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Fixture Design Automation and Optimization Techniques: Review and Future Trends

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ABSTRACT

Fixture design is a crucial part of manufacturing process. Fixture design is a critical design activity in which automation plays an integral role in linking computer-aided design (CAD) and computer-aided manufacturing (CAM). This paper presents a literature review in computer aided fixture design (CAFD) in terms of automation and optimization techniques over the past decades. First, the reason behind necessity of automated fixture design is stated. According to the degree of automation, fixture design methods are then categorized based on significant works done in the CAFD field. Regarding the need of automated fixture design systems, optimization techniques, which are mostly used for automated CAFD methods, are closely considered. The significant optimization techniques are then studied in case of applications and working principles. At the end, the current weaknesses of the existing methods and the research fields, which require deeper studies as future trends are presented as well.

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1. INTRODUCTION

Fixtures are a type of fundamental tooling which are used throughout manufacturing, assembly, inspection and other operations to form and secure the required position and orientation of the workpiece as needed by design specifications [1]. Proper fixture design has a crucial effect on product quality in terms of precision, accuracy and finish of the machined part. Around 40% of the rejected parts are caused by dimensioning inaccuracies which are related to poor fixture design [2]. Its design is under the combined influence of workpiece, machining methods, material performances, etc. It demands rich experience of the designer, which leads to significant increase in design cycle time and costs. Diminishing the need of potential rework on parts can also lower the time and cost of manufacturing process [3].

To reduce the lead-time and cost of product development in fixture design field, automation and computerization of fixture design are required. Therefore, CAFD has been developed and used as a part of computer aided design and manufacture (CAD/CAM) integration [4]. Even though several innovative CAFD approaches have been employed, fixture design still remains a central bottleneck in improving of current manufacturing process [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.[5].

Fixture design is mostly based on experience, capability and knowledge of fixture design engineers and there is not any throughout theoretical method to support the whole process. On the other hand, the industrial environment still seeks automated fixture

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design systems. According to these reasons, intelligent optimization techniques, which are theoretical and numerical based such as GA and Ant Colony Algorithm (ACA), combined with Finite Element Method (FEM) have been employed in CAFD field. They have been mostly used to automate some micro steps of fixture design. And finally, these micro-steps can be integrated with each other or with the other existing methods to arrive at automated fixture design systems. Based on this industrial demand, we try to clarify applications, position, strengths and weaknesses of these techniques in fixture design systems in this paper.

This paper is organized as follows: Section 2 describes significances of CAFD and requirements. Section 3 is to classify fixture design systems based on degree of automations and some of significant works for clearness.

Next section is devoted to optimization techniques regarding criteria, applications and so on. Final section contains some conclusions about gaps as well as some future trends in fixture design field and specifically in optimization techniques based methods. The value of this paper is to provide an in-depth review and critique of current optimization approaches in CAFD. Besides, it clarifies the classification of fixture design systems based on degree of automation, which can give a better understanding of fixture design studies a well as future trends in this field.

2. COMPUTER AIDED FIXTURE DESIGN

CAFD is the use of computers to help aid in the design of fixtures [6]. Since 1980s, CAFD has grown considerably and much effort has been put in to improve the fixture design process [7].

Recently, computers affectedly decrease the design process time. By using computers, designers are able to design in a virtual environment. It enables them to test and identify potential problems, which may occur so they can undertake different ideas without actually physically creating the fixture. Basically, these programs reduce the cost and time spent into a design by keeping the designer away from missing steps and also making mistakes while designing [6].

According to many design situations during fixture designing, the conflicting nature of these requirements is very problematic [8]. For instance, heavy fixtures could solve and make some design problems at the same time. It can be advantageous in terms of stability, but it would also affect cost (due to increased material costs) and usability (because the increased weight may affect manual handling). Such conflicts add to the complexity of fixture design and contribute to the need for the CAFD research especially in order to achieve automated fixture design systems [9].

3. FIXTURE DESIGN SYSTEM IN CASE OF AUTOMATION

Along with much work being carried out to develop an efficient CAFD system, fixture design systems can be categorized into three main categories based on their degree of automation; i.e. fully automated, semi-automated and interactive class [7, 10]. The fully automated and semi-automated fixture design systems based are established through incorporating the experience and knowledge of designers into rules and algorithms in order to automate the selection of fixturing elements and locating points. Interactive fixture design module enables designers to select the fixturing faces, points and elements for fixture structure [11].

At the initial stage of CAFD two decades ago, The earliest research [12, 13] mainly developed the interactive CAFD systems, based upon an understanding of workpiece and process information. These systems usually provide fixture designers rules to evaluate the design and a list of components to be used interactively[14]. They mostly utilize expert systems as empirical device, which is often used to help fixture designer in interactive environments to achieve a complete fixture design solution especially for fixture configuration design [15]. In majority of these approaches, several IF-THEN rules are created based on design knowledge to lead the design process. Then, the solution of design in the interactive process of fixture design would be determined using created rules through a prearrange set of questioning-answering actions. Though, there are usually some difficulties for reasoning procedure mostly in case of constructing the logic tree and also sufficient comprehensive rule set which affect highly on the design result quality as well as efficiency of the design. Moreover, the reasoning procedure is also very boring in the interactive design modes.

Accordingly, some researchers have proposed semi-automated fixture design systems by using combined fixture design knowledge and existing fixture design experience. Those methods mostly applied case based reasoning technique to solve fixture planning and fixture unit design [5, 10, 16]. These systems are mostly constructed based on the assumption that ‘similar workpieces have similar fixture designs’[17]. Therefore, by discovering the similar workpiece in database, the proper fixture design is retrieved from database and then is used for new workpiece. To improve the performance of existing systems, some other intelligent techniques are combined with CBR such as Rule Based Reasoning (RBR), fuzzy logic, Model Based Design, GA, Neural Network (NN) [1, 7, 18, 19] and so on to facilitate and automate more steps of fixture design such as layout planning, verification.

Many researches related to fixture design have concentrated on the micro aspects of fixture design on the matter of fixture design automation which are referred to singular problems e.g. deformation analysis, stability evaluation, fixture repeatability, tolerance analysis, geometric reasoning and so on. For instance, Nee [20] developed a rule-based automated fixture design based upon determining which type of fixture component usage and checking displacement of any locating point. Recently, Nelaturi developed an algorithm in case of automated fixture planning and configuration using the principles of force and form closure [21]. Interestingly, Wan applied a method to match design environment with fixture design requirement for fixture design configuration using smart modular fixture unit constitution. The method is a uniform ontology model containing required resources. The smart fixtures can perceive the design environment by themselves and drive themselves to complete appropriate design activities automatically [3].

As mentioned before, most of the existing fixture design methods are able to solve micro design problems automatically that are mainly constructed based on optimization techniques. Now comprehensive fixture design systems, which are established based on integrating those methods to help solving fixture design problems automatically, is needed [22].

4. OPTIMIZATION TECHNIQUES AND COMBINED APPROACHES

Intelligent methods, also known as artificial intelligence methods simulate the processes that a human undergoes when reasoning through a problem [6]. On the other hand, the fixture design is a mainly subjective procedure, which is mostly experiential knowledge based [22]. Therefore, the intelligent methods have been focused and employed by many researchers in order to improve efficiency of CAFD systems[23]. Among these intelligent methods, GA and ACA have been found as best optimization techniques in fixture design field. These two methods have been used for automating some micro-steps of fixture design. In the next sub-sections the strengths and weaknesses of both methods and the way of combing them with FEM them in fixture design area is discussed.

4. 1. GA in Fixture Design Methods

GAs are coded as binary strings for supporting fixture configuration design, layout plan and fixture planning solutions [24]. GA has been evaluated, examined and exposed to biological modification via reproduction, mutation, and crossover. In order to produce enhanced solutions, the modification keeps on till an optimal condition is reached.

Goldberg [25], Deb [26], and Kumar et al. [27] have shown that GA is a reliable and applicable technique for optimization problems in engineering. By using GA, Ishikawa et al. [28] could determine the condition of optimal clamping based on the assumption that the workpiece is elastic. A set of points of contacts are encoded and tested. The GA is utilized to create the new contact point sets till an optimum is derived which minimizes deformation of the workpiece as a result of clamping forces and machining [28]. Wu et al. [29] employed GA to optimize the fixture layout and fixture–workpiece is modeled as a rigid body. In that method, elastic deformation of the workpiece which is caused by clamping and machining forces is ignored. Krishnakumar et al. [28] proposed a method to achieve a fixture layout that can minimize the machined surface deformation because of static machining forces. Thus, they developed a GA-based fixture layout optimization technique. This method optimized the fixture layout based on only a single node system that would not be enough to find the minimum elastic deformation of the workpiece.

Stability based optimization normally concentrates on a layout plan in case of absurdly meeting the kinematic form closure constraint. It is examined so that infinitesimal part motion for each set of contacts should be completely constrained. Furthermore, increasing constraints with optimization in contradiction to some form of stability-based requirement such as force minimizations at the clamping and/or locating points should be considered [30-32]. Chan et al. [29] considered optimizing stability by a GA which is often used for deformation based optimization.

4. 2. Combinations of GA and FEM

Most often for fixture layout optimization problems, GA has been combined with FEM [33]. Accordingly, Finite element analysis (FEA) has become a usual platform for various manufacturing processes in case of the simulation and modeling [34-36]. Normally a FEA is employed when deformation testing is needed so that a workpiece is considered in discrete section to generate a series of nodes which indicate possible clamping and locating contact points [37].

In certain fields of fixture design, FEM and GA are used, for instance in the generation of an optimal fixture configuration layout [38]. The layouts identify optimum positions at the point where the fixture should have contact with the workpiece that is undergoing machining. These optimal positions are achieved by performing these three steps. Firstly, the usage of the process analysis method of machining to estimate the machining force that is used on the workpiece is considered [2]. Secondly, a deformation analysis of the system of fixture-workpiece is carried out by using the pre-determined load cases. Deformation analysis typically utilizes the FEM approach. The last step involves employing a process of optimization (GA is commonly utilized) to look for a possible solution space and decide on the fixtures locations within an acceptable candidate region with minimized deformation of the workpiece[39]. A typical framework of FEM based fixture design solution is shown in Figure 1 [34].

Many relevant works assume some conditions such as regarding treat fixture-workpiece contact as point contact, the workpiece being deformable while the tools and fixtures are rigid. Thus, a limitation of these approaches is that they normally offer a list of coordinates identifying the location of the fixture, without offering the fixture unit's actual physical form [28, 40-42].

Based on the above statement, Kulankara et al. [41] regarded the fixturing elements as rigid and the workpiece to be elastic and then utilized the FEM to simulate the machining operation. The machining forces are regarded as point forces acting over the tool path. Static analysis is considered to determine the workpiece deformation. Weifang Chen et al. [43] established a multi-objective optimization model to minimize the deformation and improve the uniform distribution of deformation by considering the friction and chip removal effects. The optimization process was performed through the integration of GA and FEM. FEM was used to calculate the machining deformation for various clamping force and cutting force under a specific fixture layout. GA to optimize the fixture design used the fixture layout and the clamping force as design variables. KaYiuYeung and Xun Chen [44] also optimized the fixture layout for a 3D component using GA. Prabhaharan et al. [45] optimized the fixture layout to minimize the dimensional and form errors. FEM was used to predict the workpiece deformation.

Deformation analysis focuses mainly on studying workpiece deformation by FEA [34, 37, 46]. This includes three steps namely (1) considering the discretization of the workpiece into elements, which are to form a mesh, (2) choosing the analytical elements type to indicate the mesh in analysis, and (3) determining the boundary conditions which there is for the workpiece for instance at the workpiece/fixture interface. Typically, Rai et al. [47] developed the FEA to examine the impacts of changes of workpiece geometry which is caused by material removal in machining.

4. 3. ACA in Fixture Design ACA has been adopted as the optimization method in fixture design. To find out the strengths of ACA, the performance of GA and ACA have been tested and compared based on different node systems as the workpiece deformation varies according to the node system. To estimate the efficiency of GA and ACA, three different number of node systems are defined on the same geometry. The minimum workpiece deformation for the possible layout, i.e., optimal solution was predicted for all the three node systems using both GA and ACA. A comparison was made between both the algorithms on the basis of minimum objective function value, and it was found that ACA solutions are better than those of GA [45]. Padmanaban et al. [48] applied continuous optimization methods and ACA-based discrete to optimize the machining fixture layout. The optimization was to minimize the elastic deformation of the workpiece. By using FEM, The workpiece dynamic response was determined regarding the clamping and machining forces. Some assumptions made for this method are: (1) the workpiece is a elastic body, (2) number of degrees of freedom are two per node, (3) external loads is taken as planeloads, (4) machining force is taken as impulse force, and (5) the workpiece exposes in only plane stress. The dynamic effects of the workpiece were taken into account. From the results of the case study, it is concluded that the ACA is suitable for problems where no direct relation exists between the objective function values and the constraints [49].

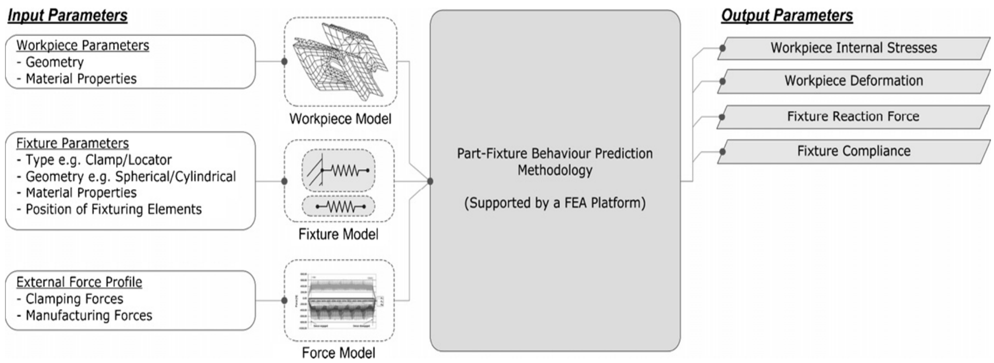

Figure 1. A typical framework of FEM based fixture design

5. CONCLUSION

Considerable outcomes in the development of CAFD approaches and applications targeting on aspects of optimization techniques and degree of automation have been examined. There are still some general and specific shortcomings in this field which could also be as gaps in future studies. General shortcomings in CAFD can be as follows:

1. Along with the research maturity, considerable CAFD research need to be conducted to develop more automated comprehensive functioning systems in order to support the total fixture development process automatically.
2. Most of the CAFD methods have been verified for simple workpieces which are not representative of those combated in industry; hence, the helpfulness of developed approaches cannot be stated with confidence.

The specific shortcomings, which still remain in optimizations approaches based on our review is as follows:

1. Only few researchers have used either discrete GA or continuous GA in the fixture layout optimization problems, and their applicability with respect to solution region of each fixturing element has not been addressed.
2. FEM can be embedded with optimization techniques along with other intelligent methods.
3. In order to improve the fixture design performance in terms of optimization and verification, the existing modeling and control techniques in this field need to be integrated to achieve more applicable methods.
4. The modeling and prediction of part–fixture behavior need to be more concentrated especially to attain a clear and accepted formalized approach.

Another attractive field for future direction of study could be Micro and Nano machining fixture deign. Because Nanometric machining has quite different physics compared to usual machining as in the material and physical properties and the manufacturing process.

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چکیده

طراحی فیکسچر یکی از مهمترین قسمتهای فرایند تولید است. طراحی فیکسچر یک طراحی بحرانی است که در آن خودکارسازی نقش یکپارچه کننده بین CAD و CAM را بازی می‌کند. در این مقاله، مروری بر طراحی فیکسچر به کمک کامپیوتر در زمینهٔ خودکارسازی و تکنیک‌های بهینه سازی ارایه داده شده است. در ابتدا، دلیل لزوم طراحی فیکسچر به صورت اتوماتیک بیان شده است. سپس، با توجه به درجه اتوماتیک بودن، روشهای طراحی فیکسچر دسته بندی شدهاند. بر طبق نیاز سیستم‌های اتوماتیک طراحی فیکسچر، تکنیک‌های بهینه سازی که به صورت گسترده استفاده می‌شوند بدقت بررسی شده است. در نهایت، نقاط ضعف روشهای موجود خودکار سازی و بهینه سازی طراحی فیکسچر که نیاز به تحقیق بیشتر دارند آورده شده است.

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