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Design & Development of Fixture for CNC – Reviews, Practices & Future Directions

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Abstract—Various areas related to design of fixture are already been very well described by various renowned authors. This section reviews some of the developments in fixture design and proposes directions for future research initiatives.

Index Terms— Fixture, Design, CNC, Computer Aided Fixture Design, Modular Fixtures, Dedicated Fixtures, Flexible Mechanical Fixtures

1 Introduction

The machine tool industry has undergone sufficient changes as the requirement of user engineering systems changed; first it started with the manufacture of basic general purpose machine tools. These machines though offered higher flexibility were not suitable for mass production owing to longer set up times and the tedious adjustments of machine and tools besides requiring highly skilled operators. With growing need of fast production to meet the requirements of industry, mass production machines are conceived. Hydraulic, tracer control machine tool, special purpose automatic and semi automatic machines were introduced with the advancement of technology. These machines were highly specialized but inflexible. The use of these machines was with a success for mass production and they have considerably reduced the production costs by way of reduced machining times and labor costs. Because of inflexibility these machine tools could not however be adopted by units involved in small lot and piece production. Because of the above, great need is felt for tools that could bridge the gap between highly flexible general purpose machine tools (which are not economical for mass production) and highly specialized, but inflexible mass production machines. Numerical control machine tools with proper fixture set up have to take up this role very well.

The fixture designing and manufacturing is considered as complex process that demands the knowledge of different areas, such as geometry, tolerances, dimensions, procedures and manufacturing processes. While designing this review work, a good number of literature and titles written on the subject by renowned authors are referred. All findings and conclusions obtained from the literature review and the interaction with fixture designers are used as guide to develop the present research work.

2 Fixture Studies

Studies in fixturing began in the 1940's. The results lead to several manuals on jig and fixture design such as Houghton (1956) and Wilson (1962). Henriksen (1973) considered many features of fixture design, and Boyes (1989) assembled a handbook that contained a set of guidelines for analytical design. Comprehensive research on fixturing systems probably did not begin until Imhof and Grahl (1977).

Although fixturing contributes significantly to overall manufacturing cost, it is sometimes neglected for the reason of cost reduction. The design and manufacture of fixtures can be time consuming, and it increases the manufacturing cycle time of any product that needs machining and/or assembly. The main reason is that fixtures are designed to tight tolerances, typically 30-50% of the overall workpiece tolerance. In addition, since most fixtures are made of hardened steel, the kinds of machining operations that can be used for their manufacture are constrained (Bidanda and Muralikrishnan 1992, Kusiak 1993).

2.1 Basic Requirement of Fixture

The basic requirement of a fixture is to locate and secure the workpiece in the correct orientation and relationship so the manufacturing process can be carried out according to design specifications (Nee and Kumar 1991). A typical fixture for prismatic parts consists of three components: locators, clamps, and supporters. Locators are used to position the workpiece in static equilibrium thus removing all degrees of freedom. Clamps are for holding the workpiece firmly against the locators during machining for rigidity. The external cutting forces and tool direction are the major considerations. Additional support is added to reinforce the stability of the workpiece. The use of these fixturing elements can be determined manually or analytically.

Since the workpiece is subjected to the external cutting forces of machining, the three above fixture elements must make sure that the workpiece is positively located, is rigid, and assures repeatability. Repeatability refers to the workpiece and subsequent workpieces can be located by the fixture in precisely the same place. This activity is considered a 'set-up' in manufacturing.

To make sure the workpiece maintains the dimensional specifications and tolerances, the external cutting forces must be resisted by the fixture so that the workpiece remains in equilibrium. The workpiece has unconstrained spatial motion

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of 12 degrees of freedom in 3D space. These movements are along the positive and negative directions of the x, y and z-axes and clockwise and counter clock wise rotations about the three axes. The degrees of freedom are constrained by the locators and clamps.

Four general requirements of a fixture are recognized, and they are discussed next (Sakurai 1992).

(a) Accurate locating of the workpiece

To ensure that the workpiece meets its quality standards by tolerance specifications, a fixture must locate the part accurately in relation to the machine coordinate system and the workpiece coordinate system. This discrepancy is usually recognized as the locating error, and should be minimized. If the locating error is too large, a different locating face must be selected, or the tolerance of the locating face must be tightened. Hence, accurate locating means holding the workpiece precisely in space to prevent each of the spatial movements, i.e. linear movement in either direction along x, y and z axes and rotational movement in either direction about the axis (Gandhi and Thompson 1986).

(b) Total restraint of the workpiece during machining

The fixture must hold and restrain the workpiece from external forces, e.g. generated during machining. Therefore strong clamping forces that act against locators are essential. Optimization approaches have been developed to determine the number of fixture elements required and forces to oppose cutting conditions (Menassa and DeVries 1991).Common locating rules in practice are the 3-2-1 or 4-2-1 methods for clamping (Henriksen 1973). Both rules provide the minimum number of fixture elements and the greatest rigidity. The 3-2-1 method involves locating the workpiece in three orthogonal planes and clamping against the locating planes to ensure rigid fixturing. The 4-2-1 method simply applies four orthogonal planes instead of three.

(c) Limited deformation of the workpiece

The fixture clamping forces or the cutting forces may deform the workpiece elastically or plastically. Strict requirements must make sure any deformation is within specified limits. These limits must be determined from given tolerances of the workpiece. Finite element analysis is an excellent tool for this activity. Functional alternatives include additional fixturing supports in multiple locations.

(d) No machining interference

It is important that none of the fixturing components or elements interfere with the cutting tool during machining. Obviously, this would cause damage to the tool as well as other contact surfaces. Two approaches were proposed for interference avoidance: configuration space approach (CSA) and the generate and test approach (GTA)

2.2 Phases of Fixture Design

The fixture design process essentially contained three phases: planning, design, and assembly. During the planning stage, an initial configuration of the fixture is determined. Decisions made here are referenced to machine resources and facilities available, material handling, and quality specifications. In the fixture design phase, more detailed analysis is examined concerning locating, clamping, and supporting the workpiece. Subsequently, the particular fixture elements are selected to meet the design requirements. The final phase of assembly focuses on the construction of the fixture.

Fixture assembly can be done manually, or in an automated system. Many researchers have examined fixture assembly using robots (Chan et al. 1990, Giusti et al. 1991). Shirinzadeh (1993) discussed a prototype system for flexible fixtures in robotic assembly using a CAD package that is capable of setting up a number of fixture modules and automatically changing and adjusting the assembly robot without human intervention.

2.3 Dedicated Fixtures vs Modular Fixtures

Most fixtures are designed for a particular workpiece, thus being called 'dedicated fixtures'. Due to the current trends in manufacturing promoting a larger product mix, flexibility, and quality, many companies are demanding fixturing systems to be more 'flexible'. Flexible systems allow a variety of individual parts to be held during machining or assembly, thus minimizing cost to produce each dedicated fixture, and reducing storage of a multiplicity of fixtures (Grippo et al. 1987). With typical costs of dedicated fixtures amounting to 10-20% of the total manufacturing costs, the economic impact of flexible fixturing could be dramatic (Gandhi and Thompson 1986).

Manufacturers have been designing fixtures as long as there have been machining operations. Fixtures are required to hold parts and workpieces in order for certain manufacturing processes to be performed. The traditional method has been to design and create a 'dedicated' fixture with the sole objective of producing a high quantity of the same part. However, the trend toward greater flexibility in production volume and product variety has led to more multi-purpose fixtures.

Flexible fixtures for rotational components have been in use for several decades (Ridanda and Muralikrishnan 1992) and they are capable of holding a large variety of workpieces. Common fixtures for rotational parts are centres, mandrels, collets and chucks. A centre is used to help mount and hold a workpiece typically one centre at each end. The mandrel is a device in which through holes are provided to hold the workpiece and machining operations are performed within specific regions of the part. Collets are tapered bushings used typically for holding bar stock of circular, square, and hexagonal cross sections. Chucks are the most popular fixture for rotational components, specifically for lathes, and are usually equipped with three or four jaws (Kalpakjian 1992). Because of their versatility, there are many types of chucks. Most turning machine tools also have advanced features for holding different shapes of workpieces.

Traditional fixtures of prismatic parts consist of steel base plates with locating and clamping elements. These elements were usually welded together for repeatability, loading and unloading, and meeting stringent design specifications such as tolerances. The fixtures were hardened and grounded to help satisfy these requirements.

With the need for flexibility and the increasing design complexity of products, modular fixtures have emerged. A modular fixture attempts to achieve flexibility via multipurpose fix-

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turing elements. A modular fixturing system consists of a large number of standard fixturing elements such as base plates, locators, clamps, and supporting elements. Using these standard components, elements are selected to build a fixture configuration to hold the workpiece. Modular fixturing elements can be re-used for other products once disassembled, and they are manufactured with high tolerances to meet workpiece requirements.

Two other main factors that have created the need for modular fixtures include smaller batch sizes in production, and the greater usage of multiple axis CNC machine tools. The interchangeability of modular fixture elements supports these trends.

Most of modular fixtures can be classified as kits with T-slotted, grid holes, or dowel pin base plate fixtures. For fixture assembly, the T-slots, grid holes or dowel pin holes are located on all faces of the base plate. The construction sets similar to Lego blocks are fastened together with bolts held in T-nuts or with capped screws. Several commercially available modular fixturing systems are listed below:

(1) T-Slot base plate
- (a) Erwin Halder Modular Jig and Fixture System, USA
- (b) CATIC (China National Aeronautical Technology Import and Export Corporation) System, China

(2) Grid base plate
- (a) Venlic Block Jig System, IMAO Corporation, Japan
- (b) Yuasa Modular Flex System, USA

(3) Dowel pin base plate
- (a) Bluco Technik, Germany
- (b) SAFE (Self Adapting Fixture Element) System, USA

The positional, geometrical and dimensional accuracy of these fixtures together with their location features are manufactured to an order of +0.01 mm. However, modular fixtures tend to be larger than dedicated fixtures and base plates with grid holes have greater positional accuracy and strength than those with T-slots.

Modular fixtures reduce the need for storage space compared to dedicated fixturing, and the time and labour cost in designing dedicated fixtures. Machine shops have demonstrated these advantages in many instances (Friedmann 1984). The major faults of modular fixtures are in accounting for repeatability and tolerance stack up with the assembly of standard components. Vendors of modular fixtures attempt to resolve these inadequacies by hardening and grounding fixture elements. Hence, modular fixtures are more commonly used for low production volume components with a wide product variety.

Other types of fixturing hardware have been developed though most of the advancements remain within the prototype state. Gandhi and Thompson (1985) developed a phase-changing fixturing system to conform to workpieces with complex shapes and features. A phase-change fixturing material is transformed from a solid into fluid or pseudo fluid by the application of heat or an air stream, such as sand or wax. This process is reversible. The complex workpiece is typically immersed in the fluid and then is 'fixtured' by phase-changing the fluid into a solid material. The solid material holds the workpiece while certain manufacturing processes are performed and is changed back to a liquid to remove the workpiece. The process only involves light cutting operations and has been used in the aerospace industry for parts such as turbine blades.Please note that math equations might need to be reformatted from the original submission for page layout reasons. This includes the possibility that some in-line equations will be made display equations to create better flow in a paragraph. If display equations do not fit in the two-column format, they will also be reformatted. Authors are strongly encouraged to ensure that equations fit in the given column width.

2.4 Flexible Mechanical Fixtures

Flexible mechanical fixtures use various clamping techniques hold workpieces. Two types still in the development stages arc petal-collet fixtures and the multileaf vice. Both use special clamping procedures consisting of tetrahedral 'petals' and 'jaws' respectively to hold specific shapes of workpieces. Benhabib et al. (1991) developed a modular programmable fixturing system. Other types of fixturing hardware as discussed by Bidanda and Muralikrishnan (1992) are programmable clamps and numerical control (NC) fixturing machines. However, despite developments in fixturing hardware, modular fixtures are the only ones commercially available. Therefore, most of the fixturing research has included the benefits of these types of fixtures.

Within the past decade, the manufacturing research community has focused on developing and improving technologies such as computer-aided design and manufacturing (CAD/CAM), computer-aided process planning (CAPP), and flexible manufacturing systems (FMSs). Eversheim and Schneewind (1993) discuss the emerging developments in CAPP alone as evolutionary. Kochan (1992) has introduced the development of the first-ever commercial CAPP software as an add-on to current CAD/CAM systems. Only recently has the literature documented research on prototype fixtures. This has been motivated by studies indicating that flexible and adaptable fixtures could reduce the cost of fixturing by as much as 80% (Friedmann 1984).

One of the fixturing requirements discussed is that the fixture must limit deformation of the workpiece. It is important to consider the cutting forces as well as the clamping forces on the workpiece. Without adequate fixture support, machining operations do not conform to designed tolerances and specifications. Excessive cutting and clamping forces result in workpiece deflections and deformations depending on the elasticity of the part. Finite element analysis has demonstrated to be an excellent tool to resolve some of these problems. A finite element model is created of the workpiece, and cutting and clamping forces can be created and determined to reflect the behaviour of the modelled workpiece.

Lee and Haynes (1987) used finite element analysis (FEA) to minimize fixturing force and workpiece deflection. They were able to determine the deflection of a part for a specific fixture assembly. Menassa and DeVries (1990) further extended this work using specific fixturing elements considering the complete fixture as an elastic body. Finite element analysis can provide an excellent tool to analyze the configurations of fixtures before the actual assembly, thus reducing setup time and labour costs.

Bidanda and Muralikrishnan (1992) recognized two other research directions needed for the advancement of automated fixture design. There is a need for standardized databases and information systems for manufacturing planning and analysis, interfacing the domain of fixture design. They also conclude that a standardized graphical interface for manufacturing would be advantageous.

2.5 Locating and Clamping Considerations

As stated by Koji Teramoto, Masahiko Anasoto and Kazuaki Iwata, Fixturing Plan (FP) and Machining Plan (MP) are mutually dependent. The design of machining fixtures relies on designer experience and his/her implicit knowledge to achieve a good design. In order to facilitate its application, the explicit definition of the fixture design process and the knowledge involved is a prior and a fundamental task to undertake. Additionally, a fundamental and well-known engineering principle should be considered: the functional requirements and their associated constraints should be the first input to any design process. A relevant issue when considering requirements, taking this as a general concept, is to make explicit the meaning of two main terms: Functional Requirement (FR) and Constraint (C). Functional Requirement (FR), as it stated by different authors, 'represents what the product has to or must do independently of any possible solution'. Constraint (C) can be defined as 'a restriction that in general affects some kind of requirement, and it limits the range of possible solutions while satisfying the requirements'.

In machining, work holding is a key aspect, and fixtures are the elements responsible to satisfy this general goal. Usually, a fixture solution is made of one or several physical elements, as a whole the designed fixture solution must satisfy the entire FRs and the associated Cs. Centering, locating, orientating, clamping and supporting, can be considered the functional requirements of fixtures. In terms of constraints, there are many factors to be considered, mainly dealing with: shape and dimensions of the part to be machined, tolerances, sequence of operations, machining strategies, cutting forces, number of set-ups, set-up times, volume of material to be removed, batch size, production rate, machine morphology, machine capacity, cost, etc. At the end, the solution can be characterized by its: simplicity, rigidity, accuracy, reliability, and economy (2).

The methodology proposed for design of a fixture includes the realization of two stages. The first stage represents the knowledge of the objects like part geometry, machining process, functional and detailed fixture design, and fixture resources. The second stage describes the inference process (design and interpretation rules) needed to obtain a first solution for the machining fixture .

Inaccuracies in workpiece location lead to errors in position and orientation of a machined feature on the workpiece. The ability to accurately locate a workpiece in a machining fixture is strongly influenced by rigid body displacements of the workpiece caused by elastic deformation of loaded fixture–workpiece contacts. The accuracy of location of a machined feature depends on the machining fixture's ability to precisely locate the workpiece relative to the machine tool axes.

Workpiece location in a fixture is significantly influenced by localized elastic deformation of the workpiece at the fixturing points. These deformations are caused by the clamping force(s) applied to the workpiece. For a relatively rigid workpiece, the localized elastic deformations cause it to undergo rigid body translations and rotations which alter its location with respect to the cutting tool. It is therefore important to minimize such effects through optimal design of the fixture layout.

S. K. Hargrove and A. Kusiak recognize four general requirements of a fixture: (i) Accurate location of the workpiece, (ii) Total restraint of the workpiece during machining, (iii) Limited deformation of the workpiece, (iv) No machining interference.

In general, the fixture layout design has to satisfy four functional requirements.

i. Locating stability: Locating stability is related to the design of a fixture layout that can provide static equilibrium of a workpiece when it is placed on fixtures. Locating stability is one of the most important requirements in fixture design since a workpiece has to satisfy this requirement before achieving other functional requirements. Locating stability is mainly concerned with static equilibrium under the given fixturing condition in the presence of manufacturing forces. In addition, the fixture layout design has to ensure that all locators maintain contact with the workpiece throughout the manufacturing operation. Issues involving locating stability begin when the workpiece is placed on locators as these locators provide a support against gravity forces until the workpiece is processed. Thus, locating stability also involves fixture force and kinematic analysis to estimate the necessary clamping forces to maintain a workpiece in equilibrium.

ii. Deterministic workpiece location: The fixture should provide the deterministic location for the workpiece to ensure position accuracy during operation. Deterministic workpiece location involves designing the locator positions or a fixture layout to provide a unique and accurate position and orientation of a workpiece with respect to its fixture reference frame. Common challenges involving the fixture layout design that will meet this functional requirement include the positioning accuracy, which is subject to a random manufacturing error of fixture elements, geometric variability of the workpiece and workpiece positioning errors induced by fixture position. In general, the position variability of the workpiece can be predicted from the statistical characterization of the dimensioning and tolerancing scheme assigned to the fixtures and their contact points on the workpiece. Thus, determining the fixture layout, which is not sensitive to these variation sources, can minimize the workpiece positional variability.

iii. Clamping stability: Clamping stability involves determining the sequence of clamping and its layout that does not disturb the stability and position accuracy of a workpiece established by locators in the previous two functional requirements. Clamping stability and total restraint are functional requirements that are related to determining the clamping positions and forces, which do not affect the part locating stability and position accuracy of workpiece provided by the locators. Clamps apply forces on the workpiece against any external force to ensure total restraint. The challenge in designing clamping locations is to minimize the workpiece deformations under clamping and external forces.

iv. Total restraint: Clamps should completely restrain the workpiece to withstand any forces and couples to maintain the workpiece in an accurate position.

In addition, as set forth by R. T. Meyer and F. W. Liou (6), dynamic machining conditions occur when a workpart is subject to machining forces that move through the work part or along its surface. A viable fixture designed for a workpart experiencing dynamic machining must ensure: the workpart is restrained for all time, the clamping forces are not too large or small, deterministic positioning, accessibility, stability of the workpart in the fixture while under no external forces, and a positive clamping sequence.

Workpiece motion arising from localized elastic deformation at the workpiece/fixture contacts due to machining and clamping forces significantly affect the workpiece location accuracy and hence the machined part quality. The tangential friction force plays an important role in fixture configuration design as it can be utilized to reduce the number of fixture components, thereby the workpiece features accessibility to machining operations and providing a damping mechanism to dissipate input energy from machining forces out of the workpiece/fixture system. Contact problems with friction are generally complicated by the fact that the contact surface can experience slipping, sliding, rolling or tension release depending on the magnitude of the normal and tangential forces at the contact interface (7).The design of a fixture that permits accurate machining of the workpiece by keeping the contribution of workpiece/fixture elastic deformation to the machining error within the specified tolerance is a critical step in process planning. The important aspects of fixture design are positions of locators and clamps, and clamping forces, such that workpiece deformation due to clamping and machining forces is minimized.

2.6 Fixture Design Process

Fixture design is one of the most important design tasks during process design for a new product development since it involves defining the locations and orientations of parts during assembly processes as well as providing physical support, which can greatly affect product dimensional variations and process yield. Generally, fixture design process can be divided into three stages.

i. Fixture planning: In the fixture planning stage, issues related to the number of fixtures needed, the type of fixtures, the orientation of fixture corresponding to orientation, and the joining or machining operations, which fixtures have to handle are identified.

ii. Fixture configuration: The fixture configuration stage determines the layout of a set of locators and clamps on a workpiece surface such that the workpiece is completely restrained.

iii. Fixture construction: Finally, the fixture construction stage involves constructing fixture components and then installing them to support the workpiece. Specifically for complex assemblies such as an automotive body, a ship hull, and an aircraft fuselage, fixture layout design, which falls under the domain of the fixture planning and fixture configuration stages, is a primary concern and it involves adjusting the design nominal of locator positions in order to eliminate mean shifts.

Careful review of the literature conveniently places research activities in one of the categories shown in Table 1.

In the fixture planning phase, production requirements indicate batch sizes, types of machines, human resources, and the overall cost. Other requirements such as quality standards may dictate functional considerations such as inspection and tolerance specifications. Research in this area focus on production planning optimization techniques such as scheduling models and algorithms. In the design phase, where most of the documented research has been concentrated, there are two subphases.

During the design phase, a detailed 'analysis' is examined to locate and position the workpiece. The next subphase is 'synthesis'. This phase can also be referred to as 'fixture representation'. The selection of fixture elements is required to satisfy the requirements and represent the fixture configuration.

The final phase is assembly. There are basically two approaches to assembly, manual or automated. Though this research may be investigated outside the realm of fixture design, the results can be implemented in this area. The taxonomy of fixture design categorizes and organizes fixture design tools, and would serve as a good classification for research directions. It provides a visual arrangement of investigations in the fixture design area, and provides a perspective in relation to other areas of research.

Fixture planning and design is defined in this context as consisting of all the tasks and information required to design a workholder to locate, hold, and support a workpiece during a machining process. Fixture planning and design relies on the experience, skills, and knowledge of the tool designer. Though considered as an isolated activity, the tool designer requires information from preceding and succeeding functions in order to effectively locate and hold the workpiece for machining operations.

Three subfunctions are identified for fixturing that is consistent with the classifications of fixture design research discussed earlier. The first activity involves the planning of fixture design. The necessary input requires the process plan, engineering drawing, and production information. Production information contains information about batch sizes and cost per piece to manufacture. This activity is typically performed by the process planner and a manufacturing engineer and/or fixture designer. Their cooperation is essential in identifying the kind of fixtures to be used. For example, depending on the product information about production volume, it is determined at this stage whether to use modular fixturing or design a permanent fixture. In general, modular fixtures are used for lower production volume, and permanent fixtures are used for high volume production.

Table 2 shows an example of fixturing alternatives and characteristics for three types of fixtures.

General purpose fixtures and tools are universal work holders such as chucks, collet chucks and vices, machine vices, and universal workholding systems (8). They usually hold

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regular or symmetrically shaped workpieces such as squares, rectangles, cylinders, hexagons, and similar part shapes. Some manufacturing companies use computer-aided fixture design systems. Most of these systems simply allow the user to identify and select parameters required for planning and design, and are extremely 'interactive'.

Fixture planning is controlled by the type of fixtures available, facility resources, and the specific machine tools. For example, the machine tool may be limited by the number of axes and its orientation for machining, and this will determine how the fixture is constructed. The output of this subfunction is the type and kind of fixtures required.

The fixture design subfunction is the most active in terms of product description. The selection of fixture elements and the positioning process is related to their major function, contact surface, and its ability to restrict specific degrees of freedom to constrain the workpiece. Once the decision is made on the type of fixture to use (modular, general purpose, or permanent), the manufacturing features of the workpiece also determine the fixture elements and their relative position and location to constrain the workpiece. Again, this fixture configuration is controlled by the accessibility of the machine tool and the machining features required. The fixture designer is the major participant in developing the fixture. However in smaller companies, the machinist may be responsible for developing and designing the fixture. The output is a description of the fixture design indicating the location and position of the elements, and a listing of these elements.

The last subfunction is fixture assembly. This activity may happen concurrently with fixture design, and is typically performed by the machinist and / or the fixture designer. In advanced manufacturing operations, a robotic assembly may be used. The activity is controlled by the number of setups required and the fixtures available and requires the layout of the fixture design activity. The final output is the fixture / workpiece assembly ready for the machining operations.

Table 3 provides a systems view of fixture planning and design. Lower level relationships would also reveal crucial data exchanged between the functions. The model identifies the activities and information transferred, but Table 3 further recognizes the sublevel data that promotes functional interdependency and is necessary to complete each major function.

Fixture design has been recognized as an art as well as a science. The science of fixturing is demonstrated by the number of fixture design systems being developed and the many optimization approaches to configuration, location and positioning of work holding elements. The art of fixturing is acquired through trial and observation, and these are the skills and knowledge the fixture designer develops over a period of time. Table III demonstrates how both of these methodologies are implemented during fixture planning and design, and the important part each plays in constructing the final fixture / workpiece assembly.

Desirable characteristics of a fixture are: positive reaction forces at the locators for all time, deterministic positioning, strong accessibility, stability of the workpart in the fixture while under no external forces, and a positive clamping sequence.

2.7 Computer Aided Fixture Design

Over the past decade, much focus has been put on intelligent methods for computer aided fixture design to seek a technical breakthrough in embedding more design knowledge into semiautomatic or automatic CAFD systems. Table 4 shows a detailed discussion [Hui Wang et al. 2010].

Fixture design includes the identification of clamps, locators, and support points, and the selection of the corresponding fixture elements for their respective functions. There are four main stages within a fixture design process—setup planning (D1), fixture planning (D2), fixture unit design (D3) and verification (D4), as Fig. 1 illustrates [Hui Wang et al. 2010, Kang Y et al. 2003 and Boyle Iain]. Setup planning determines the number of setups required to perform all the manufacturing processes, the task for each setup, e.g., the ongoing manufacturing process and workpiece, orientation and position of the workpiece in each setup. A setup represents the combination of processes that can be performed on the workpiece by a single machine tool without having to change the position and orientation of the workpiece manually.

During fixture planning, the surfaces, upon which the locators and clamps must act, as well as the actual positions of the locating and clamping points on the workpiece, are identified. The number and position of locating points must be such that the workpiece is adequately constrained during the manufacturing process. In the third stage of fixture design, suitable units, (i.e., the locating and clamping units, together with the base plate), are generated.

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TABLE 1
TAXONOMY OF FIXTURE PLANNING AND DESIGN

Phase	Requirements	Methods and tools
Planning	Production volume Machine resources Quality standards	Production planning techniques Machine capabilities
Design analysis	Accurate locating of workpiece Total restraint of workpiece during machining Limited deformation of workpiece No machining interference Optimal setup sequence	Tolerance analysis Expert systems, FEA, features CAD/CAM, CAPP Optimization methods Workpiece representation
Synthesis	Select fixture elements for locating Select fixture elements for clamping Select fixture elements for support	Modular fixtures Chucks, centre, collets Comfortable and programmable fixtures, Phase-change NC fixturing systems, etc.
Assembly	Manual assembly Automated assembly	Human factors Robotic technology Man-machine interfaces

TABLE 2
FIXTURING ALTERNATIVES AND CHARACTERISTICS

HIGH / Part variety / LOW

Modular fixturing		
	General fixturing	
		Permanent fixturing
LOW	**MEDIUM**	**HIGH**

PRODUCTION VOLUME

HIGH / Cost per part, Operations needed, Set up time, Operator skill, Machine cycle time / LOW

TABLE 3
DATA AND INFORMATION EXCHANGE BETWEEN SYSTEM PLANNING AND DESIGN FUNCTIONS

Process Plan	Engineering Drawing	Resources	Machine tool	Manufacturing features	Setup information
Sequence of operations Machine tools Workpiece number Standard times	Raw material type Workpiece configuration Surface finish Tolerances Heat treatment Hardness	Machine tools Fixtures available Manufacturing Personnel	Machine type Configuration Table size Main axis direction Machine ID code Machine location	Type of feature Tolerances Surface finish Machining process Allowances	Fixture availability Machine configuration Workpiece deformation Interference

Table 4
Current CAFD Literature

	Method	Level of detail				Application
		D_1	D_2	D_3	D_4	
Amaral, et al.	Finite element analysis				✓	
Aoyama, et al.	Genetic algorithm	✓	✓			
Asante	Finite element-based				✓	Load and pressure distribution calculation
Bansal, et al.		✓	✓		✓	An integrated fixture planning system for minimum tolerances
Boyle, et al.	Case based reasoning	✓	✓	✓		
Cai, et al.	TRIZ evolution technology					TRIZ-based evolution study for modular fixture
Chen, et al.	Case based reasoning	✓				
Choubey, et al.	Genetic algorithm	✓	✓		✓	Machining fixtures
Ding, et al.		✓	✓			Fixture fault diagnosis, assembly processes
Estrems, et al.					✓	Fixtures in machining processes
Fan, et al.	XML based information representation, Case based reasoning method	✓	✓			
Girish, et al.	Tabu search	Fixture elements management				Modular fixture elements
Hamedi	Artificial neural network, Genetic algorithm, Finite element method	✓	✓		✓	
Hou, et al.		✓	✓	✓	✓	Modular fixtures
Hurtado, et al.	Finite element method, modeling of fixture-workpiece contacts	✓	✓		✓	Machining fixtures
Kakish, et al.	Knowledge-based modeling	Universal Modular jigs and fixtures information modeling				Universal modular jigs and fixtures
Kang, et al.					✓	
Kaya	Finite element method, Genetic algorithm	✓	✓		✓	Machining fixture
Krishnakumar, et al.	Finite element method, Genetic algorithm	✓	✓	✓	✓	Machining fixtures
Kumar, et al.	CAD-based collision detection		✓		✓	Modular fixtures
Li, et al.	Finite element method, Genetic algorithm	✓	✓		✓	Sheet metal assembly with laser welding
Li, et al.	Multi-objective Optimization	✓	✓		✓	Tolerance allocation, assembly fixture
Lien et al.	Integrated measurement in clamping systems			✓	✓	On-line correction of welding paths, Robotic welding of thin-walled aluminum structures
Lin, et al.		✓	✓			Modular fixtures for measurement
Liu, et al.					✓	Assembly fixture fault diagnosis, sheet metal joining process
Mervyn, et al.	Evolutionary search algorithm	✓	✓			Modular fixtures
Peng, et al.	Desktop virtual reality technology	✓	✓	✓		Modular fixture design and simulation
Ratchev, et al.	Finite element method				✓	The prediction of part-fixture

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						deformation and tolerance
Shen, et al.		✓	✓	✓	✓	Reconfigurable fixtures, Automotive engine machining and assembly
Sikstrom, et al.	Super element (SE) fixture modeling, Coupled thermal–mechanical analysis	✓			✓	Fixture design in fusion welding
Subramaniam, et al.	Multi-agent system, Genetic algorithms and Neural networks	✓	✓			
Subramanian, et al.	Genetic algorithm	✓	✓			
Wang			✓		✓	Tolerance analysis in fixture-workpiece system
Wang, et al.	Case based reasoning	✓	✓	✓		Modular fixtures for welding
Wardak, et al.	Finite element method	✓	✓	✓	✓	Drilling fixtures
Wu		✓	✓	✓	✓	Geometry generation of fixture
Wua, et al.	Linkage mechanism theory: a four-bar mechanism and linkage curve	✓	✓			Modular fixture
Zheng, et al.		✓	✓	✓	✓	Precise modular fixture
Zheng, et al.	Finite element analysis				✓	For fixture stiffness

3 Conclusion

Fixtures have a direct impact upon product manufacturing quality, productivity and cost, so much attention has already been paid to the research of computer aided fixture design (CAFD) and many achievements in this field have been reported. Many academic and applications papers have been published in this area. But still Fixture design needs to be tested and evaluated in real manufacturing environments and integrated with other design activities, which often are related with production resources, equipment, cost and machining processes, etc.

Another important research is on the integration of various techniques directly used in computer aided fixture design. As we know, an optimal fixture solution is a hybrid result of many different considerations, such as tolerance configuration, stiffness configuration, machining process, etc. Hence attention should be paid on the establishment of a systematic way of integrating various techniques, such as Computer Aided Mass Balancing Method (CAMBM) and FEA methods for workpiece-fixture system.

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