During the last decade or so, technology has made tremendous strides in machine tool control and sophistication. A major limitation restricting production is the time required for fixture design and manufacture and also set-up time. Typically this time is computed in weeks! It is proposed that the design of fixtures could be undertaken using a knowledge base of rules and a CAD presentation for the design process serving to ensure rapidity and uniformity. Such arrangements would also provide an input/output element which would be easy to handle. A system for the automated design of fixtures is under development at the University of Minnesota, Duluth, Mn. and at the University of Birmingham, UK. This system is being developed on a microVAX and a GPX workstation using solid modelling CAD and a LISP-based inference engine. The CAD-Rulebase interface languages being used are FORTRAN and C. A structured set of rules has been assembled and is discussed in this paper.

Section 1 Background

Introduction The function of any jig or fixture is to apply and maintain sufficient counteracting forces to a workpiece or cutter to withstand all tool forces. Whereas, in the early 1900s, the forces required were estimated by tool designers based on previous experience supplemented perhaps by some empirical formulae, today machining forces may be relatively accurately determined for most standard operations such as milling, planing, shaping, drilling, tapping, welding, and chemical bonding.

The design of jigs and fixtures was, for many years therefore, carried out using a large amount of technical experience but with very few or no scientific axioms to support it. Overdesign giving cumbersome, expensive devices with longer down-times and underdesign resulting in flimsy, short life elements which were accident prone were not uncommon. In the late 1940s some effort was directed towards the scientific design of jigs and fixtures, one of the pioneers being Town [1]. He analyzed the stresses developed during machining and the forces required to hold a workpiece by means of a fixture for various operations. Several factors were considered and incorporated into the design of his fixtures including supports, degrees of freedom to be constrained, and swarf removal. In addition, one of the prime considerations was the cost of the fixture relative to the number of parts being produced. About the same time (1947) research was being carried out in the direction of specialized jigs and fixtures for mass production [2]. By the late 1950s, modular fixturing began to replace some of the conventional techniques especially when flexibility was an important criterion.

The advent of dedicated artificial intelligence languages, about a decade ago, introduced a new capability in the design of fixtures, namely the possibility for computer based knowledge being used to speed up and standardize the design process. This development is extremely important, indeed critical, in the development of flexible manufacturing.

Fixturing Requirements for Flexible Manufacturing. Recent surges in popularity of Flexible Manufacturing Systems have led to tremendous improvements in machine tool design and also in software associated with computer numerical controlled [CNC] equipment. In addition, advances have been made in engineering metrology to cater for the high level of automation associated with this form of manufacturing. Recently, CAD/CAM became available rendering the design and manufacturing process much faster and less prone to errors. Expert systems or, more precisely, knowledge based systems can now be incorporated into the process of design to produce an intelligent program for the rapid and accurate design of fixtures.

A study was conducted into the existing semi-automated systems of design. In 1984-85 two systems [3,4] were developed using computer graphics, a database of parts and a rule base which incorporated most of the rules of conventional design. Subsequently, other systems have been suggested which automate, to some extent, the design process [5,6]. Increasingly, artificial intelligence is being employed in decision structures, and the term "expert systems" is being applied particularly to mechanical design [7,8] and prototypes of expert systems for the design of jigs and fixtures have been developed [9,10,11]. It will be appreciated that, whereas such arrangements represent quantum step forward, they fail to meet the requirements of
FMS, namely to design fixtures for a family of parts. The systems developed dealt with conventional methods of manufacture and the design procedures were not drastically changed to cater for the enhanced machine performance which is now available.

It is pointed out that while many other problems in engineering may be tackled with a clear-cut set of rules, in engineering design such is frequently not the case. Traditionally, design has been based to a large extent on empiricism rather than quantified scientific principles. The Theory of Knowledge has been slow to form as, by nature, knowledge itself does not fit into any recognizable theoretical format [12]. If, therefore, design were undertaken using both design and knowledge rules largely empirically, the resulting solution would be unquantifiable, to say the least. Added to this is the fact that for FMS, fixtures should have the adaptability for families of parts suggesting alterations to fundamental design maxims which is unacceptable. To assist in formulating a more structured and scientific approach to the problem of automated design the following procedure was followed:

a. The design problem was examined and a precise domain was defined based solely on the scope of the study as identified by the investigators.

b. This problem domain was then subdivided into sub-problems and their domains were identified. Each sub-problem was addressed independently, although their domains were sometimes not well defined.

c. The knowledge acquisition phase which followed involved compilation of knowledge from existing experts in the field and from available documented sources. This knowledge, at times, could at best be represented as "fuzzy" knowledge comprising facts based on personal experience but without specific figures "a little higher", or "if using multiple cutters use slightly extra clamping force".

d. Knowledge representation was undertaken in a production system and effectively structured in a three-tier rule base.

e. A simple user interface was designed with CAD system used as the "input device" and also as a means for presentation of the design.

Section 2 Rule Structure

In this section the rules relevant to the design of jigs and fixtures will be presented. The scope of these rules is wide, embracing those which have global implications in the design process as well as those with specific applications to a particular operation only. Some rules would have to take precedence over others and some lower order rules would be derived from global rules. In deciding the structure of these rules, the following information was considered:

i. The number of distinct phases in the decision-making stage for design of fixtures as suggested by experts.

ii. The nature and complexity of the problem associated with the design decision process.

iii. The ability of the structure to facilitate a workable algorithm capable of being run economically. In other words, the structure should be such so as to make coding simple and execution expeditious.

The option of a two level structure, comprising control rules and knowledge/working rules, was considered. However, this type of structure would involve rather large groups of rules, longer search times to find appropriate matches and a large amount of user interaction to guide the program. A four-level rule base, on the other hand would be faster in operation. Four levels comprising: strategy, control, meta rules and knowledge/working rules would be suitable for very large knowledge bases, involving perhaps a generic design algorithm.

In the case of a specific design algorithm for jigs and fixtures, however, it may be appropriate to merge the control and meta rules as the dividing line between these levels is not very well defined. It has been decided, therefore, to establish a three-tiered hierarchy as follows:


b. Meta Rules.

c. Knowledge Rules.

A flow diagram and a trace of one design process are given in Figures A and B respectively.

Strategy Rules:

Rules contained in this section help to decide:

i. Whether or not any fixturing is required.

ii. If fixturing is required, the method that will be adopted for designing the fixture.

iii. The criteria for the selection of various other groups of meta rules.

Five types of rules fall into this category [13]:

Definitional Rules: those in which pre-conditions are used to establish certain information capable of being processed later in the system, eg. if the diameter of a cylinder is greater than its length the cylinder is called a short cylinder.

Cause-effect rules: conditions that can be concluded from the preconditions, the exact details of which may not be known, eg. high metal removal rates may cause vibrations.

Associational rules: rules which relate certain outcomes from certain preconditions, eg. under high cutting forces, thin workpieces will deform. The distinction between cause-effect and associational rules is that the former indicates another condition whereas the latter indicates an outcome on the 'finished product'.

Effect-cause rules: in which certain conclusions are drawn as to possible causes based on the effects noticed. This type of rule is not applicable in the context of this paper.

Self-referencing: rules in which the rule values are updated periodically based on information gathered in the process of rule evaluation.

Example of a Strategy Rule. Generally the type of fixturing required would depend on the batch size. Typically smaller batch sizes require simpler
manually operated fixturing while a large batch would require special fixturing. Similarly, the dimensions of the workpiece could indicate multiple parts per fixture or a single part in each fixture. Accessibility to the workpiece for cutting tools is a fundamental requirement and, with multiple tooling, several operations may be carried out at a single set-up, thereby increasing accuracy and reducing production time. At this point, the exact nature of the fixture is not determined but the approach to the problem of fixturing is becoming better defined. The rule dealing with type of fixture vis-a-vis batch size could be stated as follows:

Batch Size. Depending on batch size the type of fixturing may be defined according to the following norms:

a. Batch size of 1
   No special fixturing required.
   Special fixturing may or may not be required depending on the type of machine, machine accuracy, availability of probes and modular fixturing.

b. Batch size 2 - 5
   Special fixturing requirements depending on the type of machine, whether or not hydraulic power for clamping is available, auto tool changing capability, availability of modular fixturing etc.

(No note: Each factors governing subsections b. and c. is enunciated as a separate rule termed a definitional rule)

c. Batch size 5 - 30,000
   Special fixturing required.

b. Batch size > 30,000
   No special fixturing required.

The interaction of four strategy rules is illustrated in the Figure C. Normally, unless a design is rejected and no alternate solution can be determined from the existing knowledge at the end of a run, this section of the rules is fairly well demarcated and it is unlikely that the program will access these rules after the design strategy has been decided. In the event of a failure to produce a suitable design, the program would be required to return to this section and re-evaluate the parameters. Relaxation of parameters would be directed by the operator on advice from the system. For example, if the strategy rules have indicated an auto-clamping fixture and due to the fact that the size of baseplate precludes the use of pneumatics on the table, an autoclamping fixture may not be viable. In that case the design would fail and the system would have to approach the designer to relax some of the constraints.
Meta Rules

Typically the strategy rules have decided on the basic form of the design with no specific details given. For example, the rules could suggest the design of multiple workpiece holders with manual loading and auto clamping, and have indicated one set up, open fixture with accessibility from three mutually perpendicular directions. They could also have discouraged multiple chucks. Once the strategy of design has been formalized, the actual design starts. In designing fixtures, cardinal principles of geometric, dimensional and mechanical control of the workpiece are handled in that order. Meta rules are applicable to some degree no matter what form the fixture eventually takes, e.g., when deciding on the best possible position for a clamp so as to avoid machined surfaces or in order to look for machined surfaces for location. These rules apply to both open and closed fixtures comprising modular or standard elements, chucks, collets etc.

Knowledge Rules

Scope. In the course of design, certain “working rules” are used to translate the principles of design into hardware. These rules are called knowledge rules. The implication here is not that the strategy and meta rules are devoid of knowledge, but rather that these working rules form the hard core of ‘common sense’ knowledge; the ‘nuts and bolts’ of the design. These rules are applicable to specific applications and are categorized according to various types of machines, various types of fixtures and according to work-piece configuration.
### Parts

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Part Holder</td>
<td></td>
</tr>
<tr>
<td>With Manual Clamping</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
</tr>
<tr>
<td>Multiple Part Holder</td>
<td></td>
</tr>
<tr>
<td>With Manual Clamping</td>
<td>5-30000</td>
</tr>
<tr>
<td></td>
<td>30000</td>
</tr>
<tr>
<td>Multiple Part Holder</td>
<td></td>
</tr>
<tr>
<td>With Auto Clamping</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30000</td>
</tr>
<tr>
<td>Modular Design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-30000</td>
</tr>
<tr>
<td>Phase Change Fixturing</td>
<td>1-5</td>
</tr>
</tbody>
</table>

### Shape of Work Part

- Small Regular
- Large Regular
- Small Irregular
- Large Irregular

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**Testing and Revision**

Testing and revision of a knowledge-based system for design is particularly important since most of the errors in reasoning are in the set of inference rules [14]. Since such rules are seldom independent of each other, the errors could be cumulative rendering the design totally unsuitable. In diagnostic and advisory systems errors are also present, though not as pronounced, since most of the rules are clearly defined. If serious problems are detected in the testing stage, it may even be necessary to retreat to the conceptual stage of the design and include new data, new structures, new sub-problems or new solution sets. Revision is an ongoing procedure throughout the life of the design process.

**Section 3 CAD Interface.**

In deciding the type of user interface, the following points were considered:

- a. Probable level of expertise of the end user.
- b. Simplicity of the questionnaire, with as many default options as possible.
- c. Availability of simple, yet effective, graphical representation software packages.

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**Validation of Rules.** Knowledge rules used in this system for designing of jigs and fixtures have been acquired from more than 20 publications and from consultation with as many experts. During compilation, there have been occasions when certain rules have been stated with varying degrees of latitude, eg. one publication states that strap clamps should be avoided on machined surfaces and, in another, that straps are prohibited altogether on any fine surface. Under certain circumstances this could lead to two totally different designs. It has been the endeavor of the authors to quantify a degree of reliability for information contained in each of the rules and to program the system to generate, based on such numerical data, the comparative reliability of any two designs that may be produced. A design, therefore, would be assigned a number based on the reliability of the rules used to arrive at the configuration.

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**A salient feature of this category of rules is that most of them are based on experience of various designers and are often not supported by documented calculations. This being the case, there is scope for various, and sometimes contradictory, solutions to a given problem. It is here that alternate solutions are generated.**

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**Fig C. Trace of Four Strategy Rules**

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**Note**

1. Normally small batch sizes are dealt with as manual machines.
2. For small batch sizes auto probing may not be cost effective and gauges may be used.
3. Fixture design should cater for these characteristics.
Utilization of a CAD system as a user interface is considered to be most appropriate under the circumstances. Ideally, the operator needs merely to present the system with a three-dimensional representation of the workpiece indicating, if available, locating points and any required surface characteristics (machined, tapped, lapped etc.). The operator should then answer a comprehensive questionnaire to ascertain machine characteristics, operations, and other details required to determine the strategy of design. These responses would typically form the definitional strategy rules and would also assist in determining design parameters. The final design would then be generated using information in the CAD database comprising either standard or modular fixture elements.

As development of the software, it was decided to use the CAD package I-deas by SDRC. Besides a three dimensional solid modeling capability, this package also contains excellent finite element analysis software which would assist in no small way in verification of the design. Workpiece distortion, for example, can be accurately ascertained and also forces acting on risers, clamps and toggles. Data files built up by the knowledge base system are accessed with the CAD system and provide the relative position and orientation of each component of the fixture with respect to the origin of the workpiece. This software, having solid model handling and presentation, minimizes problems of collision and spatial relationships in three dimensions.

Conclusion.

With increasing use of knowledge based systems in engineering design, their utility as a powerful tool in the design process is recognized. Applicability and scope of such systems is wide and they are adaptable to almost any design configuration. The application of this design tool and a simple knowledge base to jigs and fixtures has been discussed. Reduction in time for designing fixtures and a certain standardization of the design process for a given set of parameters are two of the most important outcomes from this approach. The system would also make knowledge on design of fixtures, previously available only with a relatively few experts, more accessible to the other engineer.

REFERENCES


