sub-domains for the purpose of fixturing planning, namely the predicate logic, the frames, the production rules, and the procedural programs. The predicate logic describes the fact about a workpiece. For a feature-based workpiece model, the descriptions are the form features that comprise the workpiece. Using the example workpiece in Fig. 6, the predicate logic associated with the example workpiece can be of three distinct features; Feature_A is a Prismatic_Block; Feature_B is an Open_Slot; Feature_C is an Open_step. For a non-feature-based workpiece model, predicate logic of features can serve as the "templates" for which the feature extraction or recognition algorithms can base on. The frame is a structured data object that holds the attributes of the workpiece's comprising features. The attributes can be either quantitative or qualitative descriptions. Quantitative attributes represent the physical properties of the workpiece at the form feature level. For instance, the location of a feature is a set of numerical values representing its relative position and orientation with respect to the workpiece's reference frame in a three-dimensional space. Qualitative attributes indicate the state of operation for the designated form feature. An example will be the machining status of a feature. The attribute can be "to-be-machined", "not-to-be-used", or "pending" for further processes. The production rules are the conditional terms to be analyzed for the system to yield a feasible fixture configuration for the workpiece. The conditional terms are a collection of rules and axioms implemented to facilitate the planning process. They can be general rules or user-defined rule-of-thumb. And the last, the procedural programs are external functions or add-ons that quantitatively provide the computational simulation result to fine-tune the generated fixturing configurations. The immediate instance of such an add-on will be a function procedure of kinematic analysis to determine the state of static equilibrium of a resulted fixture configuration.

6. Inference Structure

The inference structure of the fixturing planning system acts as the "intelligent" reference mechanism. It functions both at heuristic and reasoning levels. The heuristic level contains the vocabulary, the conceptual structures and the control knowledge referred and used by the reasoning level. The reasoning level describes how to use the heuristic-level structure to achieve a given function. At heuristic level, the production rules form an integral part of the inference structure. The production rules include the ones that are designed to perfect the production process or even axioms that are generally practiced on manufacturing

shop floors. The production rules consist of logic in the form "IF <antecedents> THEN <consequences>", in which antecedents denote a set of conditions to be met and consequence a set of actions to be taken. Figure 7 shows a fragment of the production rules currently implemented in the fixturing system. For production rule 1, if the surface of a workpiece meets the antecedents, Datum and Face_Down, criteria, the action of using 4 locators to secure this surface is taken as the consequence.

At reasoning level, the inference mechanism for the production rule is based on the kinematic constraints of six degrees of freedom (DoF). Reasoning is not only about using available domain knowledge, but using it in such a way that we get to the best solution we can as quickly as possible⁽¹⁶⁾. Once the conditions to restrict a degree of freedom are met, the inference engine rejects that DoF and proceeds to match the next DoF until all six DoF are rejected, indicating that the workpiece is fully constrained. The rejection of degrees of freedom follows the 3-2-1 fixturing method for prismatic parts. The 3-2-1 fixturing method, also known as the 3-2-1 location system, places three locators on the largest planar surface, two locators on the surface perpendicular to the plane of the three locators containing the longest edge, and remaining locator on the mutually orthogonal plane. This method allows correct geometric control for any workpiece of orthorhombic shape. Figure 8 shows the inference reasoning based on the 3-2-1 fixturing method. From the beginning, rules are launched to evaluate the feasibility of locating the first plane. Once securing a plane with appropriate number of locators, clamps are applied relative to the locators and the conditions for constraining three degrees of freedom are met and thereby rejected. By the same token, the evaluation process, which also infers to the knowledge base, branches down to constrain the remaining degrees of freedom until the workpiece is

Fig. 7 Inference reasoning based on the 3-2-1 fixturing method

Fig. 8 Production rule inquiry

fully secured in the fixture (see Fig. 7). The production rules listed in this example are the applicable rules. For workpieces of different form shapes, various production rules can be introduced to reach the desired fixturing configurations. The inference logic shown for the examples given in Fig. 7 and Fig. 8 adhered to the theoretical practice. With additional information in hand, alternative fixturing configurations could therefore be suggested. For instance, if the vertical clamping force provides sufficient friction against the cutting force, it becomes unnecessary, or redundant, to apply side clamps to hold the workpiece in place. However, such configuration would require the pre-determination of clamping, frictional, and cutting forces in conjunction with machining direction of the tools. Besides the conventional 3-2-1 fixturing method, there are also some rules in the knowledge base that deal with workpieces of various geometric shapes and with the stability of a workpiece housed in a fixture enclosure. Should workpiece deflection or stability measures be compromised, rules that call for additional supports come into place. For a workpiece with datum-referenced hole features, pin locating method could be used to reduce the number of locators and clamps required as opposed to the 3-2-1 fixturing method.

7. Fixel Database

The word "fixel" takes the abbreviated form of fixture element. The fixels of interest for small- and medium-batch production are the modular fixturing elements. In fixturing planning, a feasible fixture configuration depends not only on the shape of the workpiece and type of machining processes but also the kinds of fixels to be used. Thus, for a fixturing planning system to take the available fixels into consideration, a fixel database designated for fixturing operation becomes indispensable. Figure 9 shows the generalization of the fixel attributes and architecture

Fig. 9 Architecture and attributes of the fixel database

of the fixel database. The database contains the standard types of modular fixturing elements: the base plates, locators, clamps, and supports. The inventory control tracks the availability of fixels for application and physical properties store their specifications. The information is generally available as part of manufacturer's inventory record or is provided by the suppliers. This information enables the fixturing system to determine tools available for the configuration. At the same time, the system may have to seek alternative solutions if the most suitable fixels could not be obtained. The purpose of keeping fixel inventory in check is to take the advantage of the adaptability of modular fixels. In general, modular fixels come in a wide range of specifications and functions and the use of them are interchangeable in many situations. An addition to the fixel attributes is the functional envelope of specific fixels. The functional envelope of a modular fixel is another important piece of information for the fixturing system. Figure 10 illustrates the idea of a functional envelope for a fixel. The allowable workpiece size corresponds to the design specification of the fixel. It determines the size of the workpiece the fixel is able to fit onto. The Snap-on envelope of a fixel is the clearance required for the fixel to be positioned and secured on the base plate. As the fixture configuration example shown in Fig. 10, sometimes a fixel match could not be found because there is not enough space between the workpiece and other fixels that are already in place. Greater clearance may be necessary if the assembly of the fixture is to be performed by a robot arm. By tagging the functional envelope to one of the fixel attributes, this allows an automated fixture assembly system or a robot manipulator to set up a fixture.

The system queries the fixel attributes in the database and retrieves the appropriate part numbers and modular fixels needed for the suggested fixturing configuration. The system then passes along all the

Fig. 10 Functional envelope of a fixel

Fig. 11 Utilization of the fixel database

necessary information to a fixture assembly workstation. By incorporating a fixel database, we extend the functionality of the proposed fixturing system. The application of how the fixel database is utilized is illustrated in Fig. 11. After the fixturing system identifies the locating and fixturing points with respect to the workpiece, together along with the physical attributes of the workpiece, the system makes a query to the fixel database to allocate appropriate fixels. Combinations with modular riser cylinders or supports can also be determined according to the workpiece's physical specification. Fixture assembly with applicable modular fixturing components is thereby generated.

8. Conclusion and Future Perspective

This paper introduces the domain-specific knowledge in feature-based fixturing planning. By utilizing the feature attributes of a workpiece, assessments can be made to yield more feasible machining sequences for machining operations. Coupling with the developed knowledge representation, inference mechanism can be instructed to refer to the production rules and generate fixture configurations in order to achieve a

certain level of automated fixturing planning process. The automated fixturing planning process extends to the selection of appropriate modular fixels. In comparison to various other systems, the proposed fixturing system exploits the functionality of a feature-based data model and standardizes on the representation of fixturing knowledge. The expandability of the system also allows further implementations such as the consideration of tolerance stack for the fixture configuration. The assessment of machining sequence and generation of fixturing configuration are developed with computerized algorithms in mind. That is, future work will attempt to realize the automated process of fixturing planning in a graphical-user-interfaced programming environment.

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