Flexible fixture design and automation: Review, issues and future directions

Z. M. BI†* and W. J. ZHANG†

The cost of designing and fabricating fixtures can amount to 10–20% of the total manufacturing system costs. To reduce manufacturing costs, a fixture system is designed to be competent in fixturing as many workpieces as possible. In mass volume production, this can be achieved by fixturing a large quantity of the same kind of workpieces. In low-to-medium volume production, however, improvement of the flexibility of fixture systems becomes a favourable way to reduce the unit cost of product. This paper summarizes the latest studies in the field of flexible fixture design and automation. First, a brief introduction is given on this research area. Secondly, taxonomy of flexible fixture design activities is presented. Thirdly, the flexibility strategies based on the existing flexible fixture systems are discussed. Fourthly, the contributions on design methodologies and verifications are examined. Fifthly, advances on computer-aided design and see-up systems are summarized. Finally, some prospective research trends are presented.

1. Introduction

1.1. The need for a Flexible Manufacturing System (FMS)

Increasingly intensive global competition in manufacturing and changing consumer demand are resulting in a trend towards greater product variety and innovation, shorter product life-cycle, lower unit cost, higher product quality, and short lead-time. Evolving from such a trend, both ‘market pull’ and ‘technological push’ are forcing firms towards greater flexibility. The case for flexibility and automation is reinforced further by crucial socio-economic issues such as the high cost of capital, the high cost of direct labour, and the shrinking skilled-labour pool. It becomes a key dimension of firms’ competitive priorities. As a result, a great deal attention has been directed towards the development of Flexible Manufacturing Systems (FMS) in the past decades. An FMS fills the gap between high-volume transfer lines and a highly flexible manufacturing situation, it is adopted to respond quickly, smoothly and cheaply to as yet unknown changes in product markets and production technology. It is economical in the low-to-medium volume range, because of the short time and the low cost involved for the set-up to accommodate a newly designed component.

1.2. Flexible Fixture System (FFS)

The flexibility of a whole FMS is restricted by the flexibility of any of its components, including fixture systems. The cost of designing and fabricating the fixtures in an FMS can amount to 10–20% of the total system cost. Traditionally, the public figure...
function of a fixture is to hold a part in order to keep that part in a desired position and orientation while the part is in manufacturing, assembly, or verification processes. Custom-oriented dedicated fixtures are not only time-consuming and costly to build, but they also do not have the flexibility to deal with parts or assemblies of different shapes and sizes. To reduce the cost of a manufacturing system, the fixture system should be designed to be competent in fixturing as many workpieces as possible. In low-to-medium volume production, FFSs that are competent in fixturing different kinds of workpieces, become a prospective way of reducing the unit cost of a product.

1.3. Some reviews on researches of FFSs

Fixture design and automation is an old topic in manufacturing engineering. Thousands of technical papers were published in relevant journals and conferences. To our knowledge, there are eight review papers published in this field, the latest one appearing in 1996. A brief summary of these works is given in Table 1.

Two aspects—design methodologies for determination of fixture configurations and the classification of the existing fixture systems—are the main concerns. By investigating recent research achievements in this field, the authors have revealed some limitations of these works. (1) Fixturing is always separated into some sub-functions such as locating, supporting and clamping, the integrated implementation of fixturing behaviour is less noticed. (2) To design a fixture configuration, it always means that the overall FFS is given. Some high-level issues, which are relevant to selecting a suitable FFS for the family of workpieces, are not addressed. (3) Practical issues rising from fixture application environments are rarely considered.

1.4. Our observation

With the application of advanced technologies such as Artifact Intelligent and robotic manipulators, the differences between intelligent grippers and flexible fixture systems become reduced. For example, the location of a workpiece can be performed by visual identification and supporting and clamping are often merged and carried out by compliant vice or gripper. Passive elements in a fixture system can be replaced by active elements in order to achieve more flexibility and automation. A fixturing process is traditionally regarded as a static process, but the dynamic fixturing methods are widely accepted in recent years. Moreover, fixture-less operations have been implemented in some manufacturing situations. Flexible strategies of FFSs should be thoroughly studied to help develop novel FFSs.

Manufacturing practice has also shown the problem of implementation of the FFS concept. For example, in the case of modular fixture systems, (1) the unaffordable cost of some commercial modular fixturing components and (2) the increased level of knowledge to determine a fixture configuration and to assemble it into a modular fixture system. This further implies that commercial modular fixture systems are too general to be useful in various manufacturing environments. Some application issues of flexible fixture systems need to be addressed.

Many methodologies were developed for optimal determination of fixture configurations. They are competent in solving special classes of issues in design process. However, a methodology guideline is lacking that can help the user to select a suitable method and corresponding tools to solve various issues at different design phases and aspects.
1.5. Organization of paper

First, a taxonomy of issues in flexible fixture design is provided. Secondly, flexible strategies are discussed, which leads to a classification of the existing FFSs. Thirdly, the existing design methodologies and tools are examined. Finally, some prospective directions for research are identified.

2. Taxonomy of issues in flexible fixture design

Design of a flexible fixture system refers to two level tasks: the high-level task is to determine the overall flexible fixture system based on the features of part families.
The low-level task is to determine a concrete fixture configuration, including flexible variables or assemblies based on the features of a special workpiece in the families. In most previous works, the whole flexible fixture system is supposed to be given, and only the low-level task is involved. Here, the low-level task is discussed first, and the high-level task of selection and designing of the whole FFS is mentioned in Section 2.6.

2.1. **Design process in determining a fixture configuration**

This design process refers to selecting the candidate elements, and to determining their internal variables and external assembly based on fixturing requirement supposing the overall FFS is given. Fixture design is both a science and art, there are many manufacturing-related criteria and considerations that help in the development of a procedure or methodology to design a fixture for a given product and for a specific manufacturing operation. Generally, this procedure is as shown in figure 1. Four design phases are involved: the description of the design problem, fixture analysis, fixture synthesis, and configuration verification.

![Figure 1. Process of determining a fixture configuration.](image-url)
2.2. **Description of design problem**

A design problem can always be defined as an optimization problem. An optimization problem has three elements: design variables, design constraints and design objectives. Appropriate models should be established to perform the solving of an optimization problem, e.g. analysis modelling between the design variables and the constraints, the evaluation modelling between the design variables and the design objectives.

2.2.1. **Design variables**

Design variables are determined by the architecture of a given FFS. The concept of variables represents a broad meaning. In an FFS, the selection of alternative elements, the selection of the assembly between the elements, and adjustable parameters within a modular element may all be defined as design variables. They can be a discrete or continuous. At the beginning of a design process, all the changeable parameters or factors in an FFS are defined as design variables in some way. It is a non-trivial issue to define the variables reflecting these various design options.

2.2.2. **Design constraints**

The function of a fixture is to hold a workpiece in order to keep the workpiece in the desired position and orientation when it is in its manufacturing, assembly, or verification processes. This statement also provides the fixturing requirement and is further expressed as design constraints in a design process.

1) **Form closure.** The wrenches are used to hold the object are such that they can balance, by a combination of their actions, any external tone acting on the object. This requirement has been expressed as follows in the literature.

- Resting stability: all supporting components must maintain contact with the workpiece so that the workpiece rests fully on the supports. When a workpiece is placed into a fixture, it should first assume equilibrium resting.
- Clamping stability: when clamps are applied on the workpiece in a sequence, the clamping forces should not upset the stable and accurate position previously assumed by the workpiece. After clamps are applied, the fixture should completely restrain the workpiece to counter any possible cutting forces and couples in the machining stages.
- Processing stability: in favourable processing cases, where major cutting forces are absorbed by the supporting and locating components, only small forces need to be absorbed by the clamping components.

2) **Accessibility/detachability.** The concept of fixturing accessibility/detachability covers the aspects of interference free conditions, and spatial geometric constraint satisfaction. Two types of accessibility/detachability should be considered. The first is the reachability of an individual workpiece surface; the second one is the easiness of loading and unloading the workpiece into a fixture.

3) **Deformation constraints.** Workpiece deformation during fixture set-up and process operation is the most important consideration in the fixture design process.
The design constraints may change with respect to special situations. For example, Brook et al. (1998) thought the form closure was too restricted for robotic grasping.

2.3. Fixture analysis

In fixture analysis, the relational models that map from the design variables to the design constraints, and from the design variables to the design evaluations, have to be established. These models are used to verify whether a fixture configuration satisfies the design requirements.

Kinematic analysis: refers to the kinematic models from the design variables to kinematic constraints. It is necessary that the proposed fixturing arrangement does not interfere with the expected tool path, the fixture does not restrict access to features being machined, and that the fixturing elements themselves can access desired faces or the features for clamping. For correct location, the fixturing elements should completely specify the position and orientation of the part with respect to desired datum surfaces, but should not over-determine the location.

Force analysis refers to the static models from the design variables to the static constraints. Force analysis is concerned with checking that the forces applied by the fixtures are sufficient to maintain static equilibrium in the presence of cutting forces.

Deformation analysis: refers to the tolerance models ranging from the design variables to workpiece deformation. It is the most computationally intensive step. The concern is that a part may deform elastically and/or plastically under the influence of cutting and clamping forces so that the desired tolerances will not be achieved. Deformation is particularly a concern with flexible parts and with parts in which a great deal of material is removed. Hockenberger (1995) discussed the effect of machining fixture design parameters on workpiece displacement.

Evaluation models refers to how the fixturing performance is evaluated. The following indices are often used to evaluate the performance of the configuration candidates:

- number of wrenches
- clamping forces
- workpiece equilibrium
- workpiece stability
- workpiece deformation
- fixture dexterity
- fixture set-up time

The evaluation models are used to obtain these performance indices.

2.4. Fixture synthesis

Fixture synthesis determines a set of design variables for a fixture configuration that can satisfy the design constraints while achieving the best performances. For an FFS with a small number of design variables, the synthesis activity is relatively simple using the models obtained from the fixture analysis. However, fixture syn-
thesis may become very complex if there are many design variables in an FFS. Consider a modular fixture system as an example, to reduce the calculation and improve the design efficiency, the synthesis activity is decomposed into several sub-activities: selection of types of modules, determination of locate and support points, determination of clamping, the assembly planning of fixture configuration, and so on.

2.5. Design verification

Fixture verification is an integrated part of the design process and must allow for the detection of any interference that may occur during the fixture construction (Shirinzadeh and Tie 1995). Verification of a design solution is necessary for the following reasons: (1) There are too many factors involved in the design process; it is very difficult to establish accurate analysis models. (2) Design constraints are considered individually; some contradicting constraints may be produced when they are considered together. (3) Fixture design has a close relationship with other activities (such as Computer-Aided Process Planning, and Computer-Aided Manufacturing) in a manufacturing system; the design solution needs to be verified practicable for the whole manufacturing system.

Verification or monitoring is also needed in the use of a fixture system to justify whether the system in a good condition. Choudhuri and Meter (1999) had analysed the tolerance caused by machining fixture locators, and Ceglarek and Shi (1996) used pattern recognition to perform diagnosis of fixture failure in autobody assembly.

2.6. Selection, evaluation and design of a FFS

One of the most important topics is how to select, evaluate and design an FFS for one family of workpieces. This is more difficult than the determination of a fixture configuration, because the fixtureing objects have uncertain requirements. Actually, this situation often happens. When a new enterprise is built or some new products are introduced, a decision on whether to buy or design an optimal FFS for the family of workpieces has to be made. When an enterprise changes a large-scale product paradigm into a low-to-medium product paradigm, the owner has to determine whether dedicated fixtures are replaced by FFSs, and which is better: to buy commercial FFS or to develop a special FFS for the family of workpieces.

To select, evaluate and design an FFS, more considerations should be included in the evaluation models, such as cost, efficiency, suitability, and lead-time. The analysis process becomes most difficult because there is an uncertain relationship with the fixture requirements. Empirical methodologies are, in practice, applicable to the overall process of selecting and evaluating.

3. Existing FFSs

Various FFSs have been developed; but only a few of them have become commercial. Most FFSs are limited to special-purposes; however, they are flexible enough to accommodate one class of part family. Figure 2 shows a classification of these FFSs from the view of flexible strategies.

3.1. Flexible strategies for fixture systems

There are a number of ways to achieve flexibility. The first way is to make the fixture system contain many replaceable basic elements, which are called modular elements. A fixture configuration is built by selecting modular elements and their
The benefits of modularized products were described by He and Kusiak (1996, 1997), Rogers and Bottaci (1997), Kusiak and Larson (1995), and Newcomb et al. (1998).

The second way is to make some components contain internal variables that can be adjusted to meet the different features of workpieces. The third way is to use phase-change-like materials. In figure 2, FFSs are classified into two types: Flexible Fixture Systems with a Modular structure (MFFSs) and Flexible Fixture Systems with Single structure (SFFSs).

3.2. Flexible fixture systems with modular structures

The concepts of interchangeability and modular fixturing date back to the Second World War. Modular fixturing systems first came into prominence in the late 1960s and are mainly used in conjunction with NC machine tools. The extent of their use was not widespread until the advent of multiple axis CNC machine tools and Flexible Manufacturing Systems (FMSs). A modular fixture kit consists of many elements, and these elements belong to one of the following basic types: base plate, locators, clamps and connections. Using the components from the kit one can assemble a custom-oriented fixture. Flexibility is achieved by selection of various modules and assembly of the elements.

3.2.1. Classification of FFSs with a modular structure

Table 2 shows four basic types of FFS with a modular structure and examples of location identification techniques.

3.2.2. Shortcoming of MFSs

MFFSs are very popular in industry. They can widely accommodate various changes of workpieces, i.e. in shape, size, and process, etc. However, this implies
that they are too general to be useful in some manufacturing environments. Only a few of researchers have paid attention to the failures of MFFSs; however, manufacturing practice has shown the following problems of adopting modular fixture systems.

1. Unaffordable cost: the initial cost of modular fixture is often high.
2. A large amount of knowledge: the increased level of knowledge required to determine a modular fixture system configuration and to assemble it into a modular fixture system is difficult to obtain.

<table>
<thead>
<tr>
<th>Type</th>
<th>Location identification</th>
<th>Examples</th>
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<tbody>
<tr>
<td>Grid hole system</td>
<td>Non-threaded hole</td>
<td>Venic Block Jig System, Japan</td>
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<tr>
<td></td>
<td></td>
<td>Yuasa Modular Flex System, USA</td>
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<td></td>
<td></td>
<td>Kipp Modular FFS, Germany</td>
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<tr>
<td>T-slot or Tenon system</td>
<td>T-slot</td>
<td>Eiwin Modular System, USA (figure 3)</td>
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<td></td>
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<td>Wariton Unitooll, UK</td>
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<td></td>
<td></td>
<td>CATIC (China National Aeronautical Technology Import and Export Corporation) System, China</td>
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<td></td>
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<td>Gridmaster System, UK</td>
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<tr>
<td>Dowel pin system</td>
<td>Dowel or tapped hole</td>
<td>Bluco Technik, Germany (figure 4)</td>
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<td></td>
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<td>MITEE-BITE Clamp</td>
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<td>SAFE Fixture System, USA</td>
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<td>Write Alufix System, Germany</td>
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<tr>
<td>Reconfigurable modular FFSs</td>
<td>Visual Sense</td>
<td>Developed by Asada and Andre (1985)</td>
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<td></td>
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<td>Developed by Benhabib et al. (1991)</td>
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Table 2. Classification of commercial MFFSs.

Figure 3. T-Slot Eiwin modular fixture system.
3.2.3. Set-up of MFFSs

Configurations of MFFSs should be often modified to accommodate the changes of features of workpieces. Therefore, the set-up for a fixture configuration is an important activity in the application of a MFFS. Empirical judgements are used in the process of the set-up.

3.2.4. Sense-based set-up

Modular elements must have some degree of intelligence if they are required to change automatically. One way is to use various senses. Tao and Kumar (1997) developed an experimental fixturing system for end-milling operations, in which real-time reaction forces on locators are measured and monitored through a data acquisition system. Lu et al. (1997) designed a fast flexible fixture for two-dimensional clamping, which is fitted with sensors for automatically measuring the positions of the clamping surfaces and the vice opening. Karl et al. (1994) developed a flexible automated fixturing element, in which a hydraulic positioning mechanism was designed without using a hydraulic servo valve. The device could achieve the positioning accuracy within 0.001 inch. The modular elements developed by Shirinzadeh and Tie (1995) were equipped with position and force sensors, and the motion was controlled by hybrid servo systems.

Taylor et al. (1994) addressed the problem of planning two-fingered grasps of unmodelled 3D objects using visual information. Barsky et al. (1989) proposed a robot gripper control system using polyvinylidene fluoride (PVDF) piezoelectric sensor.
Rodu and Fadi (1998) presented a visual approach to the problem of object grasping and, more generally, to the problem of aligning and end-effector with an object.

3.2.5. Robotic fixture assembly

The use of robotic systems is the main method in implementing the automation of modular fixture assemblies. The robot can configure fixtures into a wide range of workpiece configurations without operator assistance. When coupled with fixture modules designed specifically for robot assembly, these systems show promise (Youce-Toumi et al. 1989). In the reconfigurable modular systems developed by Asade and Andre (1985) and Shirinzadeh and Tie (1995), the fixture modules were set up, adjusted and changed automatically by the assembly robot without human intervention. Lim et al. (1989) used a gantry robot for the loading and unloading of modular fixtures, an automatic probe-changing coordinate-measuring machine for inspection. Ngoi et al. (1997) developed an automated fixture set-up for inspection, the system comprised a workplace with magazines, locators and a baseplate, the SCORBOT-ER VII was used to automate the system. Yu and Goldberg (1998) formalized robotic fixture loading geometrically as a sensor-based compliant assembly problem and gave a complete planning algorithm. Giusti et al. (1994) developed a reconfigurable assembly cell for mechanical products. This cell was composed of three base plates, a pneumatic screwing unit, a hydraulic press and other devices for the complete automation of the assembly operations. The handling functions of the cell were performed by a six-axes robot. As shown in figure 5, Sela and Gaudry (1997) developed a reconfigurable modular system for the fixturing of thin-walled, flexible objects subject to a discrete number of point forces.

3.3. FFSs with a single structure

The configurations of this type of FFSs are unchangeable. However, some adjustable variables are contained. Flexibility can be achieved by changing adjustable variables to accommodate various shapes and sizes of workpieces. Two types are included: the adaptive FFSs, phase-change FFSs.

3.3.1. Adaptive FFSs

An adaptive FFS achieves the flexibility through its internal variables. Daniel et al. (1998, 1999) designed a reconfigurable discrete die, which was being developed for

Figure 5. FFS for thin-walled parts by Sela.
aircraft fuselage parts, made by forming sheet metal or moulding composite materials. As shown in figure 6, each pin in the die was a simple hydraulic actuator fitted with an in-line NC solenoid valve to control its vertical position. Once the pins were set, the entire matrix was clamped into a rigid tool. Brooke (1994) introduced Fanc’s programmable fixturing system, which could hold different platforms and multiple models, change quickly, and do it for low cost. Wallack and Canny (1994) designed an adaptive fixture vice, which consisted of two fixture table jaws capable of translation in the $X$ axis, As shown in figure 7, it was used for 2.5-dimensional objects. Du and Lin (1998) developed a three-fingered automated flexible fixturing system. Most of grippers used in part assembly belong to this type. As shown in figure 8, Kopacek and Kronreif (1994) developed a modular parallel gripper system. Chan and Lin (1996) developed flexible grippers, where only one type of modular element provided locating, supporting and clamping functions. As shown in figure 9, each element consisted of four fingers with eight degrees of freedom in order to conform to any arbitrary workpiece surfaces. The eight motions of the four fingers were controlled by one motor through the use of two transmission and clutch systems. Different combinations of the multifingers could make different fixture reconfigurations for the product family. Causey and Quinn (1998) provided a guideline for designing various grippers. Smith (1998) developed a new concept of an intelligent flexible fixture system.

Figure 6. A reconfigurable discrete die.

Figure 7. A fixture vice.
3.3.2. Phase-change FFSs

Flexible fixturing based on the concept of material phase-change exploits the ability of certain classes of material to change phase. Phase changes may be temperature-induced, electrically induced or a combination of these Temperature-induced phase-change fixturing has traditionally been employed in encapsulation for special-purpose precision machining, such as the milling of turbine blades as shown in figure 10 (Hazen and Wright 1990). Electrically induced phase-change fixturing employs electro-rheological fluids as the medium undergoing the change of phase, Grippo et al. (1988) developed a prototype in figure 11, Pseudo phase change fixtures mimic the function of low melting point alloys. These alloys can be ‘fluidized’ by compressed air, and when the air supply is shut off; the alloys become solid and hold the workpiece (Gandhi and Thompson 1985). Researchers at MIT designed a set of comfortable clamps that use shape memory alloy wires for motive force. As shown in figure 12, the clamps consisted of a $4 \times 4$ array of fingers, normally locked by the squeezing action of heavy-duty Belleville springs.

Compliant mechanisms are mechanical devices that achieve motion via elastic deformation. By adapting these mechanisms, some special fixtures can be developed,
Figure 10. The particular fluidized bed.

Figure 11. Fixture made of electrophoreological fluids.

Figure 12. MIT Conformable clamp made of shape memory alloy.
Frecker et al. (1997) discussed topological synthesis of compliant mechanisms using multi-criteria optimization.

3.4. Robotics in fixture-less assembly (RFA)

Robotic fixture-less assembly refers to the performance of assembly tasks using robots without the fixtures. RFA is applicable to several industries, including automotive, aircraft, camera and photocopier manufacturing. The elimination of fixtures is expected to reduce greatly the costs and lengthy lead times associated with retooling in these industries. General Motors of Canada is developing a RFA prototype, it is being used for picking and accurate locating for a large number of complex-shaped sheet metal (and sheet plastic) parts in the assembly processes. Bandyopadhyay et al. (1993) designed a ‘fixture-free’ machining centre for the machining of block-like components.

4. Design methodologies

Once the whole FFS is bought, selected, or produced, its running efficiency depends largely on the automation degree of design, and verification of the fixture configurations. As mentioned in section 2, three basic activities are involved: (1) description of the requirements and the constraints; (2) modelling in fixture analysis; and (3) search strategies in fixture synthesis.

A description method has a great effect in choosing the appropriate tools for fixture analysis and synthesis. The geometry expression is the most direct method for describing design requirements. It is often used in the detailed design of a fixture configuration both for FFSs and dedicated fixtures. The alternatives are a GT-based code and feature-based method. To accommodate for computerization, the modular fixture elements must be encoded (Lin and Huang 1997). Group Technology (GT) codes and feature-based descriptions have appeared in recent years with the increasing usage of expert systems and rule-based systems in fixture synthesis. However, because the detailed description of design requirements might be difficult, GT is only suitable in the concept design of fixture configurations.

4.1. Methodologies used in fixture analysis

Fixture analysis builds relational models among the design variables, constraints, and evaluation objectives. The optimal formula of the fixture configuration design is not completed until all the constraint and objective models are established.

4.1.1. Geometry method

The geometry-oriented approach is a well-accepted approach in which most of the information required can be retrieved from CAD systems. Markenscoff and Papadimitriou (1989) and Markenscoff et al. (1990) discussed the geometry of grasping and optimum gripping of a polygon using geometry methods. Trappey et al. (1993) utilized the projective representation of a workpiece to find a feasible fixture configuration based on the 3-2-1 locating principle. Asada and Andre (1985) employed analytic tools based on the workpiece geometry and the assembly operation required, and the fixture configuration could be changed automatically. Boema and Kals (1988) established a CAD system used for automation of fixture design and set-ups. Considering the interference between fixture modules in a reconfigurable fixture system, Wu and Rong (1998) presented a fundamental study of automated fixture planning with a focus on geometric analysis. The initial conditions for mod-
ular fixture assembly were established together with geometric relationships between fixture components and the workpiece to be analysed. Willy *et al.* (1995) employed Boolean algebra in justify the possible fixture configurations. Cai *et al.* (1996, 1997) developed a variational method for robust fixture configuration design to minimize workpiece resultant errors due to source errors. Using the proposed variations approach, closed form analytical solutions were derived. Apley and Shi (1998) presented an algorithm to detect and classify multiple fixture faults based on least squares estimation. Hwang *et al.* (1999) used kinematics to analyse the grasping of a B-spline surface object by a multi-fingered robot hand. Hong *et al.* (1996) applied the spatial point contact constraint theory to develop a mathematical model of flexible fixturing systems.

4.1.2. **Screw theory**

Screw theory is based on the motion of a rigid body’s displacement in 3D space; the force and the motion of a workpiece can be modelled as ‘wrenches’ and ‘twists’. To build some quality measures for evaluating a grasp, Chou (1989) presented a mathematical theory for automatic configuration of machining fixtures for prismatic parts with aid of screw theory, in which twists and wrenches are used to represent the motion and force combinations. Screw theory was used to derive: (1) the minimum number of contacts (locations and clamps); (2) the permissible motions due to a contact set; (3) the reaction forces at special contacts; and (4) the clamping forces required to balance cutting forces (Fuh and Nee 1994).

4.1.3. **Finite Element Method (FEM)**

Owing to its good capability of deriving the corresponding compressive force and displacement, the FEM approach has been used in many deflection-related researches (Hou and Trappy 1997). Lee and Cuthowsky (1990) were the first to employ this method in Automated Fixture Design (AFD). De Meter (1998) proposed the Fast Support Layout Optimization (FSLO) model, it utilized a FEM model to characterize workpiece stiffness. Solution of the FSLO model improved an existing support layout by systematically altering the boundary conditions.

4.1.4. **Rule-based or feature-based analysis**

In a feature-based model, a typical approach is to represent a part with a single set of features. In machining processes, different fixturing parameters are required when different sets of features are used for machining. Tseng (1998) developed a feature-based fixturing analysis method to determine a good set of features that was more suitable from the fixturing point of view.

Dong *et al.* (1991) investigated the use of features for fixture design, concentrating on the selection of locating elements and the identification of locating surfaces for workpiece positioning. The approaches of machining feature-based design and the precedence matrix algorithm were combined to automate the process-planning and fixture design (Ozturk *et al.* 1996). By merging knowledge of manufacturing methods and machine tool information with a special-purpose computer language, Darvishi and Gill (1988) suggested developing, primarily for list processing and symbolic manipulation, ground rules for a fixture design approach. A fixture process planning system was implemented using a knowledge-based approach (Liou and Suen 1992). Perremans (1996) described modular elements by means of form
features; this permitted the description of an arbitrary modular fixturing system and the use of the same logic to determine the assembly of modular elements.

4.1.5. Mechanical analysis methods

As well as the methodologies mentioned above, the mechanical analysis method is very popular for modelling workpiece-fixture force interactions and deformations of the workpiece. King et al. (1997) presented an analytical approach based on kinematics, force and a minimization of potential energy method. Potential energy was regarded as a measure of excitability of a given physical state, the physical state considered was the fixturing configuration of locators and clamps, and an optimal algorithm was built to find a configuration with the minimum potential for perturbation. Meyer and Liou (1997) developed a comprehensive methodology for handling the dynamic external force in a workpiece-fixturing system. Considering the accurate and efficient modelling of compliant fixtures and grasps, Lin (1998) derived a stiffness matrix formula using the overlap compliance representation for quasi-rigid bodies. It could incorporate a realistic nonlinear contact model, and could be directly computed from CAD data on basic geometric and material properties of the bodies. This formula was well-suited to automated planning algorithms. Mittall and Cohen (1991) presented a dynamic modelling of the fixture-workpiece system. Most of force analysis approaches treated either the workpiece or the fixture as a deformable elastic body; however, both of them were considered as deformable elastic bodies in the mechanical analysis presented by Gui et al. (1996); a generalized method to minimize the location deviation was proposed by using optimally determined clamping forces. Nguyen (1984) discussed constructing stable grasps using mechanical modelling. Yeh and Liou (1999) developed the modelling of the response frequency of a modular fixturing system with multiple components in contact, and showed it was possible to monitor the contact conditions based on a fixturing system’s dynamic response frequency. Wu et al. (1997) considered surface contact modelling for a fixture–workpiece system. Shreyes and Melkote (1997) applied the mechanical method to improving workpiece location accuracy through fixture layout optimization.

4.2. Methodologies for fixture synthesis

Two main considerations in fixture synthesis are to simplify the synthesis process and to reduce calculations. In addition, search strategies in the feasible space of fixture configurations are important.

4.2.1. Analytical methods

Analytical synthesis can only handle a small number of design variables. Two possible situations might use analytical synthesis: (1) the determination of a fixture configuration for the SFFSSs with a few variables; (2) the determination of a few internal parameters for selected modular elements for MFFSSs when the whole complex design has been decomposed. Brost et al. (1996) presented an implemented algorithm that accepted a polygonal description of the part silhouette, and efficiently constructed the set of all feasible fixture designs that kinematically constrain the part in the plane. Rong and Bai (1997) designed a Modular Fixture Element Assembly Relationship Graph (MFEARG) to represent combination relationships between fixture elements. Based on MFEARG, synthesis algorithms were developed to
search all suitable fixturing unit candidates and mount them into appropriate positions on a base-plate with interference checking.

4.2.2. Rule-based reasoning

The use of acknowledge-based computer design scheme will help to introduce the essential philosophy to ensure that the optimum design is achieved. Nee (1987) applied AI in jig and fixture design. Nnaji et al. (1988) and Nnaji and Alladin (1990) developed a framework for a rule-based expert fixturing system for face milling a planar surface on a CAD system using flexible fixtures. Roy et al. (1997) addressed several implementation issues of a prototype AFM system. Such AFD systems proposed a preliminary fixturing configuration by synthesizing the fixture design issues and reasoning about the necessary knowledge bases. Trappey and Liu (1992) employed heuristic search techniques on the projected envelope of the workpiece to determine the locating and clamping points. King and Lazaro (1994) presented a fixture synthesis algorithm a hybrid (heuristic-cum-mathematical) model to arrive at design decisions. Lin and Huang (1997) developed different heuristic algorithms for fixture element selection corresponding to different functional requirements.

4.2.3. Genetic algorithm

Fixture Design is generally regarded as a complex multi-modal and discrete problem. While other methods have difficulties dealing with it, the trials on GAs have provided a viable alternative. Wu and Chan (1996) applied genetic algorithms to the fixture configuration optimization: based on the information provided by the verification system, a genetic algorithm approach carries out the evaluation process to determine the most statically stable fixture configuration among a large number of candidates.

4.2.4. Case-based method

In the CBR concept previous experience is stored as episodes in a case library. Each episode, termed a case, records at least two kinds of information: problem description and solution. When a CBR system faces a new problem, the most similar previous case is retrieved and modified to satisfy the new situation. Each case and the input problem are indexed according to the index system. The similarity of each case can then be evaluated by comparing the index of each case with the index of the input problem. Sun and Chen (1995) developed a seven-digit code to represent and classify the modular fixturing. Using this index system and case-based method, the designer can find a rough sketch of the fixture design.

4.2.5. Neural network algorithms

After network training, the fixture mode of the workpiece can be inferred, and selection of the fixture elements can be completed. Ong and Nee (1996, 1998) applied fuzzy theory to evaluate part fixturability. Lin integrated the GT description of modular fixturing, neural networks, and the heuristic algorithm for fixture synthesis in his automatic fixture design system. Genetic algorithms and neural networks can be combined in a fixture design system (Lin 1998); Kumar et al. (1992) applied this integration methodology in conceptual design of fixturers.
### 4.2.6. Blackboard-based design

Blackboard-based design systems are used in various other engineering applications in which concurrent or cooperative problem solving processes are achieved. Fixture design involves interdisciplinary knowledge, with the help of blackboard architecture. The developed fixture design system could perform lower level reasoning and allow the analysis to be integrated with the design process, so that reliability assessment can be accomplished when it could best affect the design (Roy and Liao 1998).

### 4.3. Summary of the methodologies in fixture design

Fixture configuration design can be separated into three phases: description of design requirements, the fixture analysis, and fixture synthesis. Fixture analysis involves the relational models among design variables, kinematic and dynamic constraints, and performance evaluation; while fixture synthesis involves finding an optimal solution for a given workpiece and its machining. Many methodologies have developed for designing a fixture configuration. However, a suitable methodology is very important for a given design requirement and design level to improve efficiency, and the harmony of the methodologies should be maintained. A brief summary on the methodologies used in fixture design is given in Table 3.

### 5. Computer-aided fixture design and set-up system

A review is presented on computer-aided fixturing design and set-up systems.

#### 5.1. Architecture of computer-aided fixture design and set-up system

Software architecture describes the system components and their relationships. Bugtai and Young (1997) discussed the information model in an integrated fixture design support system. Nederbragt (1997) proposed a theoretical framework for the design of a robotic fixture. Fuh and Nee (1995) presented the architecture and details

<table>
<thead>
<tr>
<th>Description of design requirement</th>
<th>Geometry method</th>
<th>Feature-based</th>
<th>GT codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixture analysis</td>
<td>Geometry modelling</td>
<td>Screw theory</td>
<td>Finite element method</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Analytical methods</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Rule-based</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Genetic algorithm</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Case-based</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Neural networks</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
</tbody>
</table>

× means two methodologies are not compatible.
✓ means two methodologies are compatible.

Table 3. Summary on the methodologies in fixture design.
<table>
<thead>
<tr>
<th>Developers and resource</th>
<th>Application</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pham and Lazaro (1990)</td>
<td>Jigs and fixture</td>
<td>Expert CAD system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>finite element method</td>
</tr>
<tr>
<td>Nnaji and Alladin (1990)</td>
<td>Face milling planar part, flexible fixtures</td>
<td>Rule-based expert system</td>
</tr>
<tr>
<td>Young and Bell (1991)</td>
<td>Two and half dimensional prismatic arts</td>
<td>Geometric query, product model analysis</td>
</tr>
<tr>
<td>de Sam Lajaro and King (1992)</td>
<td>Machining fixture</td>
<td>Tolerance and sequential operations analysis</td>
</tr>
<tr>
<td>Lim et al. (1992)</td>
<td>part fixturing in high-precision industry,</td>
<td>3D modular fixture design expert system</td>
</tr>
<tr>
<td>Trappy and Liu (1992)</td>
<td>Workholding verification</td>
<td>Geometry analysis</td>
</tr>
<tr>
<td>Wolter and Trinkle (1994)</td>
<td>Selection of fixture point, frictionless assemblies</td>
<td>Geometry method</td>
</tr>
<tr>
<td>King and de Sa Lazaro (1994)</td>
<td>Tolerance consideration, general fixture</td>
<td>Knowledge-based systems</td>
</tr>
<tr>
<td>Brost and Goldberg (1994)</td>
<td>Polygonal parts, modular fixture</td>
<td>Geometric analysis</td>
</tr>
<tr>
<td>Willy et al. (1995)</td>
<td>Modular fixture</td>
<td>Geometry and mechanic analysis</td>
</tr>
<tr>
<td>Sun and Chen (1995)</td>
<td>Modular fixture</td>
<td>Cased-based reasoning, index system</td>
</tr>
<tr>
<td>Perreman (1996)</td>
<td>Prismatic parts, modular fixture</td>
<td>Feature-based description, expert system</td>
</tr>
<tr>
<td>Cecil et al. (1996)</td>
<td>Prismatic parts, general fixture</td>
<td>Integration methodology</td>
</tr>
<tr>
<td>Shirnzadeh (1996)</td>
<td>Interference detection, reconfigurable modular fixture system</td>
<td>CAD-based hierarchica l approach</td>
</tr>
<tr>
<td>Wu and Chan (1996)</td>
<td>Optimal fixture configuration</td>
<td>Generic algorithm</td>
</tr>
<tr>
<td>Rong (1996)</td>
<td>Machining accuracy analysis design verification</td>
<td>Datum-machinig surface relationship graph, matrix-based reasoning</td>
</tr>
<tr>
<td>Rong and Bai (1997)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jones et al. (1997)</td>
<td>Automated assembly and fixture planning</td>
<td>Archidedes's approach holdfast software</td>
</tr>
<tr>
<td>Ho and Ranky (1997)</td>
<td>Flexible assembly system, reconfigurable conveyors</td>
<td>Object-oriented modelling, heuristic searching</td>
</tr>
<tr>
<td>Roy et al. (1997)</td>
<td>Prismatic parts, modular fixture</td>
<td>Geometry reasoning, object-oriented</td>
</tr>
<tr>
<td>Chou (1997)</td>
<td>Complex part, general fixture</td>
<td>Fixturing feature analysis, spatial inference analysis</td>
</tr>
<tr>
<td>Wu and Rong (1998)</td>
<td>Dedicated fixture</td>
<td>Fixture structure analysis, geometry-element generator</td>
</tr>
<tr>
<td>Lin and Huang (1997)</td>
<td>3D workpieces, modular fixture</td>
<td>GT, neural networks, pattern classification</td>
</tr>
<tr>
<td>Jeng and Gill (1997)</td>
<td>Prismatic parts</td>
<td>CAD-based approach</td>
</tr>
</tbody>
</table>

Table 4 (continued)
of the development of an interactive fixture design and assembly (IFDA) environment. Chou (1997) presented a three-stage system architecture from a concurrent manufacturing planning point of view. Jeng and Gill (1997) thought that artificial intelligence techniques should be used in conjunction with 3D solid CAD and database systems at the commercial level for modular fixture design, pricing and inventory control. Greater emphasis should be put on the integration of the intelligent fixture design system with the robotics fixture assembly, knowledge-based process planning system, and intelligent production scheduling system (Chou 1997).

5.2. **Computer-aided fixture design (CAFD)**

Computer-aided fixture design is mainly relevant to MFFSs and dedicated fixtures. Many CAFD prototype systems have been developed; some CAFD systems, together with applications and using methods, are shown in table 4.

5.3. **Computer-aided fixture setup (CAFS) for MFFSs**

One of the difficulties in the application of MFFSs is to plan and execute the setup of modular elements. The assembly location and sequence should be determined for all modular elements in a CAFS system. Little attention has been paid to this issue. Table 5 provides a summary of these works.

6. **Some prospective research trends**

Recent achievements in the development of flexible fixture systems, design methodologies, together with computer-aided design and set-up systems have been examined in this paper. Adaptation of FFSs can greatly reduce manufacturing costs in low-to-medium volume products, and the design and set-up automation of FFSs can reduce the lead-time of the product; however, the current design and automation theories and technologies are not mature. The researches on these fields are promising and challenging. It is our observation that three research aspects are most promising.
6.1. Development of an autonomous flexible fixture system

In today’s FFSs, especially for MFFSs, fixture design, verification, and assembly largely depend on human activities. This situation has resulted in the low efficiency, unstable accuracy, long set-up time, and high cost of FFSs. Development and application of autonomous flexible fixture systems can address this issue. The state of the art in this field shows the possibility of developing a autonomous flexible fixture system. ‘Autonomous’ means to implement the automatic running of an FFS with the aid of flexible elements and automatic servo control, artificial intelligence and sensing. An AFFS should possess the following characteristics:

1. have a large degree of freedom to accommodate the fixtureing feature varieties of the workpiece family;
2. determine optimal fixture configuration based on design requirements automatically;
3. build the fixture configuration automatically by adjusting internal variables or assembling modules;
4. load the workpiece in the fixture–workpiece system automatically;
5. monitor fixtureing processes and adjust the configuration dynamically to achieve the best manufacturing performance;
6. unload the workpiece and reset the fixtureing system automatically.

6.2. Computer-aided fixture design for manufacturing

Many researchers have realized the importance of integration CAFD systems with other CAD software systems in a manufacturing system. However, their efforts showed that they mainly concentrated on CAFD systems, and the integration was limited to obtaining the fixtureing requirements from other CAD systems and sending the result of the CAFD to CAPP systems directly; this is a single-direction connection. Most research works have neglected the effect of fixture design on product design and process planning, and the redesign of fixtures has never been seriously considered. Future research on CAFD will put the emphasis on cooperation with the other design systems, the connection should be bi-directional, and the CAFD process
information should also be fed back to the other system as early as possible. In considering the integration of the CAFD system with the other CAD manufacturing systems, combination with advanced computer technologies, such as a WWW browser, collaborative design system, integration architecture of various platforms, becomes urgent.

6.3. Applied research

Practical issues also appear when flexible fixture systems are put into use. Not all research has taken the issues seriously. However, the solutions for these issues are vital to extend the application of FFSs.

6.3.1. Select or design a flexible fixture system for workpiece families

Any FFS has favourable fixturing features in its application. An engineer has a responsibility to select or design the most suitable FFS for the manufacturing part family. Therefore, it becomes a meaningful issue to select, evaluate and design a FFS for a part family optimally. This issue is more difficult than the design of a fixture configuration, because the fixturing objects have uncertain requirements. To address this issue, some qualitative considerations should be included in the evaluation models, such as cost, efficiency, suitability and lead time.

6.3.2. From dedicated fixtures to FFSs

Liu (1994) proposed a systematic design method that helped companies change their dedicated fixturing systems gradually into modular fixturing systems. This research is very practical. Further research should be carried out, such as how to design dedicated fixture elements for evolving FFSs, how to improve the possibilities of varieties of fixture configurations from the systems, how to manage the dedicated and flexible fixture hybrid systems, etc. The solutions to these issues can bring great economic efficiency to small-scale machining enterprises.

6.3.3. Multi-fixtures and multi-fixturing tasks schedule

In a real machining workshop, there may be various FFSs, dedicated fixtures and many workpieces. Dynamic scheduling methodology is needed to distribute the limited fixture resources for fixturing workpieces. Some researchers have revealed tooling management issues in manufacturing industry (Arun and Suresh 1996, Ebrahim and Liu 1995, Elon and Burdick 1998, Perera and Sharfaghi 1995). However, they are mainly concerned with the scheduling issues of general machining tools. The schedules of FFSs and their elements pose many special characteristics.

References


