Towards Predictive Design: Tracking a CNC Fixture Design Process to Identify the Requirements

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Abstract. Training novice production engineers to design manufacturing fixtures is a time-consuming process involving significant input from experienced experts. Motivated by the vision of providing an intelligent support system for general mechanical design, this paper develops a list of requirements for predictive suggestion mechanisms focused on creating fixtures for holding components during machining. To do this, the email communications between nine novices and one expert during the design of machining fixtures were studied. The analysis classified the expert's feedback into ten coded themes. The significance of these themes was assessed by quantifying the resulting changes in the CAD models of the fixtures designs and fixture requirements. The identified results lay the foundation for developing a comprehensive CAD predictive suggestion system to support fixture design. Novice designers will benefit from this predictive suggestion system by correcting their design errors in real-time and reducing the need for experts' time in the training process.

Keywords. Predictive design, fixture design, CAD suggestion system.

1. Introduction

A fixture is a mechanism used in manufacturing to hold one or more workpiece(s), position them correctly in relation to a machine tool, and provide support during machining. Researchers report that fixture design can cost 10%-20% of the total cost of the manufacturing system [1], which is significant in the total tooling costs, and have noted that poor fixturing design can lead to about 40% of parts being rejected due to dimensioning errors [2]. So, fixture design greatly influences product manufacturing quality and productivity. The fixture design involves four important design stages: setup planning, fixture planning, fixture design, and verification. For a given machining workpiece, the setup and fixture planning stages involve studying the manufacturing processes, the required workpiece orientation, and determining the workpiece locating and clamping positions and surfaces. The subsequent two stages focus on designing the required fixture components and assessing whether the developed fixture design satisfies

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the input requirements. The first two stages play a vital role in fixture design because they significantly influence the last two stages.

Traditional fixture design rules such as the "3-2-1" locating scheme are no longer sufficient considering the complexity of current manufacturing processes, and multiple types of fixture design such as reconfigurable and modular fixtures. Fixture design is a complex process that requires consideration of various parameters such as machining part orientation, clamping locations, and surfaces, etc., to achieve intended production efficiency in terms of support needed for production stability, quick accessibility, collision avoidance, etc. Since multiple parameters need to be considered, fixture design often depends on expert engineers who possess multi-faceted experience and knowledge in production, engineering design, and mechanical analysis. Based on experience, expert engineers could identify fixture positions quickly, whereas novice engineers spend a considerable amount of time in the trial-and-error process. Rong and Samuel [3] argued that designing quality fixtures could take over ten years of manufacturing practice. In this research, fixture designs for securing machining components completely (i.e. constraining all six DoF) on a 5-axis CNC machining were studied.

2. Advances in Support System for Fixture design

To support training novice engineers and speed up efficient fixture design development, researchers developed many computer-aided fixture design (CAFD) applications over the decades. The common techniques employed in these applications developed are Rule-Based Reasoning (RBR), Case-based Reasoning (CBR), Genetic Algorithm (GA), Neural Network (NN), Finite Element Method (FEM), and Geometric Analysis [4]. Since this research aims to store and reuse fixture design knowledge to support training novice engineers (rather than automatic CAFD systems), the following literature discussion focuses on advances in the CBR approach. Case-based reasoning (CBR) is an experience-based approach to solving new fixture design problems by adapting past solutions to similar machining workpieces. Aamodt and Plaza [5] defined a formal model of CBR using four modules: Retrieve, Reuse, Revise, and Retain. The process involves finding relevant cases for a given fixture problem, choosing the best case for an application, making necessary changes to the selected case, and storing the modified case in the database. To enable this process, the CBR approach requires representation for indexing fixture design knowledge, mechanisms to retrieve similar fixture cases, and adapting retrieved cases for the current fixture problem.

Although decades of research have developed multiple techniques to support the computer-aided fixture design domain, expert knowledge still plays a vital role in all three stages. The critical missing process involved in this CBR development is the involvement of a proactive automatic learning mechanism to support all these stages. To embed effective learning and reasoning processes, intelligence needs to be gathered from CAD files, structured documents and informal communications between expert and novice engineers in normal industrial work operations. Understanding the support required to train novice engineers in developing effective fixture design would help build a better CBR approach and significantly reduce experts' time in improving the developed CBR approach. Thus, there is a need to study informal communications in fixture design and derive requirements for predictive suggestion system for training novice engineers.

This research focuses on how fixture design was developed through various development versions involving novice engineer learning processes. The variations were studied for fixture elements, functional positions, and contact surfaces for locating, supporting, and clamping a workpiece. Based on learning results, the next research stage will be to develop a better computer-aided support mechanism for novice engineers using recent predictive knowledge modelling, data mining, and machine learning approaches. The support system will provide in-situ suggestions with appropriate rationale learned in the fixture design process.

3. Aim, Objectives, and Methodology

This work aims to comprehensively understand novice designers' support requirements in creating an effective fixture design. The following research objectives are addressed in this paper:

- Identify support required for novice engineers in fixture design through analysing feedback email communications from an expert engineer.
- Map expert's feedback on fixture design requirements to understand the impact of the manufacturing process.
- Study changes made by novice engineers in fixture design by analysing versions of CAD fixture design.

Answering these objectives will enable to laying the foundation for developing an automatic learning and a predictive suggestion system that provides in-situ suggestions to support novice engineers during the process of CAD-based fixture design. These predictive suggestions could help novice engineers to train faster and lessen the need for expert input. Nine engineering students participated in fixture design exercises to answer the objectives mentioned above, and an expert trained them by giving feedback on each submitted version. The design exercises followed these steps:

- The basic principles for fixture designing were taught to the students.
- A set of 3D model components that need to be held during machining was given.
- All initial required modular fixture components provided.
- Students were asked to design a fixture layout for a given component. The shared modular components could be changed appropriately as required.
- When complete, the students upload the designed fixture (i.e. a CAD assembly file) for expert review.
- Students revised the CAD assembly model in response to the expert review and submitted it again. This process continues until the fixture design has been approved.

Fifteen distinct engineering parts were provided to recent design graduates from the ABC dataset [6]. By making changes to the nominal part, a collection of related, family parts were created; changes included minor changes to the part dimensions or hole feature sizes, significant changes which included the addition or subtraction of features, and transformative changes that allowed for two or more feature or non-feature changes while remaining functional engineering component.

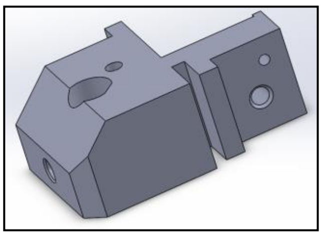

Figure 2. A sample machining component

Figure 2 illustrates a sample machining component illustrating the complexity included. Each part family was then provided to the second cohort of novice design engineers, comprised of undergraduate design students with some CAD experience. The task was to create Microloc [7] fixture designs for securing the components for the machining of hole features, using a catalogue of Microloc fixtures, and designing custom fixtures as required. An engineer with 20 years of manufacturing experience appraised each fixture design submission and provided suggestions on improving them. This created a dataset of fixtures for each family of components with sequential changes.

4. Support required for novice engineers in Fixture design

The email feedback exchanges between the expert and the nine students were analysed using the codification approach to extract the areas requiring more support to develop an error-proof fixture design. No initial classification has been generated for the coding activity. In total, ten support themes were coded. Table 1 summarises the identified suggestion coding themes with identified frequency. The observations reveal that the novice students require more support for the following five main areas: mating faces between components, a suitable alternative assembly component, an additional fixture component, a mating distance between components, and a mating location between components. The possible reasons for these frequently occurring themes could be due to the availability of many possible options in assembly, and learning that happened in one fixture design could not be easily transferred to other types of machining parts.

The expert also provided support to find similarities between machining workpiece parts and map the previous fixture design feedback. This study highlights that novice student engineers frequently required support in the feedback statements. The derived suggestion support themes will help to develop a predictive suggestion system that will provide holistic in-situ suggestions support for novice engineers to develop error-proof fixture design configurations.

Table 1 Frequency of expert suggestions using derived coding themes

Suggestion coding theme	Expert suggestion frequency	Suggestion coding theme	Expert suggestion frequency
1. Suggest mating faces between components.	25	6. Suggest orientation of the workpiece part/fixture component.	12
2. Suggest an alternative fixture component.	18	7. Suggest alteration to the fixture component.	5
3. Suggest an additional fixture component.	14	8. Suggest fixture component dimensions appropriate to the workpiece.	4
4. Suggest a mating distance between components.	14	9. Find similar workpiece parts and map previous fixture design feedback.	3
5. Suggest a mating location between components.	13	10. Suggest removing a component.	2

5. Map expert’s feedback to fixture design requirements

The derived expert suggested themes were mapped to fixture design requirements to understand the significance of these suggestions. Since the expert did not explicitly mention the rationale for the requested fixture design changes, the researcher mapped the suggested themes to fixture design requirements. The fixture design requirements were summarised based on the reported work [8-9]. The contents of expert feedback were mapped using these listed fixture requirements and suggested coding themes to understand their significance. Figure 3 represents the frequency mapping between the fixture design requirements and the derived expert suggestion themes. The darker red shade represents the higher frequency of observation between that requirement and the suggestive theme. The highest frequency mapping was between the stability requirement and the suggestion of an alternative fixture component. Based on the frequency, requirements and suggestion themes have been hierarchically clustered using cosine distance and average linkage. Figure 3 represents these clusters at the right-side for requirements and at the bottom for suggestive themes. Chip shedding, collision prevention, stability, and error-proof assembly form a cluster based on their wider coverage of suggestion themes. The mapping exercise reveals that each coded suggestion theme influences multiple fixture design requirements. Thus, the impact significance of coded suggestion themes will vary significantly based on the context of suggested fixture design changes.

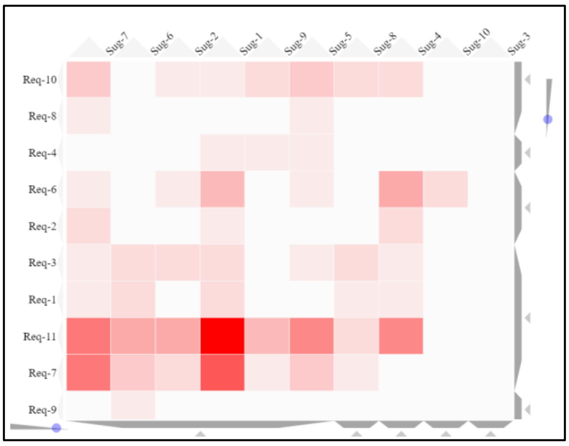

Figure 3. Presents a count of the number of changes in distinct fixture components used

Req-1: Chip shedding; Req-2: Clamping distortion; Req-3: Collision prevention; Req-4: Constraint DoF workpiece; Req-5: Ease of fixture design; Req-6: Ease of workpiece assembly/disassembly; Req-7: Error-proof assembly; Req-8: Machining accuracy; Req-9: Quick machining time; Req-10: Required machining stiffness; Req-11: Stability; Req-12: Workpiece deflection (refer Table 1 for Suggestion theme number)

6. Version changes made by novice engineers

The following results focus on the changes in which components mate with the workpiece, and/or their orientation. There were fifteen distinct part families which included, on average, eighteen family part design variations, with a minimum of eight and a maximum of 21. All the fixture designs within six of the part families were approved at the first attempt, and 98 (63%) of the remaining family parts in the first iteration. Fifty-two (33%) of the remaining fixtures required one iteration of changes, and one family part required seven iterations till approval. Each iteration could consist of multiple changes: the addition and/or removal of a single or multiple parts, the addition and/or removal of a single or multiple components mates, or the re-orientation of a component(s). Table 2 provides the proportion of common components with the same mate type that required some change to the mate parameters, e.g. change in the position. It can be seen that the initial design submission generated the greatest number of changes and that fewer changes are required as the design progresses.

Table 2 Details percentage changes in mate assembly between each version changes

	V1 vs V2	**V2 vs V3**	**V3 vs V4**	**V4 vs V5**	**V5 vs V6**	**V6 vs V7**
Family parts that have a common pair of components and mate type between versions	45	5	2	1	1	1
The proportion of these that required a change to the mate parameters	0.83	0.67	0.5	0	0	0.67

7. Discussion and Conclusion

The research paper presented the identified support required by novice engineers in designing fixture design by analyzing the feedback received from an expert. Locating suitable mating faces between components and identifying suitable alternative assembly components are the top frequent suggestions provided by the expert among the ten identified suggestion themes. The mapping of the possible impact of these suggestions on the fixture design requirements reveals that stability and error-proof assembly requirements have impacts on most of the suggestive themes. Also, the version changes highlight that the checks required at the first submission need to be comprehensive compared with the subsequent iteration. The identified results lay the foundation for developing a comprehensive CAD predictive suggestion system to support fixture design. Compared to the reported case-based reasoning research, the development of an in-situ CAD predictive suggestion system for fixture designs will cover a wider range of suggestions at various design levels (i.e. assembly mate faces, substitutable fixture components, fixture orientation, etc.).

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