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Fixture Designers Guidance: A Review of Recent Advanced Approaches

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Abstract

Fixture design is an important issue in the process of manufacturing. Fixture design is a critical design activity process which bridges Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). The present paper presents a literature review of the Computer-Aided Fixture Design (CAFD) approaches performed. The purpose of this research is to give a deep and quick understanding of fixture design, its criteria and approaches used in this field. The significant techniques used in this field along with their applications, criteria and assumptions are also considered. The shortcomings of the existing research studies are stated and some issues pertaining to handling the weaknesses of the current research are suggested to be hopefully taken into account in future research.

Keywords: *Literature Review; Computer Aided Fixture Design; Fixtures Taxonomy; Artificial Intelligence.*

1. Introduction

An important type of tooling utilized in assembling, manufacturing, inspecting and other operation processes is known as fixtures. Fixtures are to hold workpieces stable and constraint without any movement during the manufacturing process. They set and secure the orientation and position required by the workpieces based on the specifications of the design [1]. An accurate fixture design is critical for quality of product based on accuracy, precision, and final product of the designed parts. About 40% of the parts that are rejected are mainly rejected because of the dimensioning errors due to poor fixture designs [2]. Fixture design is under the combined influence of workpiece specifications, machining methods, material performances and etc. It demands rich experience of the designers, which leads to a significant increase in the design cycle time and costs. Diminishing the need of potential rework on parts can also lower the time and cost of the manufacturing process [3]. Costs related to fixturing represents 10-20% of the total costs of a system in manufacturing [4].

To reduce the lead-time and cost of product development in fixture design field, automation and computerization of fixture design are required. Thus, CAFD has been introduced and utilized as an integration of computer-aided designs and computer-aided manufacturing (CAD/CAM) [5]. However, fixture design is still an issue of concern in the present manufacturing field even though many new CAFD techniques have been introduced [2]. Various approaches have been attempted in fixture design, i.e., Case Based Reasoning (CBR), Rule-based expert system, Genetic Algorithm (GA), Multi-agent Approach, Machine Learning, Geometric Analysis, etc.[6, 7].

Although many attempts have been made in the fixture design domain, there still remains some requirements to report and evaluate the used techniques in this area sharply and simply. Therefore, the techniques need to be addressed based on their principles, applications, criteria of use, adapting in fixture design area, and so on. This can help researchers to quickly understand the fields of fixture design and the strengths and weaknesses of each technique(s) in each field. The quick understanding can save time of researchers in fixture design and facilitate boring review process.

This paper is organized as follows: section 2 is about CAFD by focusing on the types of fixtures, design requirements and steps of fixture design. The next step is about aspects of significant techniques that have been used in fixture design. The significance of this study is that it offers a deep, but simplified, understanding of the current and innovative methods of fixture design that are useful and required for fresh researchers in the manufacturing field as a guideline.

2. Computer Aided Fixture Design (CAFD)

CAFD is the use of computers to help in the design of fixtures [8]. CAFDs have grown remarkably since the 1980s, and a lot of work has been done to enhance the

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process of fixture designs [9]. Computers have dramatically reduced the design process time. By using a computer, designers are able to design in a virtual atmosphere. This helps the designers identify potential problems and undertake different ideas without actually creating fixtures physically. These programs have the added benefit of keeping a designer from missing steps while designing; and by avoiding mistakes, time and costs can be kept low [8].

However, the contrasting features of the design's requirements can be rather challenging. For instance, having a heavy fixture can be beneficial to the stability but this would make the material costs to rise exponentially and affect the usability, as the added weight would discourage handling carried out manually. These factors complicate the fixture design further and call for the necessary research of CAFD further [10].

2.1. Taxonomy of Fixtures

Fixtures are utilized as a work-holding device to locate and clamp a part surface that supports the operations of manufacturing. A normal part manufacturing process requires the use of many fixture setups to hold the working part in place as different orientations need to be operated [11]. Many manufacturing processes use fixtures widely, such as welding, testing, inspection, assembly, and machining that include milling, turning, drilling, grinding, etc. Figures 1-4 demonstrate the actual cases of fixture design in the manufacturing field. Based on the fixture's flexibility, the fixtures would be categorized in modular fixtures, dedicated fixtures and general-purpose fixtures, such as conformable and reconfigurable fixtures [2, 12].

Figure 1. Machining fixture [13]

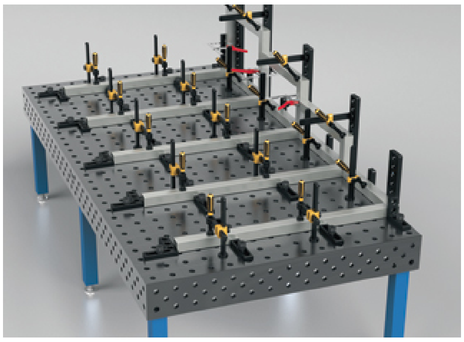

Figure 2. Assembly fixture [2]

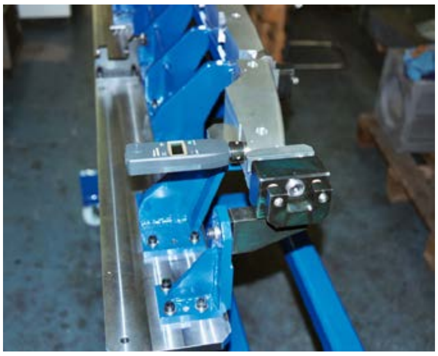

Figure 3. Inspection fixture [2]

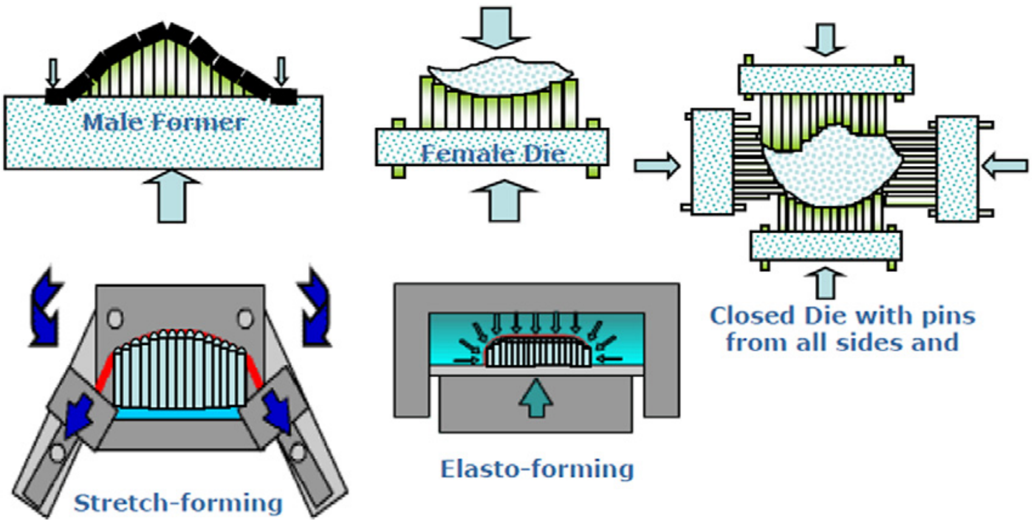

Figure 4. Typical pin-array fixture as one type of conformable fixtures [2]

Dedicated fixtures are fixtures that are produced for one specific workpiece and one setup. One of the benefits of the dedicated fixtures is that they have a high stiffness and are generally used for high batch sizes because they are created to perfectly locate and clamp a workpiece [14]. Most dedicated fixtures are, at first, originally at first designed for the purpose of one workpiece only. The dedicated fixtures have many beneficial properties, among which are high tolerances and rigidity; however, they are very expensive [8]. Dedicated fixtures are particularly essential in manufacturing for mass production and for precise, sophisticated, and advanced parts. In comparison to the modular fixtures, dedicated fixtures are carefully designed in accordance with the requirements of manufacturing and the design of the workpiece [15].

Flexible Manufacturing Systems (FMS) are dependent on fixtures that are not particularly fixed to just one workpiece. The fixtures should be reusable and changeable to suit the variations of the workpieces. The variations are inclusive but not limited to the same parts with various dimensions and oddly parts shaped. Therefore, general-purpose fixtures, such as reconfigurable, conformable and modular fixtures, are used as a solution in FMS [16].

Conformable and reconfigurable fixtures can be designed to receive portions of the different sizes and shapes [2]. Specifically, the technology on conformable pin-array fixture is used widely in a lot of fixture designs as certain components consist of internal variables which are adjustable to address the various workpieces and their features [17]. Figure 4 illustrates the typical application of the pin-array fixture. Several precision works in manufacturing utilize the materials-related phase change fixtures. In the aerospace industry, for example, metals with low melting-point are utilized to surround the turbine blades and create surfaces that are well-defined for the parts of locating and clamping the grinding processes [18].

Modular fixture technology is the most widely used type of reconfigurable fixtures. Modular fixturing systems have been looked at as a possible solution for FMS due to the high variability and standard set of parts they contained [8]. They include a base that has extensions that are highly movable, which helps the configuration changes to take place quickly. CAFD tools can be utilized to make the fixtures quickly and the advantage is that they can be reused in more than one configuration. They are made according to really tight tolerances to make sure that the number of errors is kept to a minimum in the finished product [19]. Most of the CAFD systems are developed based on the use of modular fixture design. This suggests that modular fixtures are the most suitable type of fixture design in terms of a CAFD process, which can be applied to produce a greater computerization impact in the researches [8, 20]. There are several limitations nevertheless [2]:

- These components only result in a limited number of combinations, which means that there is a possibility that no appropriate combination can be designed for some of the workpieces that contain complex or irregular geometries.
- At times, it is hard to maintain the modular fixtures with the structural properties. The modular fixtures' structural properties include features such as locating accuracy, stability, stiffness, operating speed, loading and unloading, etc. It is commonly known that utilizing modular fixtures may not gain the quality of an optimal fixture.
- It is not appropriate for mass production, such as automotive productions and the manufacturing of their components.

The principles of modular fixturing are used in many documented CAFD studies and applications to design fixture designs given the extensive usage in the present manufacturing and standardized productions [2]. Modular machining and modular assembly fixtures are widely used in the classification of modular fixtures. These kinds of fixtures' requirements are different but, comparatively, the approach to design them is quite standard [8].

Assembly fixture and welding fixture are mostly similar and they have obvious differences with machining fixture, as shown in the following [2, 6, 21]:

- The workpieces in the process of welding are normally an assembly of a few parts, while the workpieces that go through the machining process have just a single part;
- Normally, the requirements for accuracy in the processes of assembly and welding are less, compared to machining;
- The fixing and machining forces in the processes of assembly and welding are normally smaller, compared to machining; and
- The welding's thermal reactions should be considered thoroughly.

During the machining operation, the machining fixtures are utilized to locate and constrain the workpieces. The workpieces must be suitably located and clamped to make sure that they are machined based on particular dimensions and tolerances [22].

It is essential to minimize the deflection of the workpiece and fixture tooling caused by the forces of clamping and cutting to enable an accurate and quality production results in the machining process [23]. In general, there are two fundamental functions in a machining fixture [24, 25]: (1) to locate the right position of the component related to the cutting tools; and (2) to secure the components tightly to prevent it from moving in the machining process.

2.2. Steps of Fixture Design

Generally, fixtures contain four components, namely clamps, locators, base plates and supports. Fixture designs commonly assist in placing components onto a workpiece so that it remains immobile and stable in the process of machining or related operations [26].

There are normally four phases in the design process of the fixtures: fixture planning, setup planning, verification and unit design, as demonstrated in Figure 5 [27, 28]. The identification of machining setup by not moving the parts in each setup is known as setup planning. Fixture planning is defined as the physical fixture requirements, layout plan and prevention of collision. Verification is used to ensure that the developed fixture designs meet the requirements of fixturing. Unit design consists of the detailed and conceptual definition of the locating and clamp units of the fixture made with the base plate. In addition, the design must adhere to the other design issues, which may include the fixture weight, fixture cost, assembly time, etc. [14].

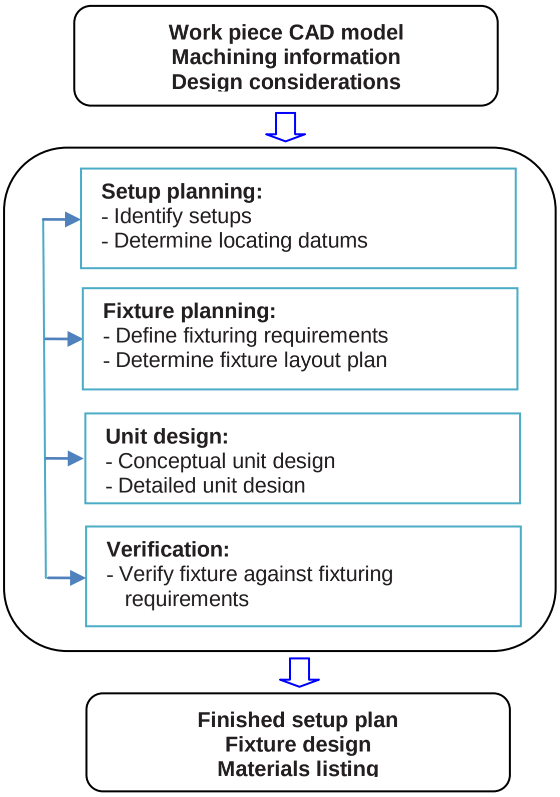

Figure 5. Steps of fixture design [27]

These steps can be generalized as: analyze the part, define the suitable locating and clamping points, identify the tooling and environmental requirements, and create a fixture to satisfy the criteria. These steps can be highly individual and can require an exhaustive trial of an error approach until experience is gained [8], which are described below.

In the fixture planning stage, the requirements of fixturing are normally created; these can be divided into six classifications as shown in table 1 [29]. Fixture planning and configuration is mainly an activity that is driven by experience to decide the location and clamping of the workpieces precisely based on the designs of the parts and the requirements of the process. The output of this step configures the fixture layout automatically, which guarantees the stability of the part [11].

The unit design phase is carried out to gain an accurate location and stiffness and to prevent the deformation of the fixture components [30]. For example, the tolerances of the locating units must be in such a way that the accuracy of the location is reached. However, the deformation, as a result of forces from the machining and clamping, must be prevented. It is critical that these requirements are followed as a guideline to design the units for locating and clamping [26].

Fixture design verification is the method of verifying the current fixture design by examining its achieved tolerance, geometric constraint's ability, fixturing accessibility, and the deformation and stability of the fixture workpiece system. The verification phase also provides the associated suggestions for improving the design [27-29]. Solutions for the verification of a fixture design are required due to the following reasons:

- The design process includes too many factors; it is quite hard to set an accurate model of the analysis in this process;
- The constraints of the design are individually viewed; some of the contrasting constraints may be created when they are regarded altogether; and
- Fixture design is closely linked to other activities such as CAM software, manufacturing systems and Computer-Aided Process Planning (CAPP) [2].

Thus, the CAFDs' strengths need to be part of the verification approaches that emphasize checking stability and the deformation of the workpieces while machining. A further advantage in this area is the layout planning techniques that aim to minimize the deformation of the workpiece made by the forces during machining [10]. Even though that several research efforts have been undertaken to support all the four phases to overcome the entire process of fixture design activity [31-33], the strength of the provided support differs across each phase and is normally not as good as the research efforts that focus on supporting particular phases only. Joneja and Chang's [32] ability, for example, to carry out the setup planning is not as impressive as that of Yao *et al.* [34], who exclusively concentrate on that particular task and consider the tolerance of the stack-ups.

3. Significant Techniques and the Applications in Fixture Design

Fixture design is a process that is complex and experience-based and requires trial-and-error to make the design. Therefore, during the past two decades various approaches have been attempted in fixture design to facilitate and computerize this task. Among these approaches are: Rule-Based Reasoning (RBR), CBR, GA, Neural Network (NN), Finite Element Method (FEM), Geometric Analysis, etc. [6, 35]. Table 2 catalogs the significant approaches used in CAFDs.

As the Artificial Intelligent (AI) technology has gained a greater level of acceptance in manufacturing, expert systems can offer a logical tool in automating the fixture design by utilizing the benefits of the management with the experience-based knowledge [36]. RBR is an experts system approach that utilizes induction rules to decide if a new problem should be further inspected or not [9]. Nnaji [37] and Nee & Kumar [38] typically used this technique. They carried a limited assessment of the likely displacement at each locating point caused by the machining forces and implemented an easy justification module that utilized heuristic rules to decide if a dedicated or modular fixture design should be created.

Fixture designs commonly and heavily depend on knowledge and experience. Simultaneously, fixture design resources and knowledge are required to be suitably retained for reuse in the future [1]. However, CBR [39, 40] includes indexing, representing, and organizing the current design cases as experience and knowledge so that they can be reused, recalled, and modified, for future design conditions. For these reasons, CBR approaches, as one of most effective methods, have been applied in this field [41].

The main assumption in CBR based fixture design methods is Kumar & Nee's assumption so that similar workpieces would require similar fixtures [18]. Thus, in this kind of system, the workpieces are grouped together into families of parts and an appropriate fixture design is attached to each workpiece. The fixture structures' similarity relies on the similarity of parts' structures and process methods where the fixtures are utilized [1, 6, 21, 42, 43]. Now automatically this seems to be a valid and sensible approach.

Applications of GAs to support the fixture planning, fixture layout plan and fixture configuration design are encoded in binary strings. GA has been examined, evaluated, and allowed to go through crossover, mutation, and reproduction. Until an optimal state is derived, the modification continues to develop improved solutions [44, 45]. GA has been interfaced with the FEM for optimization problems in the fixture layout in most cases [22, 46]. Finite element analysis (FEA) is being recognized as a typical platform for simulation and modeling of different manufacturing operations [47]. Normally, deformation testing is utilized by employing a finite element analysis where a workpiece is discretized to generate a node series that reflects the potential points of contact for locating and clamping [48]. FEM and GA are utilized in several fields of fixture design, such as in designing the optimal layouts for fixture configuration [49]. These layouts indicate the optimum points where the fixture should contact the workpiece being machined.

NNs are interconnected networks consisting of simple components. These networks can develop solutions for new problems that are entered into the network. NN techniques have been utilized to support fixture design systems that are case-based, as the similarity evaluator [50] and as the conceptual unit design. Research by Kumar *et al.* [51] utilized a combination of GA/NN techniques where the NN is trained with selections of past design problems and the possible solutions. The GA creates a possible solution that is assessed utilizing the neural network, which, in turn, works as a guide for the GA.

Geometry is an important aspect of designing individual units where the aim is to choose and to assemble the defined unit elements to offer a unit of appropriate acting heights [25, 52]. Researchers have mainly utilized geometric techniques to design a complete fixture unit [52, 53] in which the fundamental notion is to identify the essential dimensions of specific fixture units, typically being its height and to, later, link all the other dimensions of this component to the essential dimension through mathematical relationships that pre-exist. Typically, a geometry-based system is designed where the dimensions of the individual element are generated in association with the primary dimension of that element (normally the necessary height) through parametric dimension links. This is augmented with a relation knowledge base of how various elements are configured to create one unit [54].

Table 1. Requirements of fixture design adapted from [29]

General requirements	Examples of abstract sub-requirements
Tolerance	The locating tolerances should meet the design tolerances requirements of the parts
Physical	The fixture must be capable of physically accommodating the work-piece's weight and geometry.
	The fixture must allow access to the features of the work-piece that needs to be machined.
Affordability	The fixture's cost should not be more than the desired levels.
	The fixture's assembly/disassembly times should not be more than the desired levels.
	The fixture's operation time should not be more than the desired levels.
Constraint	The fixture should guarantee the stability of the work-piece by ensuring that the work-piece's moment and force equilibrium are kept.
	The fixture should make sure that the fixture/work-piece's stiffness is enough to avoid the occurrence of deformation, which could prevent the design tolerances from being reached.
Usability	The fixture's weight should not be more than the desired levels.
	The fixture should not result in damaging the surface at the work-piece/fixture's interface.
	The fixture should offer tool guidance to the features of the designated work-piece.
	The fixture should be error-proof, i.e., the fixture should be able to avoid wrong work-piece insertions into the fixture.
	The fixture should assist in chip shedding by providing a way to allow the machined chips to flow away from the fixture and the work-piece.
Collision prevention	The fixture should not result in collisions of the tool path-fixture.
	The fixture should result in work-piece fixture collisions, other than the designated clamping and locating positions.
	The fixture should not result in fixture-fixture collisions besides the designated points for fixture component connection.

Table 2. The significant techniques in CAFD

Method	Fundamental Procedure	Applications	To Improve the Performance	Working Process
RBR	Design based on basic heuristic rules	Setup planning, Fixture planning, unit design, verification Strength: Fixture planning	Mostly combined with: CBR	Evaluate and improve design by using some existing and derived basic rules in fixture design
CBR	Storing and using experiences to solve new problems	Fixture Planning, Unit design, Verification The strength: Fixture planning	Mostly used with: RBR	Finding appropriate fixture design for target work-piece in database
GA	Optimization process by generating possible solutions	Fixture layout configuration, fixture planning, verification The strength: verification	Mostly used with: FEM	Minimizing work-piece deformation by determining minimum forces at the locating and/or clamping points
FEM	Deformation analysis by meshing the work-piece and examine every single mesh	Fixture layout configuration, fixture planning, verification The strength: verification	Mostly used with: Optimization techniques	Deciding on acceptable candidate regions with minimized deformation of the work-piece
NN	A set of existing solved problem used to teach the network	Verification, unit design	Mostly combined with: GA	Supporting conceptual unit design and optimal location of units
Geometric Approaches	Pre-existing mathematical relationships based on parametric dimension relationships	Verification, fixture planning, unit design Strength: verification	Can be combined with: RBR	Determining critical dimensions of fixture units and fixture-work-piece contact points

4. Conclusion

Although many research studies have been conducted in the domain of fixture design, this task is still a blockage in the manufacturing process. A cause of that problem is that most of the CAFD techniques have been examined for simple workpieces, which do not reflect obstacles that are really faced in the industry; hence, the success of the developed methods cannot be confidently stated. Another cause is that there is a requirement to integrate the segmented CAFD techniques cohesively in a framework that includes a comprehensive knowledge of fixture requirements that can be used to drive the process of fixture design. An approach that can be helpful in this case is CBR, so that by combining CBR with other intelligent methods, effective and more comprehensive fixture design systems can be achieved.

Future research could focus on the significance of a more efficient integration of fixture systems to other systems in manufacturing. It is important to place the task of fixture design into the overall process of manufacturing to gain the best performance of each fixture design solution. Regarding the advances in nowadays technology, testing the performance of two approaches would be valuable and efficient in the case of fixture design; these approaches are: (1) placing a multi-sensor network inside the workpiece-fixture system (2) utilizing intelligent online control methods to adjust the fixturing forces and contacts.

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