IJAMS International Journal of Advanced Manufacturing Systems

An Expert System Based Methodology for Automating the Set –Up Planning in Computer - Aided Process Planning for Rotationally Symmetrical Parts

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Abstract: The relevant literature on automating the set-up planning in Computer-Aided Process Planning (CAPP) by various approaches such as algorithms and graphs, expert systems, fuzzy logic and neural networks has been reviewed, highlighting their contributions and shortcomings. The authors have developed a novel expert system based methodology, which can efficiently handle set-up planning problems for rotationally symmetrical workpieces of complex shapes. The aspects treated include the set-up formation, the operation sequencing and the datum selection. It has been implemented on a PC by using the CLIPS rule-based expert system shell. It is capable of generating set-up plans automatically by taking in, as input, data files containing part information such as the type of features present, their dimensions, the tool access directions (TAD) to machine each feature, the geometric tolerance relationship between features and the machining operations. To carry out set-up formation, a set of knowledge-based rules has been developed, which are capable of clustering the machining operations into set-ups taking into consideration the TAD of the corresponding features and the relative tolerance relationships between them. Further, a set of rules has been proposed to establish the various feature precedence constraints and to determine the operation sequence in each set-up, subject to the above precedence constraints as well as manufacturing logic for ordering the operations. Finally a set of rules, based on heuristic principles developed by the authors, are used for selection of the locating and clamping features in each set-up. The detailed description of development of the expert system methodology for set-up planning including the structure of the database and the knowledge base has been presented. The example of an industrially-relevant rotationally symmetrical workpiece has been analysed using the proposed approach to demonstrate its potential for application in the real manufacturing environment. By this methodology, the set-up planning can be accomplished automatically by investing a very limited amount of time, making it attractive, cost effective and practical for use in industrial applications.

Keywords: Computer-Aided Process Planning, set-up planning, rotational parts, expert systems.

1. INTRODUCTION AND BACKGROUND

Process planning is an important activity in manufacturing that systematically determines the detailed steps of manufacturing a part according to the design specifications and within the limitations of the available manufacturing resources and their technological capabilities. An automated process planning system involves automating the interface between design and process planning, and various functions like process selection, machine tool and cutting tool selection, set-up planning, fixture selection and machining parameter selection. An automated process selection system for machined rotationally symmetrical parts based on artificial neural networks had been earlier developed by the authors (Deb et al, 2006). The present paper deals with automating the set-up planning function of process planning for rotationally symmetrical parts.

1.1 General problem in set-up planning

Set-up planning involves mainly three tasks: set-up formation, operation sequencing within a set-up and selection of datum features. The decision on set-up formation is based on commonality of tool access directions (TADs) (either left or right) for machining the features and geometric tolerance relationships between them. First each feature having multiple TADs is assigned a unique TAD, depending on the feature with which it has the tightest tolerance. Then for a given machine tool, the operations on features with the same TAD are grouped together, resulting in two set-ups (left and right). The decision on operations sequencing is based in accordance with the constraints imposed by the feature precedence relationships and the manufacturing logic in ordering the operations. The selection of set-up datum features is

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performed to obtain the critical tolerance relationships between features that could not be satisfied during the set-up formation, while leaving the tolerance chain errors to the unimportant relationships with looser tolerances. For each set-up, a vertical and a cylindrical surface are selected as datums for locating and clamping respectively, with the two surfaces on the left used to machine the surfaces on the right and vice versa.

1.2 Review of previous research

Different approaches taken by previous researchers for automating the set-up planning problems in generative CAPP systems are reviewed below.

1.2.1 Algorithmic and graph based approaches to set-up planning

Huang et al (1996) used a graph theoretical approach for set-up planning of rotational parts. The features are grouped into set-ups based on commonality of TADs and tolerance relationships, followed by selection of datum features for each set-up. Huang (1998) used an algorithmic approach for set-up planning of rotational parts. The problem was formulated mathematically as finding the set of features to be machined in each set-up, and the locating and clamping features, subject to various constraints. For set-up planning of turned parts, Lee et al (2001) used a precedence-directed graph to represent the operation precedence constraints followed by a searching strategy to search through the graph for feasible operation sequences for the different set-ups.

The above approaches have been reported to give good and accurate results. However, to be successful, the program must contain all possible input-output combinations. In an extremely complex problem, the size of the program could become large and may need large computing resources. It is inflexible, responding poorly to new situations, where it may require rewriting of the original program.

1.2.2 Expert system based approach to set-up planning

Joshi et al (1988) used an expert systems based set-up planning approach in prismatic parts. Rules are used to assign machining operations to different set-ups based on commonality of TAD, resting face, machines and material condition, and to establish operation precedences for determining the operations sequence. Sabourin et al (1996) used a combined expert system and constraint programming based set-up planning approach in prismatic parts. The set-up generation and operations sequencing problems are solved using a constraint programming strategy subject to constraints generated by rules based on technological and topological relationships between features and kinematic constraints imposed by the machine tool and work holder. Kim et al (1998) used a combined expert systems and mathematical programming based approach for set-up planning in prismatic parts. Rules are used to generate the feature precedence constraints and to cluster operations according to tool commonality. A mathematical programming model is used for grouping of operations into set-ups based on commonality of TADs and for sequencing them subject to the precedence constraints.

The expert system offers numerous advantages. It offers a structured knowledge representation in rule form that is easily understandable and editable. The modular nature makes it easier to encapsulate the knowledge and expand them by incremental development. Separation of control knowledge or inference engine from the knowledge base gives added flexibility. By keeping track of the rules fired, it can present the chain of reasoning leading to a certain conclusion, giving added confidence to the system. It is able to adapt to the changing manufacturing environment by its ability to acquire new knowledge through introduction of new rules. It, however, suffer from some weaknesses. Firstly, it is restricted to the fields where expert knowledge is available and is unable to infer when information provided is incomplete. Further it is known to perform exhaustive searches of their knowledge base for matching the patterns resulting in increased execution times with increase in number of rules. It is unable to automatically acquire the inference rules.

1.2.3 Fuzzy logic based approach to set-up planning

A fuzzy logic based approach was used by Ong et al (1997) for set-up planning in prismatic parts. Fuzzy rules are used to establish feature relationships, which along with the set-up planning knowledge, encoded as fuzzy rules, are used to formulate the set-up plan of the part. The fuzzy logic enjoys a significant advantage over expert systems in that it is able to handle uncertainty and reason with imprecise information. Its main weaknesses are that it is restricted to the fields where expert knowledge is available and the number of input variables is small, and it is unable to automatically acquire the inference rules. Another problem is that of finding appropriate membership functions for the fuzzy variables.

1.2.4 Artificial neural network based approach to set-up planning

Chen et al (1993) used an Artificial Neural Network (ANN) approach for set-up generation in prismatic parts. An unsupervised ANN was used for clustering the features into set-ups based on commonality of cutting tools and TADs. Mei et al (1995) used a ANN approach for datum selection in set-up planning of rotational parts with 10 or fewer surfaces. A three layer back propagation ANN was used to select the surfaces for locating and clamping. A hybrid AI approach was used by Chen et al (1998) for set-up planning of prismatic parts. The feature sequencing problem was solved using the Hopfield ANN approach and an algorithm based on simulated annealing was used to search for the optimum feature sequence based on minimisation of number of set-ups and tool changes. For set-up planning in prismatic parts, Ming et al (2000) used a self-organising ANN to group the operations into set-ups and then a Hopfield ANN for operation sequencing.

The ANN offers advantages including its capability to automatically acquire knowledge from examples, high processing speed, capability to adapt to changing environments through re-training, and ability to generalise and produce meaningful solutions to the problems where input data contains errors or is incomplete. It has some shortcomings in that it provides no explanation of the rationale behind its inference procedure. Its lack of explicitly stated rules and vagueness in knowledge representation leads to a black box nature. The configuration of the ANN including training is time consuming and its topology is chosen by trial and error.

1.3 Comments on the literature review

The literature review indicates that the potential for application of expert systems for set-up planning particularly in rotational parts has yet to be fully explored. Most of the previous research efforts have been limited to the prismatic parts domain. For set-up planning in rotational parts, however, a different approach needs be adopted. This is so because in case of machining rotational parts, each feature can have only 2 possible TADs, i.e. the left and/or the right while for prismatic parts, each feature may have upto 6 possible TADs. As a result, only two set-ups are possible for machining rotational parts, while there are more than two set-ups possible for prismatic parts. Also, in most of the previously reported expert systems based approaches, a mixture of the expert systems and some algorithmic approach had been adopted to solve set-up planning problems. The limitation of it is that the resulting system tends to be inflexible, responding poorly to new situations. In particular, when it comes to modification of the current set-up planning knowledge or acquiring new knowledge, it might require rewriting of the original program for the algorithm.

Keeping the above in mind, the authors in this paper have developed an expert system based methodology for set-up planning in CAPP systems for machined rotationally symmetrical parts to solve the three main set-up planning problems, namely set-up formation, operations sequencing and datum selection. In section 2, the proposed approach is presented including development of the overall structure of the expert system. Sections 3 and 4 present and discuss an illustrative example showing application of the developed approach. Section 5 presents the scope for further work and future research directions. Finally Section 6 presents the important conclusions.

2. PROPOSED EXPERT SYSTEM BASED METHODOLOGY FOR SET-UP PLANNING

The proposed expert system based methodology for set-up planning caters to the rotationally symmetric parts containing features such as external step, external taper, hole, face, groove, keyway, chamfer, thread and so on. It has been implemented on a PC by using the CLIPS rule-based expert system shell (Giarratano 1998). It is capable of generating set-up plans automatically after taking in, as input, the data files containing the information about different features present in the part to be machined along with the operations required for machining them.

2.1 Development of the overall structure of the expert system

The block diagram of the expert system is shown in Fig. 1. It consists of a database, a rule-based knowledge base and an inference engine, the details of which are given below.

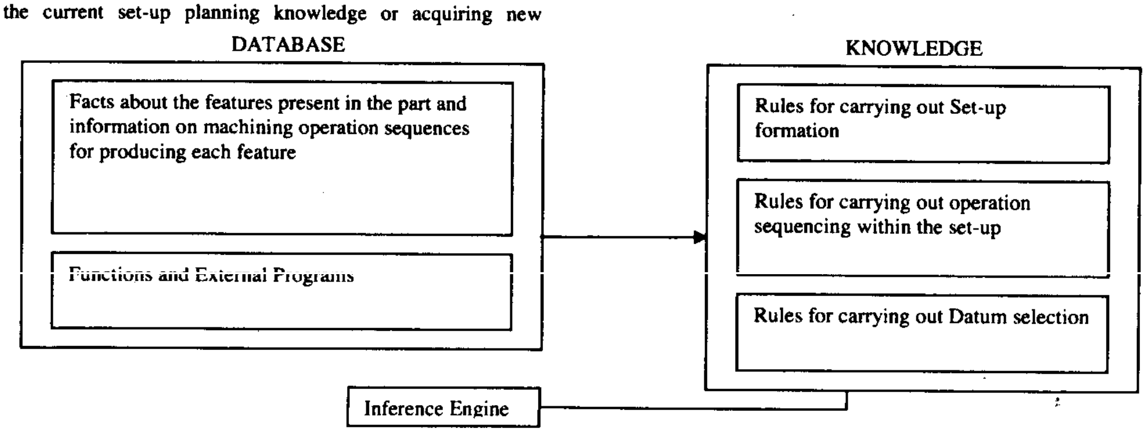

Figure 1. Block diagram of an expert system

2.2 Database

The database of the expert system comprises of data files containing information about the features present in the part and the operations required for machining them. The following will explain the format of representation of the above input data. In addition, the database also comprises of functions and external programs used for performing certain calculations.

2.2.1 Data files

The input information for solving the set-up planning problem includes the type of features present in the part, their dimensions, the geometric tolerance relationships between features, and the TADs to machine each feature which need to be obtained from the original part design. The input also includes the machining operations to produce each feature which need to be obtained from the process selection module. A format for representation of the above input data about features has been developed as shown in Fig. 2(a) using the template that is the commonly used input data representation format in CLIPS. It is a list of named fields called slots used to store values, which can be restricted to a certain range or selected from a set of predefined values. It has one slot for each of the following, namely, the feature identifier, name of the feature, type of feature (internal or external), sub-type of feature (primary or secondary), the feature to which it is secondary, adjacent feature identifiers, names of all the adjacent features, identifiers of the reference features, feature diameter, the adjacent feature diameters and finally the TAD (left, right or both) in order to machine the feature. Using the above template definition, the input data on a typical feature may be entered as follows:
(feature (number 4) (name EXTERNAL_STEP) (type EXTERNAL) (subtype PRIMARY) (adjacent_features 3 5) (adjacent_features_names FACE EXTERNAL_TAPER) (step_diameter 49) (TAD right-left))

A format for representation of the input data about machining operations has been developed as shown in Fig. 2(b) also using the template. It has one slot for each of the following, namely the operation identifier, type of operation, details on the stage of machining (rough, semi-finish or finish), identifier of the feature on which it acts, its TAD, list of features with which it has a tolerance relationship and the respective tolerance values in μm. Using the above template definition, the input data for a typical machining operation may be entered as follows:

(operation (number 401) (type turn) (machining_stage rough) (on-feature 4) (TAD right-left) (relation-with-feature 2 13) (tolerance 0.1 0.2))
The input data can be saved as a data file with the extension .clp and loaded from the file into the expert system environment. Alternatively, it may be also directly entered manually by typing through a user interface.

(deftemplate MAIN::feature
(slot number (type INTEGER) (default ?NONE))
(slot name (type SYMBOL) (allowed-symbols CHAMFER EXTERNAL_STEP FACE GROOVE HOLE KEYWAY EXTERNAL_TAPER THREAD HOLE))
(slot type (type SYMBOL) (allowed-symbols EXTERNAL INTERNAL))
(slot subtype (type SYMBOL) (allowed-symbols PRIMARY SECONDARY))
(slot secondary_feature_to (type INTEGER) (default ?DERIVE))
(multislot adjacent_features (type INTEGER) (default ?DERIVE))
(multislot adjacent_features_names (type SYMBOL) (allowed-symbols CHAMFER EXTERNAL_STEP FACE GROOVE HOLE KEYWAY EXTERNAL_TAPER THREAD HOLE))
(multislot reference_features (type INTEGER) (default 0))
(slot step_diameter (type NUMBER))
(multislot adjacent_step_diameters (type NUMBER))
(slot hole_diameter (type NUMBER))
(slot hole_depth (type NUMBER))
(multislot adjacent_hole_diameters (type NUMBER))
(multislot adjacent_hole_depths (type NUMBER))
(slot TAD (type SYMBOL) (allowed-symbols left right right-left) (default ?NONE)))

(a) Feature template

(deftemplate operation
(slot number (type INTEGER) (default ?NONE))
(slot type (type SYMBOL) (default ?NONE))
(slot machining_stage (type SYMBOL) (allowed-symbols rough semifinish finish) (default rough))
(slot on-feature (type INTEGER) (default ?NONE))
(slot TAD (type SYMBOL) (allowed-symbols left right right-left) (default ?NONE))
(multislot relation-with-feature (type NUMBER) (default 0))
(multislot tolerance (type NUMBER) (default ?DERIVE)))

(b) Operation template

(deftemplate MAIN::operation
(slot number (type INTEGER) (default ?NONE))
(slot type (type SYMBOL))
(slot machining_stage (type SYMBOL) (allowed-symbols rough semifinish finish) (default rough))
(slot setup-cluster (type SYMBOL) (allowed-symbols left right))
(multislot preceding_opn (type INTEGER) (default 0)))

(c) Modified Operation template

Figure 2. Format of representation of the input data

2.2.2 Functions and external programs

Additionally, functions have been included in the database of the expert system for performing various calculations, such as finding the most critical tolerance relationship of a given feature with respect to other features, and tasks such as updating the tolerance relationship vectors by removing those tolerance relationships between features that have already been satisfied after assigning the corresponding machining operations to the same set-up.

2.3 Knowledge base

The knowledge base consists of rules to solve the problems of set-up formation, operation sequencing and datum selection, details of which are given below. The inference engine for the CLIPS expert system shell is based on a forward chaining strategy.

2.3.1 Rule-based knowledge base for solving the set-up formation problem

A set of rules has been defined for clustering the machining operations into two groups or set-ups: operations to be performed from the right and those from the left, after considering TADs of the corresponding features and the relative tolerance relationships between them. The following are some of the rules that have been included as part of the knowledge base for solving the set-up formation problem. For example, if a machining operation on a feature is encountered in the facts list, having both TAD's (left and right) but no specified tolerance relationship with any other feature, then it is assigned to any one of the setups from the left or from the right. If a machining operation on a feature is encountered having both TADs and having tolerance relationship with a feature B having a single TAD, then it is assigned to the same set-up as B. If a machining operation on a feature is encountered having both TADs and having tolerance relationships with multiple features each having a single TAD, then the tightest tolerance relationship among them is identified. The operation is assigned to the same set-up as the operation on the other feature with which it has the tightest tolerance.
The example of what a typical rule for set-up formation looks like is shown in Fig. 3.

```
(defrule sample_rule_setup_formation
        ?f1 <- (operation (TAD right-left))
        (test (>= (length$ (fact-slot-value ?f1 tolerance)) 2))
        (operation (TAD left) (on-feature =(feature-with-
tightest-tolerance ?f1)))
=>      (modify ?f1 (TAD left) (relation-with-feature
=(update-relation-with-feature ?f1)) (tolerance =(update-
tolerance ?f1))))
```

Figure 3. Typical rule for set-up formation

It states that if there exists a fact "operation" about machining on feature A having both TADs and if the slot "tolerance" has two or more values, i.e. A has tolerance relationship with more than one feature each having a single TAD, and if the feature B with which it has the tightest tolerance has the TAD "left", then operation on A is also assigned the TAD "left" and it is assigned to the same set-up as the operation on B. The above rule calls three functions. The function "feature-with-tightest-tolerance" analyses the tolerance relationships and returns the feature identifier having the tightest tolerance relationship with A. The functions "update-relation-with-feature" and "update-tolerance" update the "relation-with-feature" and the "tolerance" slots of the "operation" fact by removing B from the list of features with which A has tolerance relationships.

2.3.2 Rule-based knowledge base for solving the operation sequencing problem

The decision on determining the sequence of machining operations within the set-up has been based in accordance with the constraints imposed by the precedence relationships between features and certain manufacturing logic to be followed in ordering the operations that will be discussed below.

A precedence constraint between features A and B, abbreviated as A→B, implies that B cannot be machined until A has been machined. The following are some of the rules developed, based on heuristic and expert knowledge from machining textbooks and handbooks and are included as part of the knowledge base for determining the precedence constraints. For example, if a feature C is the reference for features A and B, then C has to machined prior to A and B. For a rotational part, the end faces that are usually considered the reference features are to be machined first. Some features need to be accessible first before they can be machined, which results in another precedence constraint. For example, before machining of a groove between two adjacent cylindrical surfaces, both the cylindrical surfaces should be machined (Fig. 4a). Another example is that before machining a chamfer between a face and a cylindrical surface, both the face and cylindrical surface have to be machined (Fig. 4b). Further, there may be certain constraints requiring that the subsequent features should not destroy the properties of features machined previously, which results in another precedence. An example is that the machining of a chamfer and a groove must be completed prior to that of the adjacent thread (Fig. 4c). In case there exists several coaxial holes having the same TAD, a good manufacturing practice is to machine the minimum diameter hole first (if its length to diameter ratio is within allowable limits of the tool), followed by the subsequent holes in order of their diameters from small to large (Fig. 4d).

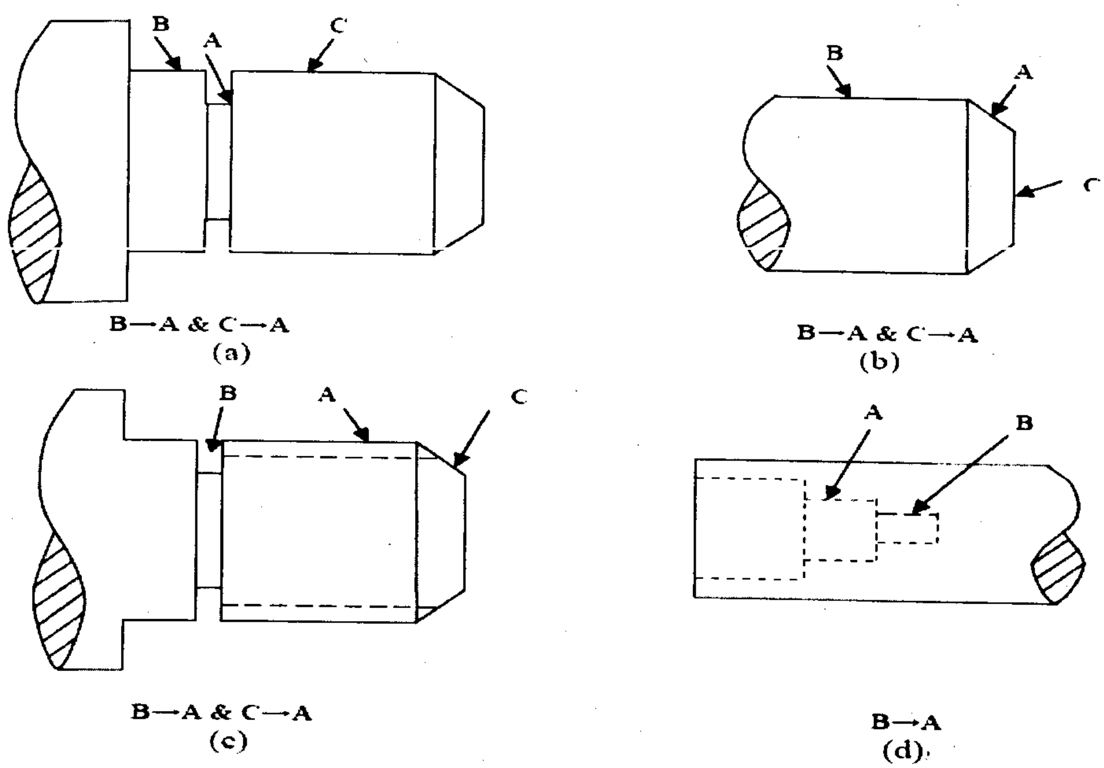

Figure 4. Different kinds of feature precedence relation

```
(defrule sample_rule1
        (feature (number ?A) (name THREAD)
(adjacent_features $? ?B $?) (adjacent_features_names $?
GROOVE $?))
=>      (assert (precedence ?B ?A)))

(defrule sample_rule2
        ?f1 <- (feature (number ?A) (name HOLE)
(hole_diameter ?d1) (adjacent_features ? ?B)
(adjacent_features_names HOLE HOLE)
(adjacent_hole_diameters ? ?d2) (adjacent_hole_depths ?
?h2))
        (test (> ?d1 ?d2))
=>      (assert (precedence ?B ?A)))
```

Figure 5. Typical rules for deriving machining operation precedence's

Fig. 5 gives examples of some rules for determining the precedence constraints. The sample_rule1 states that, if there exists a feature A of the type thread having one of the adjacent features B of the type groove, then the precedence between the machining operations on A and B will be first machining of B, followed by machining of A (Fig. 4c). The sample_rule2 in Fig. 4 states that if there exists a feature A of the type hole and of diameter d1, having adjacent features also of the type holes of which one of the adjacent features B has diameter d2 that is smaller than d1, then the precedence between the machining operations on A and B will be first machining of B, followed by machining of A (Fig. 4d).

For sequencing of operations, in addition to the above precedence constraint information, two types of manufacturing logic for ordering the various machining operations have been used: first machining of external surfaces, followed by machining of internal surfaces and first rough machining, followed by semi-finish machining, and then followed by finish machining. The overall priorities in the order for sequencing of machining operations are as follows:

- rough machining of external surfaces along the given TAD, followed by
- semi-finish machining of external surfaces along the given TAD, followed by
- finish machining of external surfaces along the given TAD, followed by
- rough machining of internal surfaces along the given TAD with the following priority order, namely drilling followed by rough boring, followed by rough reaming and so on, followed by
- semi-finish machining of internal surfaces along the given TAD in the following priority order, namely semi-finish boring followed by semi-finish reaming, followed by counterboring and so on, followed by
- finish machining of internal surfaces along the given TAD in the following priority order, namely finish boring followed by finish reaming and so on, followed by
- grooving, followed by
- chamfering, followed by
- threading.

It is to be noted that by grouping together all the similar operations (e.g. all roughing operations), it is possible to reduce the number of tool changes and idle tool motions. Also another priority for sequencing of operations is that for a given set-up, the machining of the features is done starting from one end of the part, while respecting the precedence constraints between the features. This preference in machining helps to reduce the tool travel distances and idle motion of the tool by machining as many adjacent features as possible in a given set-up.

Using the above precedence constraint information and the manufacturing logic, a feasible sequence of operations within each set-up is automatically generated as a string of operations arranged in the sequential order in which they are to be performed. The following explains how it has been accomplished. The information about the set-up cluster and the preceding operations are incorporated as new slots into the "operation" facts template, which is redefined as shown in Fig 2(c).

The sequencing of operations within the set-up is accomplished using a set of rules. First two multi-field variables are defined namely, the set-up clusters from the left and from the right. They contain the ordered set of operations to be performed from the left and from the right, with each field of the variable standing for an operation identifier. Then all the "operation" facts are scanned and a set of rules explained below is used for assigning each operation to one of the two set-up cluster variables in the sequential order they must be performed. For example, if a machining operation having no preceding operations is encountered, then it is assigned as the first element of the set-up cluster variable, or assigned to it following the operation that was last assigned. If a machining operation is encountered that has all of its preceding operations already assigned to the set-up cluster variable, then it is also assigned to it following the operation that was last assigned. All the assignments are done while maintaining the priority order for operations sequencing. The scanning of "operation" facts is continued until all the operations have been assigned to one set-up cluster or the other.

Fig. 6 gives some examples of rules for determining the sequence of operations within a set-up. First, two global variables have been defined, namely "sequence-left-cluster" indicating the set-up cluster from left and "opn-left-cluster" indicating an operation belonging to the left set-up cluster, and they have been initialised to 0. The sample rule 1 states that if an operation n1 belonging to the left set-up cluster is encountered and it is meant for rough-machining of an external step, and if it has one preceding operation n2 that also belongs to the left set-up cluster and has been already assigned to the "sequence-left-cluster" variable, then operation n1 may be assigned to the "sequence-left-cluster" variable. The priority in execution of the rule 1 among other rules present is set as 99. The sample rule 2 is similar to sample rule 1 except that it is meant for semi-finish machining of an external step and its priority in execution set as 79. The priority in execution of the sample rule 1 is higher than that of sample rule 2, signifying that if the conditions for firing both the rules 1 and 2 are satisfied, then the actions of rule 1 are executed first followed by that of rule 2, which, in turn, causes the rough machining operation to be assigned to the operations sequence ahead of the semi-finish machining operation. This is in accordance with the manufacturing logic.

```
(defglobal ?*sequence-left-cluster* = 0
           ?*opn-left-cluster* = 0 )

(defrule sample-rule-1

        (declare (salience 99))
        ?f1 <- (opn (number ?n1) (machining_stage rough)
(setup-cluster left) (preceding_opn ?n2))
        (operation (number ?n1) (on-feature ?N1))
        (feature (number ?N1) (name EXTERNAL_STEP))
        (test (not (= ?n2 0)))
        (opn (number ?n2) (machining_stage rough) (setup-
cluster left))
=>      (bind ?*opn-left-cluster* (fact-slot-value ?f1
number))
        (if (subsetp (create$ ?n2) (create$ ?*sequence-left-
cluster*))
          then
          (bind ?*sequence-left-cluster* (create$
?*sequence-left-cluster* ?*opn-left-cluster*))))

(defrule sample-rule-2
```

```
(declare (salience 79))
?f1 <- (opn (number ?n1) (machining_stage semifinish) (setup-cluster left) (preceding_opn ?n2))
(operation (number ?n1) (on-feature ?N1))
(feature (number ?N1) (name EXTERNAL_STEP))
(test (not (= ?n2 0)))
(opn (number ?n2) (machining_stage semifinish) (setup-cluster left))
=> (bind ?*opn-left-cluster* (fact-slot-value ?f1 number))
(if (subsetp (create$ ?n2) (create$ ?*sequence-left-cluster*))
then
(bind ?*sequence-left-cluster* (create$ ?*sequence-left-cluster* ?*opn-left-cluster*))))
```

Figure 6. Typical rules for operation sequencing

2.3.3 Rule-based knowledge base for solving the datum selection problem

The decision on determining as to which of the surfaces are suitable for datum selection has been based in accordance with the following principles.

- select as datum that surface of the part, which has an orientation different from the surfaces being machined (recall that in case of machining of rotational parts, two orientations are possible namely, orientation from the left and that from the right) and has the tightest tolerance with one of the surfaces to be obtained in the set-up
- in the case when no tolerance relationship exists between the surfaces of different orientations. select as datum that surface of the part which has an orientation different from the surfaces being machined and has the largest diameter or the longest cylindrical surface.

The above principles for datum selection have been implemented using a set of rules to determine the locating and clamping surfaces for a given set-up.

Fig 7 gives some examples of rules for datum selection. The sample-rule-1 states that if a feature C encountered in the facts list, is of the type external step and if the TAD for machining C is left and if C has the tightest geometric tolerance relationship with a feature X of the type external step and if the TAD for machining X is right, then the external cylindrical surface of X may be chosen as the clamping surface and the vertical surface of X may be chosen as the locating surface for the left set-up. The sample-rule-2 states that if none of features to be machined in the left set-up has a tolerance relationship with features to be machined in the right set-up, and if a feature A of the type external step is encountered in the facts list and happens to have the largest diameter among all the features present in the part and if the TAD for machining A is right, then the external cylindrical surface of A may be chosen as the clamping surface and the vertical surface of A may be chosen as the locating surface for the left set-up.

```
(defrule sample-rule-1
(feature (number ?c) (name EXTERNAL_STEP))
?f1 <- (operation (on-feature ?c) (TAD left))
(test (>= (length$ (fact-slot-value ?f1 tolerance)) 2))
(operation (on-feature =(feature-with-tightest-tolerance ?f1)) (TAD right))
=> (assert (datums_selected (setup left) (clamping_surface =(feature-with-tightest-tolerance ?f1)) (locating_surface =(feature-with-tightest-tolerance ?f1)))))

(defrule MAIN::sample-rule-2
(not (operation (TAD left) (relation-with-feature ~0)))
(feature (number ?a) (type EXTERNAL) (name EXTERNAL_STEP))
(feature-with-largest-dia (number ?a))
(operation (on-feature ?a) (TAD right))
=> (assert (datums_selected (setup left) (clamping_surface ?a) (locating_surface ?a))))
```

Figure 7. Typical rules for datum selection

3. ILLUSTRATIVE EXAMPLE

The rotationally symmetrical part shown in Fig. 8 is used to demonstrate the application of the proposed approach. The set-up plan for machining the part has to be generated. The raw stock is a forged blank made of 4140 alloy steel. The part contains the following 30 machining features: features 1, 3, 14 of the type face, features 2, 4, 6, 7, 8, 9, 13 of the type external step, feature 5 of the type external taper, features 10, 12 of the type groove, feature 11 of the type external thread and the features 15, 16, 17, 18 of the type hole, feature 19 (8 in number) of the type hole and feature 20 (4 in number) of the type slot. Apart from features 19 and 20, all other features are rotationally symmetrical.

The TAD for machining 1, 2, 3, 15 and 16 is from the left, and the TAD for machining 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18 and 20 is from the right, and the possible TAD for machining 4, 17 and 19 may be either from the left or from the right. The feature 4 has geometric tolerance relationships of $0.1\mu m$, $0.3\mu m$ and $0.2\mu m$ respectively with the features, 2, 7 and 13. The machining operations selected to produce each feature of the part that have been obtained from the process selection module (Deb et al) are shown in Table 1. The machine tool selected for machining the features 1 to 18 is CNC lathe and that for machining the features 19 and 20 is CNC milling machine. The above information, which constitutes the input to the expert system based set-up planner, is represented in the input data format of CLIPS following the syntax given in the template definition of "features" and "operations", and stored in data files with the extension .clp.

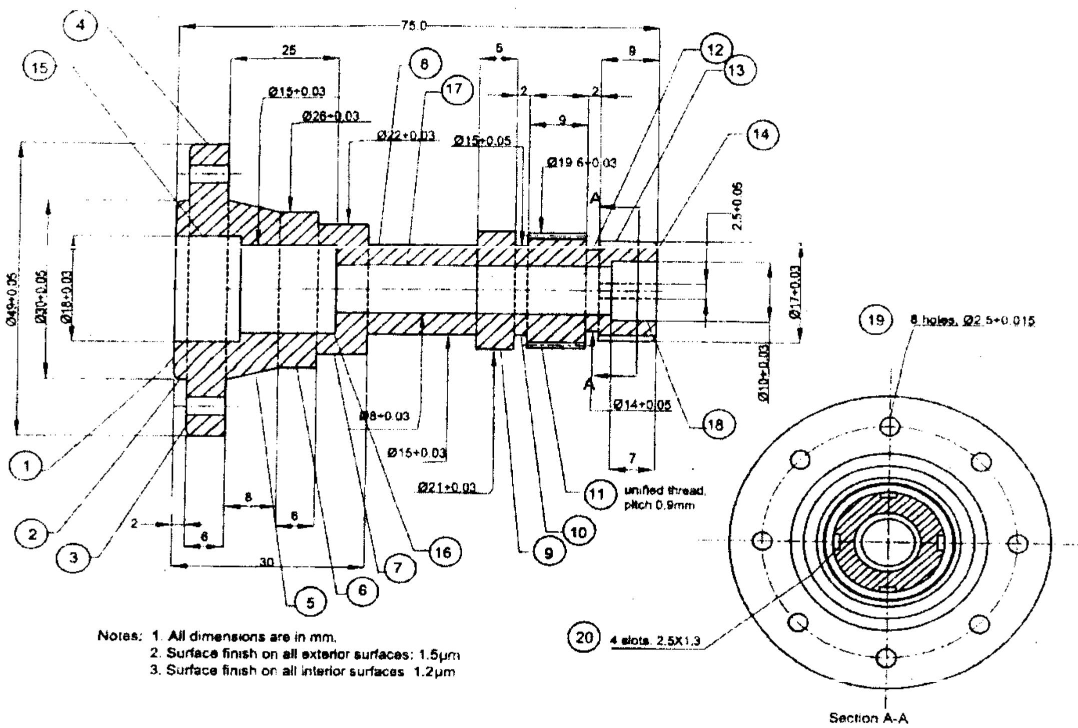

Figure 8. A Rotationally symmetrical part

The data files are then loaded into the CLIPS environment and the expert system program is executed. Table 2 summarises the results of the output generated by the expert system that includes the group of operations in each set-up, the sequence of operations and the method of locating and clamping the part in each set-up. It took a little over 2 minutes on a Pentium 4, 1.7 GHz PC with 1GB RAM to generate the above output. The set-up plan for machining the rotationally symmetrical features on CNC lathe has been generated automatically by the expert system, while that for machining the features 19 and 20 has been selected manually. The results in Table 2 indicate that the machining of rotationally symmetrical features of the part on CNC lathe has to be carried out in two set-ups. The machining operations on 1, 2, 3, 15 and 16 have been assigned to the left set-up since the TAD for machining the above features is from the left. Similarly the machining operations on 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 18 have been assigned to the right set-up since the TAD for machining the above features is from the right. The machining operations on 4 have been assigned to the left set-up. This is so because feature 4, which has geometric tolerance relationship with features 2, 7 and 13, has a tighter geometric tolerance relationship with the feature 2 as compared to that with the features 7 and 13, and so the machining operation on 4 has been grouped along with that on 2 in the same set-up, namely left. The machining of features 19 and 20 has to be carried out in two different set-ups on the CNC milling machine as shown in Table 2. Also in Table 2, the different machining operations have been listed in the sequence in which they are to be actually performed in each set-up. The expert system has taken into consideration the various precedence constraints as well as manufacturing logic to be followed in sequencing the operations to come up with the above operations sequence. Further, the features to be used for locating and clamping the part for each set-up have been identified in Table 2. The expert system has taken into consideration the heuristic principles discussed in section 2.3.3 to select the datum features. For carrying out machining operations of the left set-up on CNC lathe, the cylindrical surface of the external step feature 13 has been selected for clamping the part and the end face 14 for locating it. For carrying out the machining operations of the right set-up on

CNC lathe, the cylindrical surface of the external step feature 4 has been selected for clamping the part and the vertical face 3 for locating it. For carrying out machining operations on feature 19 on CNC milling machine, the cylindrical surface of the external step feature 13 has to be used for clamping the part and the end face 14 for locating it. For carrying out machining operations on feature 20, the cylindrical surface of the external step feature 4 has to be used for clamping the part and the vertical face 3 for locating it.

Table 1. Machining operation sequences for producing different features of the part shown in Figure 8

Feature identifier	Feature type	Operation description	Operation identifier
1	Face	Rough turn	101
		Semi finish turn	102
		Finish turn	103
2	External step	Rough Turn	201
		Semi finish Turn	202
		Finish Turn	203
3	Face	Rough turn	301
		Semi finish turn	302
		Finish turn	303
4	External step	Rough Turn	401
		Semi finish Turn	402
		Finish Turn	403
5	External taper	Rough Turn	501
		Semi finish Turn	502
		Finish Turn	503
6	External step	Rough Turn	601
		Semi finish Turn	602
		Finish Turn	603
7	External step	Rough Turn	701
		Semi finish Turn	702
		Finish Turn	703
8	External step	Rough Turn	801
		Semi finish Turn	802
		Finish Turn	803
9	External step	Rough Turn	901
		Semi finish Turn	902
		Finish Turn	903
10	Groove	Groove turning (two passes)	10
11	External thread	Rough Turn	1101
		Semi finish Turn	1102
		Finish Turn	1103
		Threading	11
12	Groove	Groove turning (two passes)	12
13	External step	Rough Turn	1301
		Semi finish Turn	1302
		Finish Turn	1303
14	Face	Rough turn	1401
		Semi finish turn	1402
		Finish turn	1403
15	Hole	Drill	1501
		Rough Bore	15001

		Semi finish Bore Finish Bore	15002 15003
16	Hole	Drill Rough Bore Semi finish Bore Finish Bore	1601 16001 16002 16003
17	Hole	Drill Rough Bore Semi finish Bore Finish Bore	1701 17001 17002 17003
18	Hole	Drill Rough Bore Semi finish Bore Finish Bore	1801 18001 18002 18003
19	Hole	Drill Rough Bore Semi finish Bore Finish Bore	1901 19001 19002 19003
20	Slot	Rough mill Semi finish mill	2001 2002

Table 2. Set-up plan recommended by the expert system based set-up planner

Machine tool	Set-up	Sequential order of machining operations	Datum features	
			Clamping	Locating
CNC lathe	Left	101 201 401 301 102 202 402 302 103 203 403 303 17 1601 16001 1501 15001 16002 15002 16003 15003	13	14
	Right	1401 1301 11101 901 701 601 801 501 1402 1302 11102 902 702 602 802 502 1403 1303 11103 903 703 603 803 503 12 10 11 1801 18001 18002 18003	4	3
CNC milling machine	-	1901 19001 19002 19003	13	14
CNC milling machine	-	2001 2002	4	3

4. DISCUSSIONS

The differences between the set-up planning approaches developed by the authors of the present paper and by previous researchers will be discussed here along with their advantages and limitations. The previous researchers have used algorithms and graphs, mathematical programming, expert systems and unsupervised ANN to solve the set-up formation problem; constraint programming, mathematical programming, expert systems, fuzzy logic and Hopfield ANN to solve the operation sequencing problem; algorithms and graphs, expert systems and back-propagation ANN to solve the datum selection problem. In the present paper, all of the above set-up planning problems have been solved using the expert systems approach. Further, most of the previous expert systems based approaches had been developed for the prismatic parts domain. In the present paper, an expert system based set-up planning methodology has been developed for rotationally symmetrical parts. It is to be noted that although the problem in above two application domains appear to be similar in nature, a different approach for implementing set-up planning needs to be adopted for each of them.

This is so because in machining rotational parts, only two set-ups are possible, while in prismatic parts, more than two set-ups are possible. Furthermore, in most of the previously reported expert systems based approaches, a mixture of the expert systems and some algorithmic approach had been adopted. The limitation of it is that the resulting system tends to be inflexible, responding poorly to new situations; particularly, when it comes to modification of the existing algorithms, it might require rewriting of the original program, which could be tedious and time-consuming. In the present paper, the authors have adopted a pure expert system approach to solve the different problems in set-up planning. The input description of the part being planned, the heuristic rules representing the domain knowledge on set-up planning and the general problem solving knowledge to control the way in which the rules are to be applied to the facts have been organised into different modules of the expert system, such as the database, the knowledge base and the inference engine. The modular nature of the expert systems and separation of control knowledge or inference engine from the knowledge base gives added flexibility to the proposed approach. Any modification of the current set-up planning knowledge can be done by simply modifying the rules in the knowledge base of the expert system that is less time consuming than having to modify the original program as in the case of approaches using algorithms. Also new knowledge can be easily acquired by the expert systems through introduction of new rules to its knowledge base. However, while updating the knowledge base, whether it is done by modifying the existing rules or by introducing altogether new rules, care must be exercised to ensure that the new rules are consistent with the existing rules. If there is any contradiction of the newly entered rules with one or more existing rules, it must be accounted for while updating the knowledge base. An important advantage of the developed expert system based methodology is with regard to the computation time to generate the set-up plans. The developed expert system was tested on a variety of example parts. The results of the tests show that the computation time for generating the set-up plan by the developed expert system is reasonably fast so that it can be used to quickly solve most practical problems. This, in turn, translates directly to the planning time saved in the process planning stage and hence reduces the cost. Furthermore, although in the present work, the expert system for set-up planning has been developed as a stand alone application program, it is possible to extract the source code of the program in C and then embed it within any user defined C application program. This feature enables the expert system module for set-up planning to be integrated with other modules of the CAPP system such as modules for machining operation selection, cutting tool and machine tool selection, and module for automatic feature extraction from CAD system.

5. SCOPE FOR FURTHER WORK AND FUTURE RESEARCH DIRECTIONS

The scope of application of the developed expert system based methodology for set-up planning may be also expanded further by considering various other set-up planning constraints e.g. fixturing constraints that have not been considered in the present work. Although the developed expert system can generate good plans, the optimality of the generated plan is not necessarily guaranteed. So there is scope for further optimization of the set-up plan considering all possible operation sequence alternatives by using AI based optimization algorithms such as genetic algorithm. In the present work, the authors have assumed the different types of relative tolerances between features to be of equal importance in order to generate the set-up plans, due to lack of a reliable common measure for different types of relative tolerances. However, recently Huang et al (2003) have reported some work on developing a common measure for different types of tolerances between features based on the concept of normalised tolerance. So a direction for future research could be modification of the set-up planning methodology developed by the author in the present work by considering the normalised values of relative tolerances and seeing if it can lead to more optimal set-up plans. Further work also needs to be done on integration of the expert system module for set-up planning with other modules of the CAPP system and module for automatic feature extraction from CAD system.

6. CONCLUSIONS

In this paper, a review of the previous research to solve set-up planning problems in generative CAPP systems has been given, highlighting the advantages and shortcomings of different approaches such as algorithm and graphs, expert systems, fuzzy logic and ANN. An expert systems based methodology has been developed by the authors for solving the problems of set-up formation, operation sequencing and datum selection for rotationally symmetrical parts. It has been implemented on a PC by using the CLIPS rule-based expert system shell. It takes in as input the data files containing information such as the part feature types, the dimensions, the TADs in order to machine each feature and the geometric tolerance relationship between features, which need to be extracted from the original part design. In addition, the input must provide the operation sequences selected for machining each feature, which need to be obtained from the process selection module. It is capable of generating set-up plans automatically. The detailed description of development of the expert system methodology for set-up planning including the structure of the database and the knowledge base for solving the above set-up planning problems has been presented. The example of an industrially-relevant rotationally symmetrical workpiece has been analysed using the proposed approach to demonstrate its potential for application in the real manufacturing environment. By this methodology, the set-up planning of rotationally symmetrical machined parts of complex shapes can be accomplished automatically by investing a very limited amount of time, making it attractive, cost effective and practical for use in industrial applications.

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