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Computer aided fixture design: Recent research and trends

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ABSTRACT

Widely used in manufacturing, 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.

In this paper, a literature survey of computer aided fixture design and automation over the past decade is proposed. First, an introduction is given on the fixture applications in industry. Then, significant works done in the CAFD field, including their approaches, requirements and working principles are discussed. Finally, some prospective research trends are also discussed.

1. Introduction

A fixture is a mechanism used in manufacturing to hold a workpiece, position it correctly with respect to a machine tool, and support it during machining. Widely used in manufacturing, fixtures have a direct impact upon product quality, productivity and cost. Generally, the costs associated with fixture design and manufacture can account for 10%–20% of the total cost of a manufacturing system [1]. Approximately 40% of rejected parts are due to dimensioning errors that are attributed to poor fixturing design [2]. Fixture design work is also tedious and time-consuming. It often heavily relies on fixture design engineers' experience/knowledge and usually requires over 10 years manufacturing practice to design quality fixtures [3]. Traditionally, the design and manufacture of a fixture can take several days or even longer to complete when human experience in fixture design is utilized. And a good fixture design is often based on the designer's experience, his understanding of the products, and a try-and-error process.

Therefore, with the increasingly intense global competition which pushes every manufacturer in industry to make the best effort to sharpen its competitiveness by enhancing the product's quality, squeezing the production costs and reducing the lead time to bring new products to the market, there is an strong desire for the upgrading of fixture design methodology with the hope of making sound fixture design more efficiently and at a lower cost. The development of computer-aided fixture design (CAFD) technology over the past decades can be attributed to the fulfilling of this goal.

As an important field in manufacturing, research and applications of fixture design has been paid much attention over past decades [4,5]. Many academic and applications papers have been published in this area. In this paper, we will focus on an investigation of computer aided fixture design research in the past decade. The following sections will give a survey on the state of the art of these researches. Some conclusions on research trends are also discussed.

2. Fixtures in manufacturing

A fixture is designed to position and hold one or more workpiece(s) within some specifications. It is widely used in manufacturing, e.g. machining (including turning, milling, grinding, drilling, etc), welding, assembly, inspection and testing. The following Figs. 1–9, are some real fixture design cases in manufacturing. Fixtures can be classified with different principles. However, compared with the publications of CAFD research in machining fixture field, only a few [6–16] have been focused on other important manufacturing fields, for instance, assembly fixtures and welding fixtures.

2.1. Welding fixtures

Welding is essential to a high dollar volume of manufacturing processes, including national defense industries. According to *Economic Impact and Productivity of Welding, Heavy Manufacturing Industries Report*, by American Welding Society and Edison Welding Institute on June 2001, "The contribution of welding to the US economy in 1999 via these industries was no less than $7.85 billion. This figure represented 7% of total expenditures by these firms in 1999" [17,18]. So there are significant technical and commercial

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Fig. 1. Machining fixtures (*IMAO corp.*) [19].

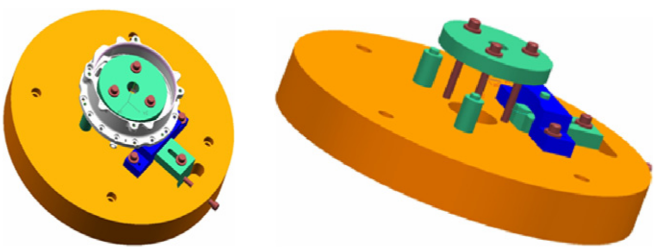

Fig. 2. Machining fixtures of aircraft-used bearing housing.

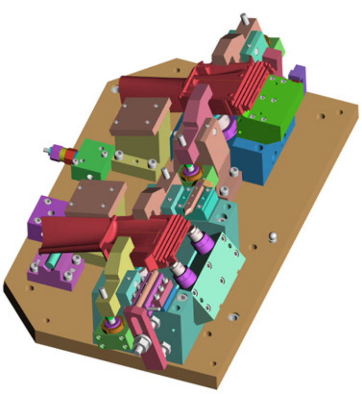

Fig. 3. Grind fixture for turbine blades (*aerocad design, inc.*) [20].

advantages in the development and deployment of welding fixture design systems.

There are obvious differences between machining fixture design and welding fixture design. As in the following:

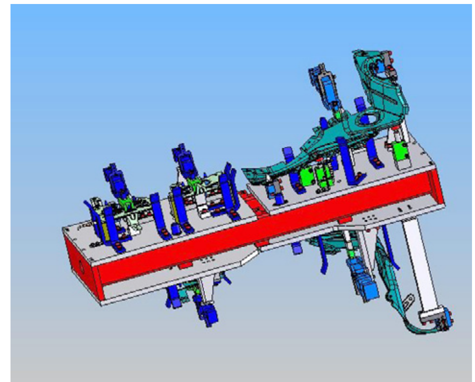

Fig. 5. Automotive stud weld fixtures on a trunion frame, (*DBM innovation inc.*) [22].

- The workpiece in a welding process is usually an assembly of several parts, while workpieces undergoing a machining process contain only one part.
- Usually, the accuracy requirement in a welding process is less than in machining.
- Fixing forces and machining forces in a welding process commonly are smaller than in machining.
- Thermal reactions in welding should be seriously considered.

Furthermore, these factors also should be paid some attention in welding fixture design cases:

- Electrical conductivity is critical for arc welding stability.
- In addition to thermal conductivity, when selecting fixture material thermal expansion properties also should be considered.
- Refined welding waveforms require an optimized welding circuit to maintain short arc lengths while reducing spatter, stubbing, arc flare, and arc outages to maximize travel speeds.
- More complex applications may require a dedicated fixture. The design and installation of a dedicated fixture frequently involves installing and routing wiring and pneumatic or hydraulic lines.

In the past decade, only very limited CAFD research and applications have been reported in the welding sector. In this field, due to the importance of welding for sheet metal assembly in automobile and aerospace industries, the assembly and welding of sheet metal has received some special attention. A weld fixture is often developed to reduce the deformation of each workpiece due to heat and residual stress in the welding process and, hence, to reduce the dimensional variation of the assembly. Therefore, some methods of offline or online deformation analysis were developed to enhance the fixtures' ability on deformation controlling [8,9]. In

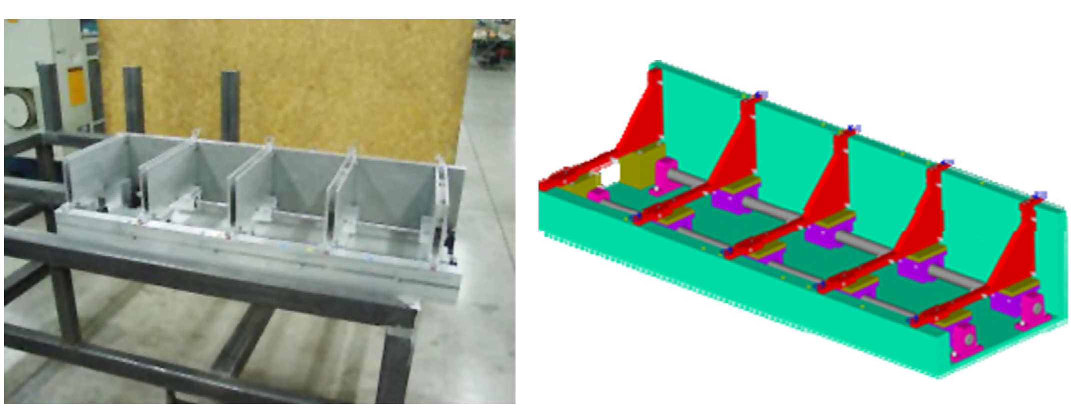

Fig. 4. Assembly fixture to locate shelves for assembly of cabinets (*pioneer industrial systems LLC.*) [21].

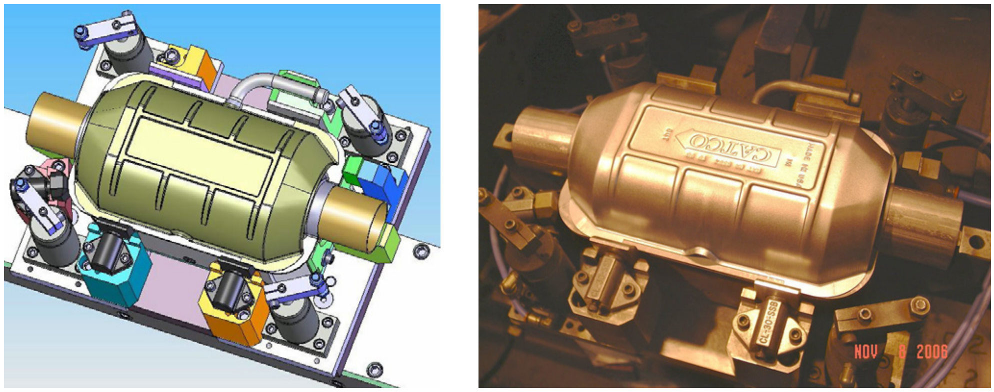

Fig. 6. Robot weld fixture (*IMPROVE solutions LLC.*) [23].

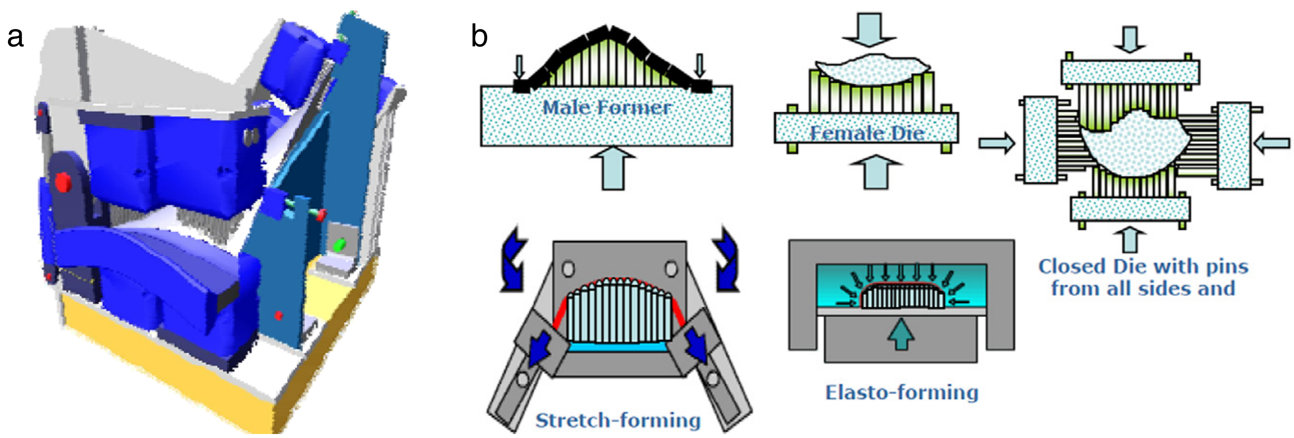

Fig. 7. Pin-array fixture application [29].

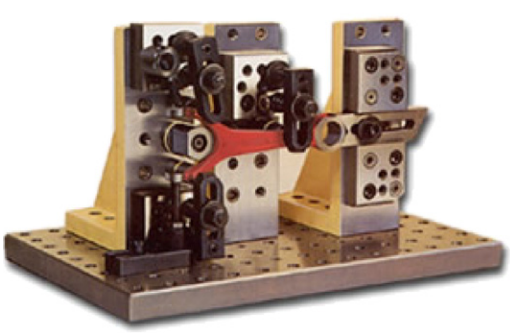

Fig. 8. Modular fixture for a part for the construction machinery (*BLUCO corp.*) [30].

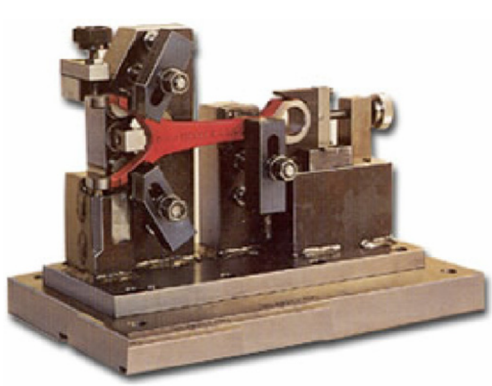

Fig. 9. Dedicated fixture for a part for the construction machinery (*BLUCO corp.*) [30].

sheet metal assembly with laser welding fixtures also should ensure a fit-up of the mating surfaces to ensure proper laser beam weld operation and laser weld quality. As a result, a traditional "3-2-1" locating scheme is extended to a mixed locating idea, "total locating and direct locating for welds" [10–13]. The total locating scheme is used to locate the entire assembly, and the direct locating scheme is used to locate the weld joints to meet the metal's fit-up requirement.

2.2. Applications of modular fixtures and dedicated fixtures

According to the fixture's flexibility, fixtures also can be classified as dedicated fixtures and general purpose fixtures (e.g. reconfigurable and conformable fixtures, modular fixtures). Reconfigurable and conformable fixtures [24–26] can be configured to accept parts of varying shapes and sizes. Particularly, conformable pin-array fixture technology [27] is widely used in many fixture designs because some components contain internal variables that can be adjusted to meet the different features of workpieces (as Fig. 7). And phase-change materials-related fixtures also are used in some precision manufacturing. For instance, in the aerospace industry, low melting-point metals are used to enclose turbine blades and produce well-defined surfaces for part location and clamping for grinding operations.

The most important and widest used within the general purpose fixture classifications are modular fixtures. As the flexible manufacturing system has been adopted by more and more manufacturers who are trying to remain competitive in this rapidly changing market by running production with short lead times and well controlled cost, modular fixtures have gained in popularity because of its performance on easy usage, versatility, and its adaptability to product changes.

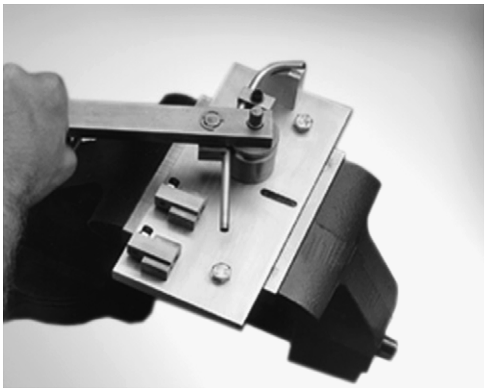

Fig. 10. A dedicated tube bending fixture (*Winton machine company*) [31].

Modular fixtures allow a wider flexibility by making use of standard workholding devices and components. Their flexibility is derived from the large number of possible fixture configurations from the different combinations of fixture components. The application of modular fixtures contributes considerably to shortening the lead time and reducing the cost in small-volume production with versatile products. However, it also has some limitations [28]:

- Only limited combinations can be achieved from these components, meaning that it is possible that no suitable combination can be built for some workpieces with irregular or complex geometries.
- Structural properties of modular fixtures are sometimes difficult to be maintained. Structural properties of modular fixtures include locating accuracy, stiffness, stability, loading and unloading, operating speed, etc. It is common that using modular fixtures may not achieve an optimal fixturing quality.
- Not suitable for mass production, e.g. automotive production and its components' manufacture.

For comparison's sake, Fig. 8 shows a modular fixture used for a part for the construction machinery, and the same part also used in Fig. 9, where a dedicated fixture solution is given.

The dedicated fixtures are also important in manufacturing, particularly, for advanced, sophisticated and precise part or mass production. Because a dedicated fixture is designed for a specific product, the designer can carefully tailor the design to not only meet the basic fixturing requirements such as the locating accuracy, stability, stiffness, but also optimally facilitate the operational requirements such as loading/unloading convenience and efficiency, and effective chip disposal etc. And Fig. 10 is a dedicated tube bending fixture.

Compared with modular fixtures, dedicated fixtures are designed carefully according to workpiece's design and manufacturing requirements. So there are more uncertainties imposed on dedicated fixture design tasks. In modular fixture design, there is a component library with pre-designed and dimensioned standardized fixture components. Thus, the modular fixture configuration design is actually to assemble the fixture components into a configuration.

Due to its extensive use in current manufacturing and standardized production, in many reported CAFD researches and applications, modular fixturing principles are employed to generate fixture designs [32–43]. Early CAFD in modular fixtures merely used the drafting capabilities of a CAD system in assembly. Modular fixture elements such as baseplates, locators, supports and clamps are stored in a database. Based on the fixturing idea, first, the designer specifies the primary locating surface (point) and its locator positions, the suitable clamping surfaces and positions, and then selects and places the appropriate fixturing components in the desired positions. Although there is a reduction in the total time taken

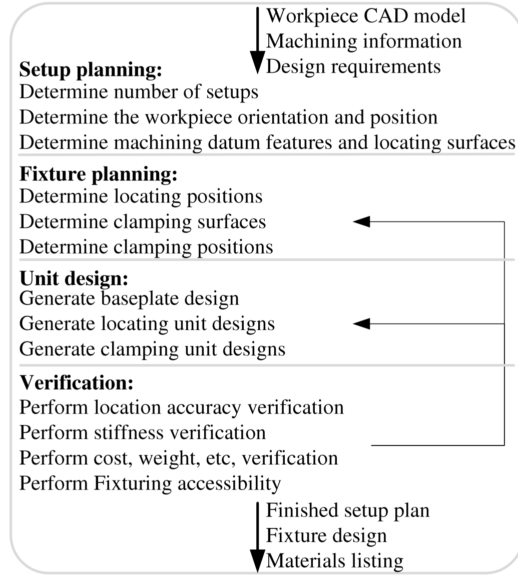

Fig. 11. The basic elements of the fixture design process.

to produce a fixture assembly, the final design depends largely on the designer's experience. Thus they only provide fixture engineers with a simple tool to do fixture design manually based on some extended functions of commercial CAD software. As a result, current industrial applications of CAFD are very limited even though there are many reported research achievements.

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 semi-automatic or automatic CAFD systems. A detailed discussion will be done in the following sections (Table 1).

3. State of the art

3.1. Intelligent and automatic fixture design methods

Typically, fixture design involves 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* (D_1), fixture planning (D_2), fixture unit design (D_3) and verification (D_4), as Fig. 11 illustrates [48,63]. 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. During the verification stage, the design is tested to ensure that all manufacturing requirements of the workpiece can be satisfied. The design also has to be verified to ensure that it meets other design considerations that may include fixture cost, fixture weight, assembly time, and loading/unloading time of both the workpiece and fixture units [50].

Currently, even though numerous techniques concentrating on fixture design have been proposed and made some achievements,

Table 1
Current CAFD literature.

	Method	Level of detail				Application
		D_1	D_2	D_3	D_4	
Shen, et al. [6]		✓	✓	✓	✓	Reconfigurable fixtures, Automotive engine machining and assembly
Liu, et al. [7]					✓	Assembly fixture fault diagnosis, sheet metal joining process
Lien et al. [8]	Integrated measurement in clamping systems			✓	✓	On-line correction of welding paths, Robotic welding of thin-walled aluminum structures
Sikstrom, et al. [9]	Superelement (SE) fixture modeling, Coupled thermal–mechanical analysis	✓			✓	Fixture design in fusion welding
Zheng, et al. [32]		✓	✓	✓	✓	Precise modular fixture
Peng, et al. [33–35]	Desktop virtual reality technology	✓	✓	✓		Modular fixture design and simulation
Kumar, et al. [36]	CAD-based collision detection		✓		✓	Modular fixtures
Mervyn, et al. [38]	Evolutionary search algorithm	✓	✓			IMAO modular fixtures
Subramaniam, et al. [44,45]	Multi-agent system, Genetic algorithms and Neural networks	✓	✓			
Fan, et al. [46,47]	XML based information representation, Case based reasoning method	✓	✓			
Wua, et al. [37]	Linkage mechanism theory: a four-bar mechanism and linkage curve	✓	✓			Modular fixture
Hou, et al. [39]		✓	✓	✓	✓	Modular fixtures
Girish, et al. [40]	Tabu search	Fixture elements management				Modular fixture elements
Lin, et al. [41]		✓	✓			Modular fixtures for measurement
Kakish, et al. [42]	Knowledge-based modeling	Universal modular jigs and fixtures information modeling				Universal modular jigs and fixtures
Cai, et al. [43]	TRIZ evolution technology					TRIZ-based evolution study for modular fixture
Boyle, et al. [48,49]	Case based reasoning	✓	✓	✓		
Wang, et al. [50]	Case based reasoning	✓	✓	✓		Modular fixtures for welding
Chen, et al. [51]	Case based reasoning	✓				
Wardak, et al. [52,53]	Finite element method	✓	✓	✓	✓	Drilling fixtures
Krishnakumar, et al. [54,55]	Finite element method, Genetic algorithm	✓	✓	✓	✓	Machining fixtures
Subramanian, et al. [56,57]	Genetic algorithm	✓	✓			
Hamedi [58]	Artificial neural network, Genetic algorithm, Finite element method	✓	✓		✓	
Choubey, et al. [59]	Genetic algorithm	✓	✓		✓	Machining fixtures
Kaya [60]	Finite element method, Genetic algorithm	✓	✓		✓	Machining fixture
Aoyama, et al. [61]	Genetic algorithm	✓	✓			
Li, et al. [10–13]	Finite element method, Genetic algorithm	✓	✓		✓	Sheet metal assembly with laser welding
Ding, et al. [14,15]		✓	✓			Fixture fault diagnosis, assembly processes
Kang, et al. [62–65]					✓	
Amaral, et al. [66]	Finite element analysis				✓	
Zheng, et al. [67–69]	Finite element analysis				✓	For fixture stiffness,
Hurtado, et al. [70–72]	Finite element method, modeling of fixture-workpiece contacts	✓	✓		✓	Machining fixtures
Ratchev, et al. [73]	Finite element method				✓	The prediction of part-fixture deformation and tolerance
Asante [74]	Finite element-based				✓	Load and pressure distribution calculation
Wang [75–79]			✓		✓	Tolerance analysis in fixture-workpiece system
Estrems, et al. [80]					✓	Fixtures in machining processes
Bansal, et al. [81]		✓	✓		✓	An integrated fixture planning system for minimum tolerances
Li, et al. [16]	Multiobjective Optimization	✓	✓		✓	Tolerance allocation, assembly fixture
Wu [28]		✓	✓	✓	✓	Geometry generation of fixture

Note: *Setup planning (D1), fixture planning (D2), fixture unit design (D3) and verification (D4).*

mature and commercial CAFD applications also are very limited. Fixture design still continues to be a major bottleneck in the promotion of current manufacturing. This work currently, is implemented by a typical designer-centered pattern, that is, all fixture design related work is heavily dependant on the experience and knowledge of fixture designer. This situation hampers the improvement of productivity, requires a long time to cultivate an experienced fixture designer and make the fixture design job weak with a major bottleneck. Thus, new intelligent or automatic technologies on synthesizing traditional geometric design tools, design knowledge, and past design cases have attracted much interest in both academic institutions and industries. The efforts over past decades in this field have resulted in numerous computer aided fixture design (CAFD) applications using various intelligent methods, such as expert system, case based reasoning, and genetic algorithm (GA), etc.

In essence, developing fixture design methodology needs to clear two crucial problems: how to represent fixture design knowledge in a computer and how to implement the problem solving procedure.

At the initial stage of CAFD two decades ago, expert systems were often used as a heuristic tool, which can enlighten fixture designer to a complete fixture design solution, particularly, fixture configuration design in an interactive environment [82]. In most of these methods, design knowledge is modeled as a set of many IF-THEN rules. Then, during the interactive fixture design process, the design solution would be concluded by a series of questioning–answering actions based on these rules. However,

Table 2
Some CBR methods in CAFD.

	Case representation	CBR procedure
Chen, et al. [51]	Define fixture design by attributes template	Interactive mode: *Designer selects some important attributes to match current design case with stored cases*
Fan, et al. [46,47]	XML and UML	
Boyle, et al. [48,49]	Divide fixture design information into two libraries: *conceptual design library and fixture unit library*	Combination of the search results from two case libraries
Sun, et al. [83]	Using MOP (Memory Organization Packages) method to define classes	Cases matching according to four basic objects relevant to workpiece and fixtures
Wang, et al. [50]	XML and semantic objects modeling	Interactive mode: *Three tiers CBRs (rough indexing, solution configuration and physical form determination) + designer intervene*

difficulties on building an enough completed rule set and the logic tree for reasoning procedure have an obvious impact on the design efficiency and the quality of the result. Furthermore, the interactive mode also makes the reasoning procedure very boring.

In comparison, Case based reasoning (CBR) does not require so much complicated domain knowledge system as the expert system. It is mainly concerned on how to create a new solution by imitating past cases, based on the assumption that *similar workpiece will have a similar fixture design solution*. So first, it focuses on structuralizing fixture design cases and to emphasize some crucial data which will be the focus in measuring similarities. Then, the final solution will be generated by modifying the best similar design case according to case comparison. The CBR technique gives the possibility to avoid time-consuming and expensive experiments and is able to propose a good starting point for the detailed design (physical form) without many complicated calculations. Table 2 gives a comparison among some CBR methods in the past decade.

Two techniques remain necessary and crucial in CBR. One is for an efficient method to refine, model and utilize fixture design domain knowledge (fixture design cases), and the other is for an effective technical system which can assist the fixture designer not only by simplifying the design process, but also by generating design ideas.

The prevailing methods on case modeling are based on an attribute set. For example, Chen [51] used a case template to structuralize all fixture design cases, and Fan divided fixture design data into three attribute groups, part representation, setup representation and fixture representation. However, there are few guidelines on defining and choosing appropriate attributes. So this mostly relies on the designer's experience: The designer selects some important attributes which he thinks are important to the current design case and use these attributes as a vector to compute and match stored cases. Thus, it results in a demand for systemizing fixture design domain knowledge to clarify the design requirement in CAFD. Therefore, Boyle [48,49] developed a methodology to classify fixture design information into two libraries: conceptual design information and fixture unit information. Furthermore, Hui re-organized fixture design information into three tiers: workpiece ("design requirements"), fixturing plan ("fixture configuration") and fixture units.

The fixture design domain knowledge representation has a crucial impact on the CBR procedure. Actually, a single CBR system using attribute similarity often has not a good performance on accurate results. Sometimes, the attributes which the designer determined this time do not fit the next time for case indexing, or a high similarity between cases does not necessarily result in a case that can be easily adapted.

The CBR procedure in most of those articles is similar, a cycle such as Aamodt's classic model []. But as a typical experienced based design process, after one cycle of CBR (without a designer's interaction), current fixture design does not have a good performance on obtaining a good solution. That is why we proposed interactive multi-tier CBRs for a fixture design system [50]. Multi-level CBRs, from rough indexing, solution configuration to physical form determination, each cycle the result can get a chance to update and become more close to the ideal result. Each time, after one CBR process completes case indexing and retrieval, the system will present the designer with a selection of cases for a detailed decision, rather than just one that is preferred more than any other. And the designer is required to select the preferred case(s) and determine what changes need to be made to solve the new case and how this change can be achieved. Hence, this is an interactive design process, that requires multiple rounds of CBR reasoning and human intervention before approximating the final solution.

3.2. Generating optimal fixture configuration layouts

The research of generating optimal fixture configuration layouts has received much attention in the CAFD community [58–61, 10–15]. These layouts specify the optimum positions where the fixture should contact the workpiece being machined. The main ideas are similar in these typical fixture layout optimization research articles (as Fig. 12). The first step is the application of the machining process analysis method to predict the machining forces exerted on the workpiece. This analysis is typically carried out for a large sample of cutting tool positions and orientations throughout the machining cycle. The second step is the deformation analysis of the fixture-workpiece system, utilizing the pre-determined load cases. Typically deformation analysis is based on the finite element method (FEM). The loads and the shape of the machined surface are calculated, and hence, the deformation of workpiece, under a given locating and clamping scheme, will be analyzed as to whether or not it is in an acceptable region. In general, if considering the clamping and machining forces over the entire machining process, by simulating the dynamic machining process, the analysis on workpiece deformation will be more accurate [54,55], with a cost of time-consuming computation. Finally, it will employ an optimization process (GA is mostly used) to search for a potential solution space and determine the locations of the fixtures within acceptable candidate regions with a minimized workpiece deformation [56,57].

Most of relevant works assumed some conditions: treat fixture-workpiece contact as point contact [54–57], the workpiece is deformable while the tools and fixtures are rigid. So one limitation of these methods is that they usually give a list of coordinates specifying where the fixture should be located, without providing the actual physical form of the fixture unit. Even though by considering more relevant factors, e.g., using the workpiece and process information, some performance criteria (ease of loading unloading, cost and rate of production), in the design process [44, 45], fixture unit information also is a high level concept that only specifies its basic type and the nature of its components. Currently, the design of a physical form of fixture is geometric based and there is a long way to go before systemizing the research on automatic or intelligent fixture physical design.

One interesting method is using the required height as the critical dimension for fixture unit generation, then to complete the detailed fixture shape. Particularly, this method is useful for modular fixture unit design where a fixture unit is usually assembled with several existing modular fixture components. So the fixture height can play a crucial role on searching potential elements to assemble.

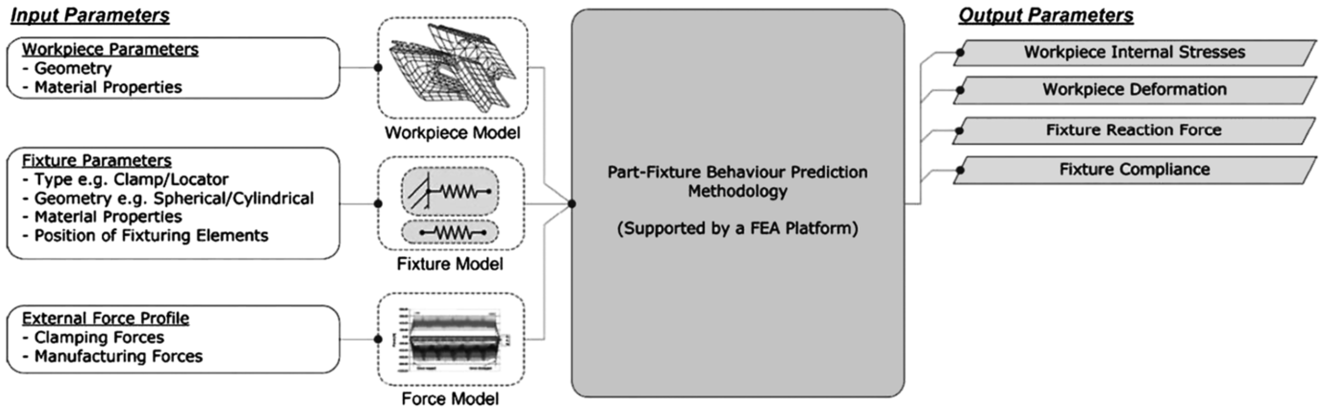

Fig. 12. Typical FEM based fixture design solution analysis framework [73].

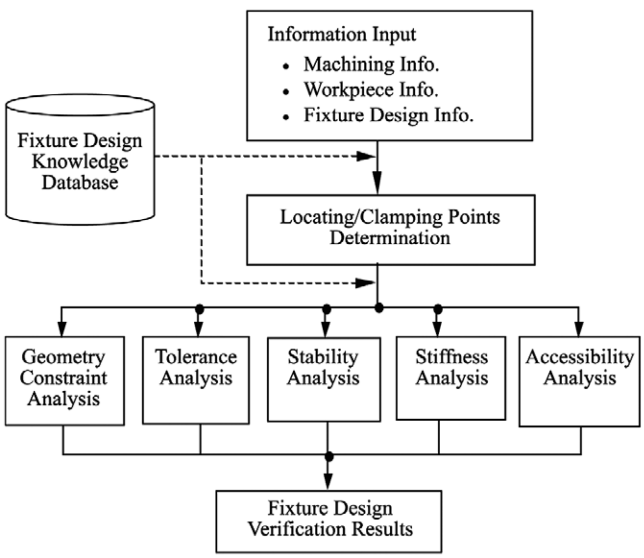

Fig. 13. Overview of fixture verification system [62–65].

3.3. *Fixture design verification*

Fixture design verification is the technique to verify existing fixture design by analyzing its geometric constraining ability, achieved tolerance, the deformation and stability of fixture-workpiece system, and fixturing accessibility, etc., and to provide related improvement suggestions on the design [62–65]. 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's construction. Verification of a fixture 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 in the process. (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 as practicable for the whole manufacturing system. Verification or monitoring is also needed in the use of a fixture system to justify whether the system is in a good condition. As the Fig. 13, Kang and Rong have developed a methodology concept of computer aided fixture design verification to unify various verification aspects into a framework.

In this field, the stability of the workpiece-fixture system, particularly, the deformation and accuracy of the system, always attracts most of the attention. Research on the stability of the fixture-workpiece system, can provide a mechanism for the deformation and error chain in the workpiece-fixture system which will guide the user to choose perfect fixtures, adjust suitable fixturing forces and fixture positions to generate adequate contact forces to keep the workpiece in an accurate position during machining. By contrast, due to the fact that most research focuses on machining fixtures where there is only one workpiece, seldom does research put attention on the degree of freedom and geometric constraints of whole system, even though this problem also is important in assembly related fixturing situations.

Typical research on the stability of a workpiece-fixture system needs to model workpiece boundary conditions and applied loads during a machining process, before the analysis on the deformation of a workpiece, as the work by Amaral et al. [66]. However, they only considered the positions of locators and clamps, and did not consider the deformation of fixtures in this process. The tolerances are defined based on surface sample points, and the workpiece-fixture system is assumed to be rigid. This kind of workpiece-fixture system for fixtures of rigid bodies and of point contacts without friction has been well described and studied in the literature.

However, in machining, particularly, in precision and ultra-precision manufacturing, the understanding of the sensitivity characteristics of workpiece-fixture system could be of particular benefit to the manufacture of intricate and/or precise parts of complex shapes. So in the analysis and numerical simulation process, the stiffness of fixtures should be considered, and the contact model of the workpiece-fixture system also needs to be more accurate.

Some significant efforts have been done in the modeling of workpiece-fixture contact. Ratchev et al. [73] used spring elements to represent the point contact between the fixture and workpiece. And Asante [74] presented a surface–surface contact model of the workpiece-fixture, and also considered the friction between these surfaces, with the assumption that the contact interface between the workpiece and locator/clamp obeys the laws of linear elasticity and so elastic deformation is the linear summation of the influence of all forces in the normal and tangential direction acting on the contact interface. Assuming a case of only single workpiece-fixture contact, Satyanarayana [71] have presented a comparative analysis of the different boundary conditions – contact elements (nodal and surface-to-surface), nodal boundary conditions (nodal displacement constraint and nodal force) – available for spherical–planar and planar–planar contact models.

However, they also regarded the fixture as a rigid body. Understanding the stiffness model of the fixture unit is very useful

[67–69], particularly when predicting the contact load and pressure distribution at the contact region in a workpiece-fixture system. Thus, this can help the designer very much in the detailed design of a fixture (including its shape, material, etc.), even though currently, the physical form of the design of the fixture usually depends on the geometric analysis from the designer's experience.

3.4. Deformation and error analysis of workpiece-fixture system

Fixture positioning error has a direct impact on the machining errors of a workpiece. In this field, two problems have usually been discussed: one is the forward problem that involves predicting the tolerance deviation resulting at a feature from a known set of errors on the locators and another is its inverse problem that involves establishing bounds on the errors of the locators to ensure that the limits specified by geometric tolerances at a feature are not violated. So the essential problem is how to represent the relationship between the machining error, fixturing error and the deformation of the workpiece-fixture system.

Locator positional errors, locator surface geometric errors, and the workpiece datum geometric errors can result in a localization error of the workpiece, which in turn yields a relational form error in a machined feature. Fixture positioning error (or fixel error, by M.Y. Wang) comes mainly from three sources. (1) A variation in the position of a locator is a direct contribution to the fixel error of the locator (Asada and By, 1985; Wang, 2000). The variation is usually specified in the locator's position tolerance defined during the fixture design. (2) Another source of fixel error is the variation in the geometric shape of the locator, such as profile tolerance specified for a spherical locator. During operation, mechanical wear and tear of the locator will also contribute to the fixel error. (3) The third source is related to geometric variations that may exist in the physical datum features of the workpiece. The datum geometric variations will have an equivalent result of fixel errors in the reference frame embedded in the workpiece body. The primary objective of a fixturing scheme is to reduce the manufacturing error as related to the three types of fixel errors that are essentially caused by the positional and geometric variability of the locators and the geometric variability of the workpiece itself.

Inaccuracies in a fixture's location scheme result in a deviation of the workpiece from its nominal specified geometry (position and orientation of datum references). For a workpiece, this deviation must be within the limits allowed by the geometric tolerances specified. Various methods on controlling the manufacturing errors have been suggested, for instance, (1) using stiffness optimized machining fixtures (and configuration layout) to ensure the tolerance limit specified for the machined part surface [70]; (2) during the manufacturing process, clamping forces of active fixtures can be adjusted according to the FEA analysis result to compensate for machining errors [73], or (3) adjust suitable clamp forces to generate adequate contact forces and pressure distribution at the contact region to keep the workpiece in position during machining [74].

However, modeling of a workpiece-fixture and the manufacturing process using sophisticated FEM is usually affected by several basic sources of error which can lead to improper results: (1) poor input data due to the lack of information about the process, (2) unreasonable simplifications, idealization and assumptions of the manufacturing process, (3) improper modeling of the boundary conditions, (4) numerical round-off (in solving the simultaneous equations), (5) discretization error and (6) errors associated with re-mapping. Besides those sources, in the research of the relationship between machining error and fixture positioning error, some assumptions on modeling the workpiece-fixture system also can affect the validity of the results. For instance, assuming that the workpiece-fixture system is a rigid body [76,70], and the workpiece-fixture contact as a theoretical non-friction point contact [76].

4. Conclusions and future research

Recent achievements in the development of computer aided fixture design methodologies, systems and applications have been examined in this paper. Various novel papers in the computer aided fixture design field have been published in recent years, up to 2010. However, current design and automation theories and technologies are still not mature. Most current commercialized fixture design tools in manufacturing are traditional geometric-based, for instance, the tooling and fixture design functions in some CAD systems, e.g., Unigraphics and Pro/Engineer, the software by some fixture components manufacturers, e.g., Bluco Corp., Jergens Inc. They only provide engineers with a fixture component library or simple modules to do fixture design manually based on some extended functions of commercial CAD software. Fixture design still continues to be a major bottleneck in the promotion of current manufacturing, though numerous innovative CAFD techniques have been proposed. Those techniques also need time to be tested and evaluated in real manufacturing environments and integrated with other product and process design activities. Therefore, several research aspects are promising and challenging.

4.1. To develop intelligent techniques for computer aided fixture design

It is already recognized that developing a computerized fixture design can result in high efficiency, stable accuracy, short set-up time, and low cost. But the real performance of a computerized fixture design system is rooted in a powerful ability of the system to "replace" or exceed that which is done manually by a fixture designer. For instance, an increasing research interest is using various meta-heuristic methods to obtain optimal fixture layout solutions [58–61], which often requires much precise calculations in geometry and mechanics. Actually, computer supported intelligent algorithms can have a better performance on this kind of work. Meanwhile, deploying a multi-sensor network into a workpiece-fixture system and using online intelligent control techniques can adjust fixturing contacts and forces adaptively in a machining process to keep an optimal fixture-workpiece situation [84–86]. That is an important reason for the rapid progress of intelligent techniques on fixture design applications over the past years.

Furthermore, recent achievements on some new knowledge-related techniques, such as knowledge modeling, data mining, machine learning, and so on, indicate a more promising and fruitful future for the development of advanced computer aided fixture design. In many manufacturing companies, the technical knowledge of experienced fixture designers, a huge amount of technical files and many good design cases are a very valuable resource for fixture design. Using new technologies in the knowledge engineering field to refine, model and utilize fixture design domain knowledge as an information base for intelligent and automatic systems can assist a fixture designer not only by simplifying the design process, but also by generating design ideas. For example, some interesting progress on using XML technology as a fixture knowledge representation tool to support case-based reasoning in the fixture design process is attractive, despite the reality that it need more effort on the systemization of intelligent techniques in fixture design [47,50].

4.2. Integrated fixture design system for manufacturing

In essence, fixture design only is a partial process in manufacturing, and it should obey to the total objective of workpiece manufacturing requirements which often are related with production resources, equipment, cost and machining processes, etc. Therefore, it is necessary to put the fixture design task into an overall manufacturing process to obtain best fixture design solution.

Many researchers have accepted the viewpoint of integration of CAFD systems with other manufacturing related technologies, even though many early researches are very limited in obtaining the manufacturing requirements from and send the result of fixture design to other systems, e.g. PDM or PLM systems. Future research should emphasize the importance of more efficient integration of fixture systems with other manufacturing systems. Particularly, view the fixture design as one node in a whole chain of manufacturing process. So we have to consider the impact of fixture design result on the cutting center and machining toolpath, and meanwhile, we also may find a necessary redesign of the fixture solution due to various conditions of cutting tools, production amount and cost, 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. Thus more attention should also be paid on the establishment of a systematic way of integrating various techniques, such as FEM methods for workpiece-fixture system stiffness analysis, advanced mathematical analysis on tolerance design, 3D path planning and collision detection analysis on the cutting toolpath.

4.3. Applications in more wide manufacturing fields

It is apparent that almost all the literature is focused on machining fixtures field beside a few on welding fixture research. This puts a question of the theoretical value of fixture research in other industrial fields and a more rigid comparative study of fixture design among those fields and the traditional machining field. In fact, besides the traditional machining field, there is a wide usage of fixtures in other industrial fields, e.g., welding, assembly. And as we have motioned in Section 2.1, there exist obvious different requirements. There is a clear demand for more research in computerized fixture design in such fields.

Another attractive field is fixture design in Micro and Nanomachining. Because nanometric machining has a very different physics from conventional machining [87], e.g. in the manufacturing process, material and physical phenomena, existing fixture design methodologies cannot handle the meso-scale fixturing problem. With respect to this, micro and nano scale fixturing technology appears promising. Additionally, trends in manufacturing flexibility and customized small production also suggest more deep comparisons, analysis and research on the applications of computerized modular fixtures and dedicated fixtures.

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