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FLEXIBLE FIXTURE DESIGN & AUTOMATION

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ABSTRACT

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 work pieces as possible. In mass volume production, this can be achieved by fixturing a large quantity of the same kind of work pieces. In low-to-medium volume production, however, improvement of the flexibility of fixture systems becomes a favorable way to reduce the unit cost of product.

INTRODUCTION

A fixture is a device for locating, holding and supporting a work piece during a Manufacturing operation. Fixtures are essential elements of production processes as they are required in most of the automated manufacturing, inspection, and assembly Operations.

Fixtures must correctly locate a work piece in a given orientation with respect to a cutting tool or measuring device, or with respect to another component, as for Instance in assembly or welding. Such location must be invariant in the sense that the devices must clamp and secure the work piece in that location for the particular Processing operation.

There are many standard work holding devices such as jaw chucks, machine Vises, drill chucks, collets, etc. which are widely used in workshops and are usually Kept in stock for general applications.

Fixtures are normally designed for a definite operation to process a specific Work piece and are designed and manufactured individually. Jigs are similar to Fixtures, but they not only locate and hold the part but also guide the cutting tools in Drilling and boring operations. These work holding devices are collectively known

As ***jigs and fixtures.***

1.1.1 ELEMENTS OF FIXTURES

Generally, all fixtures consist of the following elements:

Locators

A locator is usually a fixed component of a fixture. It is used to establish and maintain the position of a part in the fixture by constraining the movement of the Part. For work pieces of greater variability in shapes and surface conditions, a Locator can also be adjustable.

Clamps

A clamp is a force-actuating mechanism of a fixture. The forces exerted by the clamps hold a part securely in the fixture against all other external forces.

Supports

A support is a fixed or adjustable element of a fixture. When severe part Displacement/deflection is expected under the action of imposed clamping and Processing forces, supports are added and placed below the work piece so as to Prevent or constrain deformation. Supports in excess of what is required for the Determination of the location of the part should be compatible with the locators and Clamps.

Fixture Body

Fixture body, or tool body, is the major structural element of a fixture. It Maintains the spatial relationship between the fixturing elements mentioned above, ***viz.,*** locators, clamps, supports, and the machine tool on which the part is to be Processed

1.1.2 Importance of Fixtures in Manufacturing

Modern manufacturing aims at achieving high productivity to reduce unit cost. This Necessitates work holding devices to be efficient, ***i.e.*** to increase the rate of loading and unloading to speed up the manufacturing cycle time.

If t is the total time in seconds or minutes required for producing a part, then

$$Q = \frac{1}{T}$$

- is the number of pieces produced in unit time, or the production rate.

Considering the fact that the total manufacturing time is usually composed of

t=tm+th

where ***tm*** is the actual machining time and ***th*** is the setting up and handling time, hence, the production rate is given by:

$$Q = \frac{1}{tm + th} \quad \text{piece per unit time}$$

Supposing ***Qt*** is the ideal production rate whereby there is no handling time loss for a given machining operation, hence we have:

Qt=1/tm

Now,

Q=1/1/Qt+th

=1/1(th/tm)Qt=λQ

This factor

λ=1/1+(th/tm)

can be termed as production efficiency.

1.1.3 General Requirements of a Fixture

In order to maintain the work piece stability during a machining process, an Operational fixture has to satisfy several requirements to fully perform its functions as a work holding device.

The following constraints must be observed while Designing a viable fixture:

Deterministic location

A work piece is said to be kinematic ally restrained when it cannot move without Losing contact with at least one locator. The work piece is constrained by a set of appropriately placed locators so that it is presentable for the machining operation. Locating errors due to locators and locating surfaces of the work piece should be Minimized so as to accurately and uniquely position the work piece within the Machine coordinate frame.

Total constraint

A work piece should be fully constrained at all times to prevent any movement. Clamps should provide locking forces to hold the work piece in place -once it is Located. A totally restrained part should be able to remain in static equilibrium to withstand all possible processing forces or disturbance. A necessary and sufficient Condition to warrant work piece stability is to satisfy the condition of force closure. Contained deflection Work piece deformation is unavoidable due to its elastic/plastic nature, and the External forces impacted by the clamping actuation and machining operations. Deformation has to be limited to an acceptable magnitude in order to achieve the Tolerance specifications.

Geometric constraint

Geometric constraint guarantees that all fixturing elements have an access to the datum surface. They also assure that the fixture components do not interfere with cutting tools during a machining operation. In addition to these requirements, a fixture design should have desirable Characteristics such as quick loading and unloading, minimum number of Components, accessibility, design for multiple cutting operations, portability, low cost, etc.

2.2. ***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 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 fledibility to deal with parts or assemblies of deferent shapes and sizes. To reduce the cost of a manufacturing system, the fixture system should be designed to be competent in fixtureing as many work pieces as possible. In low-to-medium volume production, FFSs that are competent in fixtureing deferent kinds of work pieces, become a prospective way of reducing the unit cost of a product.

2.3. ***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 fi eld, 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 fixtureing behavior 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 work pieces, are not addressed. (3) Practical issues rising from fixture application environments are rarely considered.

2.4. ***Our observation***

With the application of advanced technologies such as Artifact Intelligent and robotic manipulators, the divergences between intelligent grippers and flexible fixture systems become reduced. For example, the location of a work piece 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 featuring process is traditionally regarded as a static process, but the dynamic featuring 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 featuring 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 con-figurations. 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 deferent design phases and aspects.

Resources	Concerns (issues, suggestions and remarks)
Grippo *et al.* (1988)	Overview of research activities dedicated to develop viable universal flexible featuring systems, highlighting the necessity for an interdisciplinary research strategy in order to develop ancient Universal fixture system
Hazen and Wright (1990)	Review of fixture designs, fixture analysis, planning, and automated fixture assembly. Further studies were suggested: (1) Design of automated fixture systems; (2) Integration of planning, mechanical automation, and sensing Strategies
Trappy and Liu (1990)	Review of featuring principles, automated fixture design, fixture hardware design in 1980s. They revealed that comprehensive automatic fixture-design systems have not been completely developed, and suggested (1) to construct a huge rule base covering a su• cient domain in the expert system; (2) to study Automated Fixture Design (AFD) software and the fixture-hardware together.
Chang (1992)	Discussion issues of fixture planning for machining processes. A tentative classification of fixture components as well as a scheme for selecting the fixture components for primary locating.
Liu and Strong (1993)	Review of Fixture Design Automation. Further studies were suggested on: (1) Application of Al techniques, expert systems, feature design Technique, group technology and 3D geometric reasoning

	techniques to automatic fixture design; (2) integration of AFD with other systems; (3) development and exploitation of new locating principles for AFD.
Hargrove and Kusiak (1994)	Suggested new directions of research on computer-aided fixture design: (1) integration with other computer-aided engineering tools
Hargrave (1995)	for total fixture design; (2) qualitative reasoning techniques can be applied to fixture design; and (3) integration with NC programming schemes
Shirinzadeh (1995)	Classifi cation FFSs from the viewpoint offlexible strategies
Shimoga (1996)	A survey of the existing grasp synthesis algorithms meant for achieving dexterity, equilibrium, stability, and dynamic behaviours. Prospective researches on this fi eld were (1) to simplify the computational complexities of the synthesis algorithm; (2) to improve the precise sensing and control capabilities of the existing grasping system.

Table 1. Summary of review papers on fixture design and automation.

3. Taxonomy of issues inflexible fixture design

Design of 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 work piece 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 fi rst, and the high-level task of selection and designing of the whole FFS is mentioned in Section

3.1. *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 featuring 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 specifi c manufacturing operation. Generally, this procedure is as shown in fi gure 1. Four design phases are involved: the description of the design problem, fixture analysis, fixture synthesis, and configuration verification

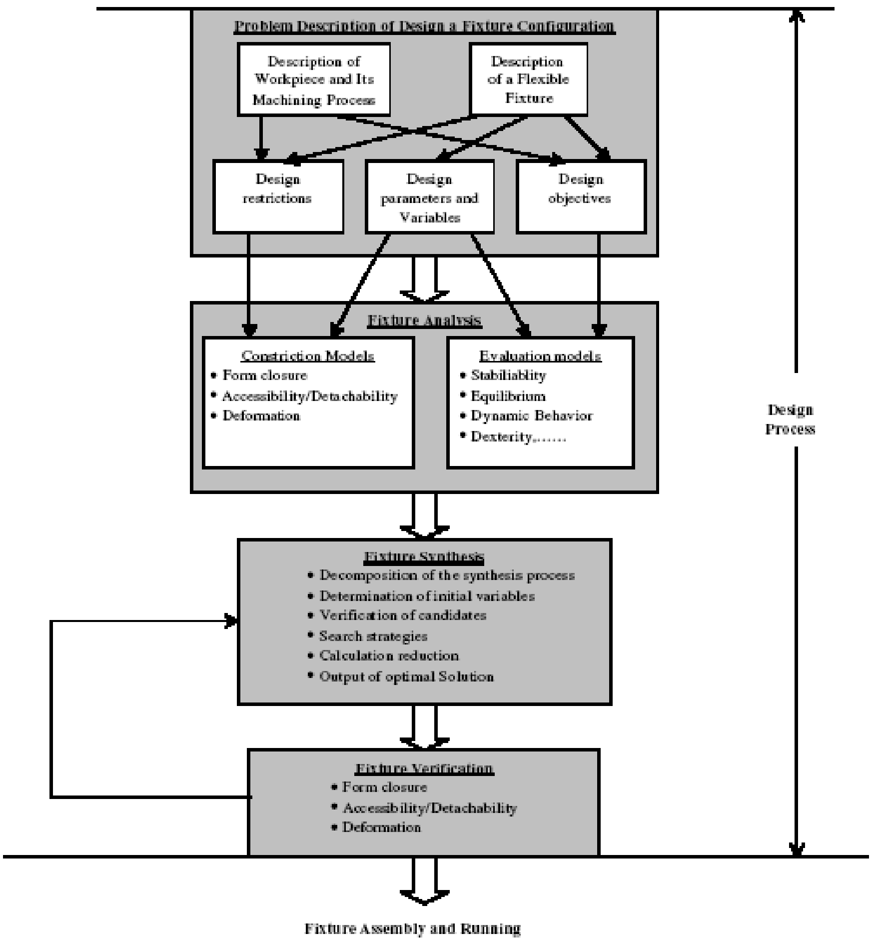


Figure 1. Process of determining a fixture configuration.

3.2. *Description of design problem*

A design problem can always be defi ned 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.

3.2.1. *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 defi ned 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 defi ned as design variables in some way. It is a non-trivial issue to defi ne the variables refiecting these various design options.

3.2.2. *Design constraints*

The function of a fixture is to hold a work piece 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 fi rst 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 work piece. After clamps are applied, the fixture should completely restrain the work piece to counter any possible cutting forces and couples in the machining stages. . Processing stability: In favorable 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 fi rst is the reachability of an individual workpiece surface; the second one is the easiness of loading and unloading the workpiece into afixturee.

(3) **Deformation constraints.** Work piece 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.

3.3. *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 fixtureing arrangement does not interfere with the expected tool path, the fixture does not restrict access to features being machined, and that the fixtureing elements themselves can access desired faces or the features for clamping. For correct location, the fixtureing 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 su• cient 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 work piece displacement.

Evaluation models refer to how the fixtureing 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.

3.4. *Fixture synthesis*

Fixture synthesis determines a set of design variables for a fixture confi guration 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 e• ciency, 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 confi guration, and so on.

3.5. *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 di• cult 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 verifi ed practicable for the whole manufacturing system.

Verifi cation 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.

3.6. *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 di• cult than the determination of a fixture confi guration, 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

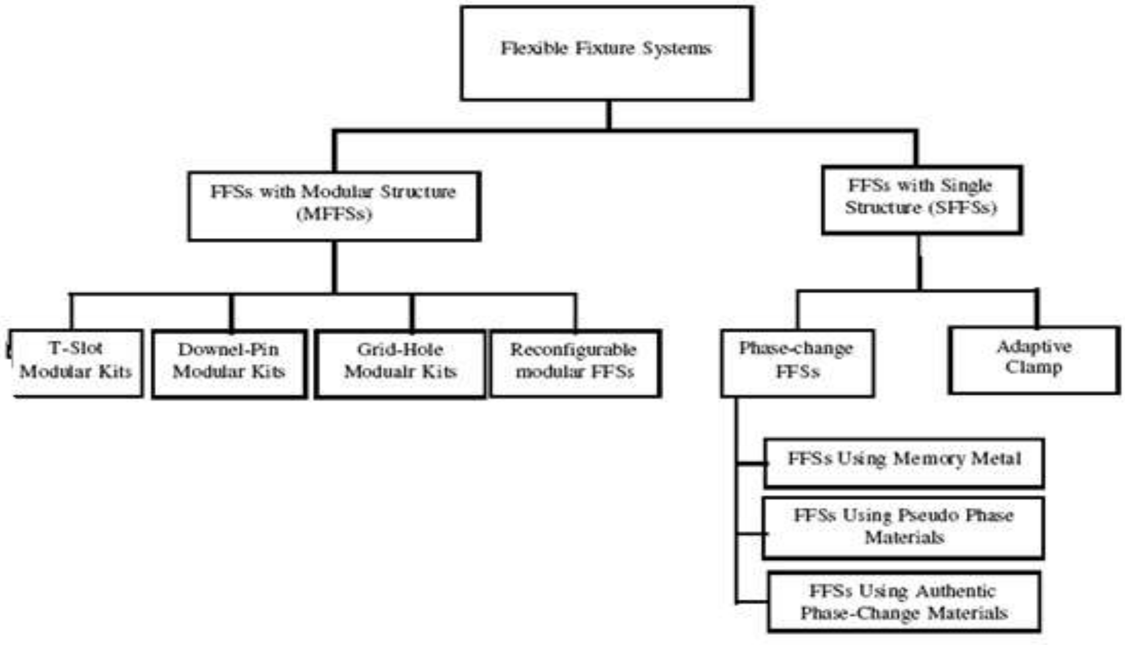
FFS or to develop a special FFS for the family of workpieces. To select, evaluate and design an FFS, more considerations should be included in the evaluation models, such as cost, e• ciency, suitability, and lead-time. The analysis process becomes most di• cult because there is an uncertain relationship with the fixture requirements. Empirical methodologies are, in practice, applicable to the overall process of selecting and evaluating.

4. 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 areflexible enough to accommodate one class of part family. Figure 2 shows a classifi cation of these FFSs from the view offlexible strategies.

4.1. *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 classification of flexible fixture systems.

assembly; these elements are then connected to each other by standard connections. The benefi ts 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 diOEerent features of workpieces. The third way is to use phasechange- like materials.

In fi gure 2, FFSs are classifi ed into two types: Flexible Fixture Systems with a Modular structure (MFFSs) and Flexible Fixture Systems with Single structure (SFFSs).

4.2. *Flexible fixture systems with modular structures*

The concepts of interchangeability and modular fixtureing date back to the Second World War. Modular fixtureing systems fi rst 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.

4.2.1. *Classification of FFSs with a modular structure*

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

4.2.2. *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 confi guration and to assemble it into a modular fixture system is diffi cult to obtain.

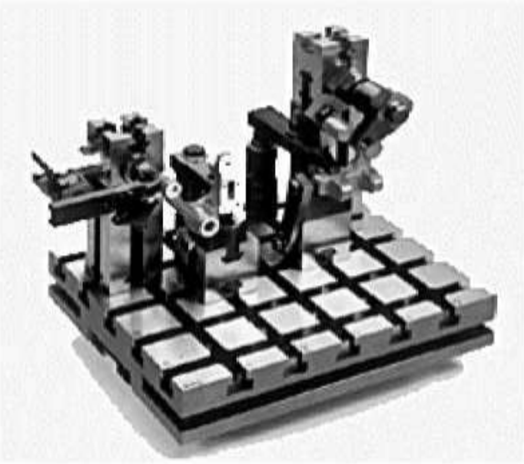


Figure 3. T-Slot Eiwin modular fixture system.

(3) Limitedflexibility: only limited combinations are available from standard fixture components to construct fixture confi gurations for different workpieces. In many cases, dedicated fixtures are needed for complex workpiece geometry and operations.

(4) Limited fixture performance: structural properties of modular fixtures, such accuracy, stiffness, stability, and convenience of loading and unloading, are maintain.

(5) Schedule: there is a problem of how to utilize modular fixture components effi ciently in production planning.

4.2.3. *Set-up of MFFSs*

Confi gurations of MFFSs should be often modifi ed to accommodate the changes of features of workpieces. Therefore, the set-up for a fixture confi guration is an important activity in the application of a MFFS. Empirical judgements are used in the process of the set-up.

4.2.4. *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 fixtureing 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 fastflexible fixture for two-dimensional clamping, which is fi tted with sensors for automatically measuring the positions of the clamping surfaces and the vice opening. Karl *et al*. (1994) developed a fiexible automated fixtureing 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-fi ngered grasps of unmodelled 3D objects using visual information. Barsky *et al*. (1989) proposed a robot gripper control system using polyvinylidenefluoride (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-eOEector with an object.

4.2.5. *Robotic fixture assembly*

The use of robotic systems is the main method in implementing the automation of modular fixture assemblies. The robot can confi gure fixtures into a wide range of workpiece confi gurations without operator assistance. When coupled with fixture modules designed specifi cally for robot assembly, these systems show promise (Youce-Toumi *et al*. 1989). In the reconfi gurable 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 reconfi gurable 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 fi gure 5, Sela and Gaudry (1997) developed a reconfi gurable modular system for the fixtureing of thin-walled, fiexible objects subject to a discrete number of point forces.

4.3. *FFSs with a single structure*

The confi gurations 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.

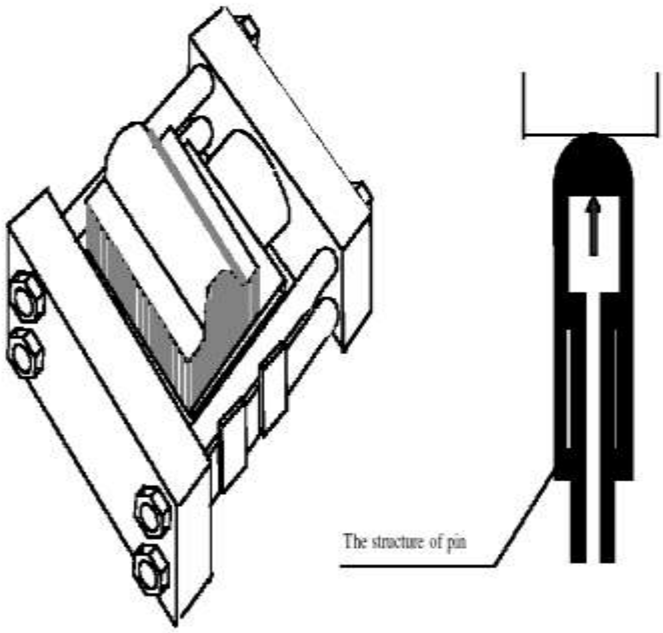


Figure 6. A reconfigurable discrete die.

aircraft fuselage parts, made by forming sheet metal or moulding composite materials. As shown in fi gure 6, each pin in the die was a simple hydraulic actuator fi tted 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 fixtureing system, which could hold diOEerent 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 fi gure 7, it was used for 2.5- dimensional objects. Du and Lin (1998) developed a three-fi ngered automatedflexible fixtureing system. Most of grippers used in part assembly belong to this type. As shown in fi gure 8, Kopacek and Kronreif (1994) developed a modular parallel gripper system. Chan and Lin (1996) developedflexible grippers, where only one type of modular element provided locating, supporting and clamping functions. As shown in fi gure 9, each element consisted of four fi ngers with eight degrees of freedom in order to conform to any arbitrary workpiece surfaces. The eight motions of the four fi ngers were controlled by one motor through the use of two transmission and clutch systems. DiOEerent combinations of the multifi ngers could make diOEerent fixture reconfi gurations for the product family. Causey and Quinn (1998) provided a guideline for designing various grippers. Smith (1998) developed a new concept of an intelligentflexible fixture system.

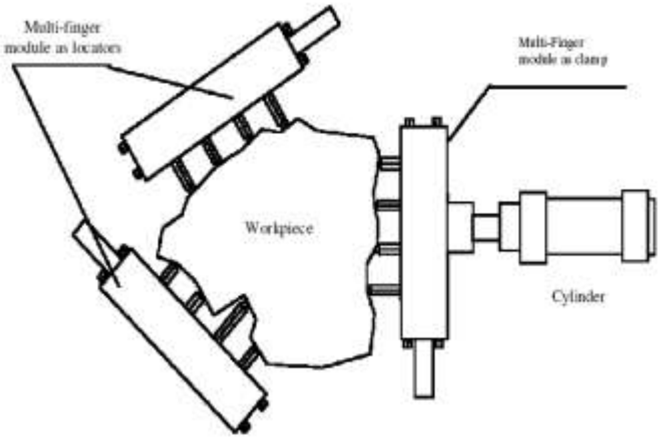


Figure 9. CNC flexible fixture for assembly.

4.3.2. *Phase-change FFSs*

Flexible fixtureing 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 Temperatureinduced phase-change fixtureing has traditionally been employed in encapsulation for special-purpose precision machining, such as the milling of turban blades as shown in fi gure 10 (Hazen and Wright 1990). Electrically induced phase-change fixtureing employs electro-rheologicalfluids as the medium undergoing the change of phase, Grippo *et al*. (1988) developed a prototype in fi gure 11, Pseudo phase change fixtures mimic the function of low melting point alloys. These alloys can be `fiuidized' by compressed air, and when the air supply is shut oOE; 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 fi gure 12, the clamps consisted of a 4 £ 4 array of fi ngers, 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, Frecker *et al*. (1997) discussed topological synthesis of compliant mechanisms usingmulti-criteria optimization.

4.4. *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 `fixturee-free' machining centre for the machining of block-likecomponents.

5. Some prospective research trends

Recent achievements in the development offlexible 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 fi elds are promising and challenging. It is our observation that three research aspects are most promising.

5.1. *Development of an autonomous flexible fixture system*

In today's FFSs, especially for MFFSs, fixture design, verifi cation, and assembly largely depend on human activities. This situation has resulted in the low e• ciency, unstable accuracy, long set-up time, and high cost of FFSs. Development and application of autonomousflexible fixture systems can address this issue. The state of the
art in this fi eld shows the possibility of developing a autonomousflexible fixture system. `Autonomous' means to implement the automatic running of an FFS with the aid offlexible elements and automatic servo control, artifi cial 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 confi guration based on design requirements automatically;
(3) build the fixture confi guration 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 confi guration dynamically to achieve the best manufacturing performance;
(6) unload the workpiece and reset the fixtureing system automatically.

5.2. *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 eOEorts 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 eOEect 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.

5.3. *Applied research*

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

5.3.1. *Select or design aflexible fixture system for workpiece families*

Any FFS has favourable fixtureing 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 di• cult than the design of a fixture confi guration, because the fixtureing objects have uncertain requirements. To address this issue, some qualitative considerations should be included in the evaluation models, such as cost, e• ciency, suitability and lead time.

5.3.2. ***From dedicated fixtures to FFSs***

Liu (1994) proposed a systematic design method that helped companies change their dedicated fixtureing systems gradually into modular fixtureing 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 confi gurations from the systems, how to manage the dedicated andflexible fixture hybrid systems, etc. The solutions to these issues can bring great economic e• ciency to small-scale machining enterprises.

5.3.3. ***Multi-fixturees and multi-fixtureing 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 fixtureing 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.

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