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Virtual Conceptual Design of a Multi-Purpose Fixture for a CNC Milling Machine Using the Controlled Convergence Technique

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Abstract: *Modern computer numerical control (CNC) machines are capable of performing numerous operations on variety of workpieces. An array of parts that are geometrically and physically dissimilar can be machined on a CNC workstation, provided an appropriate fixture is available. It is however quite common in practice to have many dedicated fixtures serving as accessories to a single CNC workstation. The intent of this paper is to present an integrated approach to designing a multipurpose yet cost effective fixture to perform several milling operations. Pugh's Controlled Convergence (CC) technique was used to generate alternative designs. Finally, the most feasible alternative was modelled using Virtual Engineering (VE) principles which can allow it to be further analysed for downstream operations. The results indicate that the proposed CC and VE principles were applied effectively to design a multipurpose milling machine fixture.*

Keywords: *Product development, milling fixture, integration, controlled convergence, virtual engineering*

1. Introduction

Computer numerical control (CNC) machines are widely used for varied material removal processes. Several laboratory-based CNC machines, like milling cutters, lathes and routers, are available in the Department of Mechanical and Manufacturing Engineering, The University of the West Indies, St. Augustine campus. These are used in the manufacturing engineering curriculum, with content on CNC programming. However, among such laboratory based CNC machines there is no on-board means for measuring and recording data relating to cutting forces and moments generated on parts as they are being machined. Additionally, the CNC milling machine, which was shipped with a fixture, is not able to complement its built-in capacity. For instance, the machine is equipped with a 100mm x 150mm vice-type fixture. Whereas the maximum X, Y and Z-axis travel of the machine are 304mm, 157mm and 213mm respectively. This indicates that the machine has a capacity for conducting operations on parts of larger sizes. There is also no facility for locating and holding free-form objects. Furthermore, the inadequate clamping mechanism sometimes leads to deformation on finished work

For the study purposes, a multipurpose fixture will be designed for the aforementioned CNC milling machine that overcomes the identified issues. The proposed fixture would accommodate larger and more geometrically diverse workpieces while minimising deformation as well as permitting greater utilisation of the machine's inherent capabilities, improving its overall effectiveness.

In practice the design and manufacture of a multipurpose machining fixture is a complex task, which involves knowledge of tolerances, geometry, dimensions, procedures and manufacturing processes (Patel and Acharya, 2014). Various aspects of the design of milling machine fixtures have been widely covered by several researchers (Patel and Acharya, 2014). However, there was need to consider an integrated design approach that combined virtual engineering (VE) principles with contemporary product design and development tools for an effective means of generating and selecting alternative designs. In this regard, the current study proposes an integrated approach of Pugh's Controlled Convergence (CC) combined with VE principles for the design of a multipurpose fixture for a CNC milling machine.

2. Background to the Study

Henriksen (1973) defines a fixture as a special tool used for locating and holding a workpiece in the proper position during a manufacturing operation. Hargrove and Kusiak (1994) described the four requirements of a fixture as: accurate location of the workpiece, total restraint of the workpiece during machining, limited deformation of the workpiece, and no machining interference. Hunter et al. (2005) proposed a fixture design methodology comprising of two stages, component geometry and the interference process. Patel and Acharya (2014) integrated the research works of various pioneers (Hunter et al., 2005; Hargrove and Kusiak, 1994; Meyer and Liou, 1997; Li et al., 1999) to develop a methodology for the design of a hydraulic fixture. Hui et al. (2016) developed a flexible fixture to adapt to varying workpieces in terms of size and shape for use in the aircraft industry. However, even though these studies reported on time savings in production, they still require a lot of information on the machining conditions which may not be readily available.

CAD systems have become indispensable in today's product design practices and provide freedom to experiment with function and shape via direct manipulation (Fujita et al., 1999). Research studies targeting the support of integrated approaches combining virtual reality and engineering tools in the early product conceptualisation phase have not been well covered. VE based prototyping is a process of computer-aided product digitisation, whose objective is to speed up the product development process and to reduce the required number of physical prototypes, leading to reduced product development costs (Brunetti and Stork, 2007). Shen et al. (2000) presented an integrated approach to innovative product development using Kano's model and quality function deployment (QFD). Chowdary and Gittens (2008) proposed an integrated approach to the development of a battery-operated passenger cart that focused on recycling and maintenance. Chowdary and Kanchan (2013) presented an integrated product design and development framework that combined DFE guidelines with CAD/CAE principles. Ali et al. (2013) proposed an integrated design approach for rapid product development of a broken product, combining reverse engineering, re-engineering and rapid prototyping. The study concluded that the integrated approach allowed for the development of an enhanced product at a reduced cost and time.

A few studies (e.g., Chowdary and Gittens (2008), Chowdary and Kanchan (2013), and Ali et al. (2013)) have demonstrated the strength of the VE tools in design of products. This study proposes an integrated approach to designing a multipurpose milling fixture that considers simultaneously the traditional product design tools and VE principles.

The machine, which is the subject of this study, is a free standing, computer controlled, 3 axis vertical machining centre designed for training in CNC programming and computer controlled machining. It is a high quality machine that has a touch-sensitive control panel. The machine has variable and programmable spindle speeds and a 1.26kw (1.9HP) DC motor, allowing various materials to be machined. These include steel, brass, wood, aluminum, plastic and wax.

The dynamometer is a device that can be used to measure quasi-static and dynamic forces as well as applied moments during machining cycles. The gathered data can enhance the knowledge of the loads and stresses as well as part distortion introduced at various stages of an operating cycle. In this regard, a multipurpose fixture that can integrate a dynamometer with the selected CNC milling machine can serve as a platform for launching in-depth research into the dynamics of CNC machining. For the purposes of this case, the device selected was the Kistler type 9272 dynamometer.

2. Integrated Approach for the Design of a Multi-purpose CNC Milling Fixture

The integrated approach is depicted in Figure 1. As shown, it begins with conducting literature survey and analysis of trends in the area. Then a case study was selected to identify shortcomings of the original work holding of the machine under consideration. After this step, a review of existing techniques for combating or eliminating such drawbacks was performed. Then the product design specifications (PDS) were formulated which allowed for conceptualisation of viable alternative designs by means of Pugh's CC technique. Modelling the selected alternative designs using VE principles and evaluation of the virtual model completes the design of the proposed multipurpose milling fixture process.

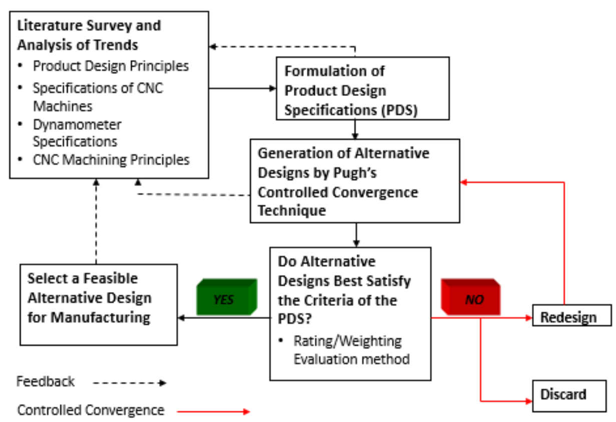
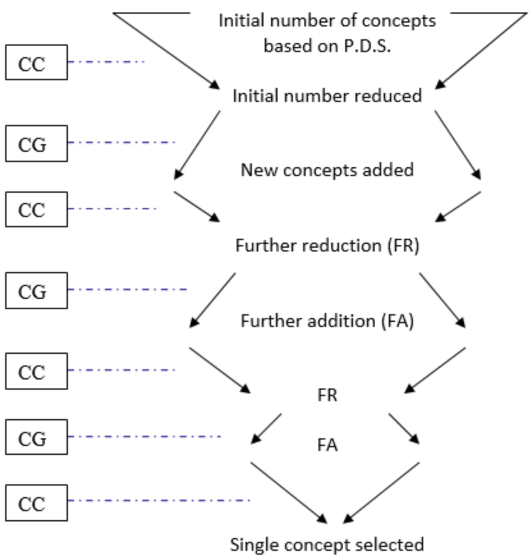


Figure 1. Proposed Integrated Approach for Design and Development of a Multipurpose Milling Fixture

2.1 Applying the method of controlled convergence

Pugh's method of CC, as shown in Figure 2, was applied throughout the proposed multipurpose milling fixture design procedure. Developed in 1980s by Stuart Pugh, CC uses a simple matrix to compare concepts against a set of pre-determined criteria (Frey et al., 2009). An initial set of concepts was first created with the aid of developed PDS. Then design alternatives were reviewed against specified criteria using the Rating/Weighting method. Wherever possible, both the stronger and weaker concepts were strengthened. Weaker concepts that could not be strengthened were discarded, thus effectively reducing the pool of alternatives for possible selection as the final design. In addition, the most beneficial features of several concepts were combined creating more innovative and feasible designs. This method guarantees the continued generation of progressively more robust alternatives with the subsequent emergence of a single final design.



Legend: CC – Controlled Convergence; CG – Concept Generation

Figure 2. Method of Controlled Convergence

2.2 Product Design Specifications

1) Size and weight restrictions:

- The final design should not exceed maximum dimensions of 500mm × 235mm × 130mm, so as to fit comfortably within the selected CNC milling machine as well as facilitate ease of installation.
- The overall weight should not cause significant deflection of the milling machine table or place excessive strain on the individual motors of the machine's X and Y axes.

2) Performance:

- The fixture should be capable of securely locating and holding regularly shaped workpieces as well as the Kistler Type-9272 Dynamometer.
- The capacity of the new design should exceed the maximum capacity of the existing fixture by 40% in at least one axis.
- The device should hold various materials to machine including steel, brass, wood, aluminum, plastic, and wax.
- The fixture should locate and hold work with zero or minimal surface marring and/or deformation of such workpieces during extensive machining operations.
- All features of the design should pose zero threat of interference with the cutting tool and tool changer.

3) Manufacturing Processes:

- Major parts of the assembly were to be fabricated using tooling and equipment available in a typical machine shop.
- Raw material and fasteners available on the local market must be used in the assembly wherever possible.

4) Maintenance:

- Chips and burrs should be easily removed from the fixture at the end of every milling operation.
- Parts requiring lubrication should be easily accessible.
- When not in use, the fixture should be stored in a clean dry environment.
- Before storing, any accumulated coolant is to be removed from the device.
- Any parts made of steel must be regularly oiled to prevent surface corrosion.
- No specially designed or uncommon tools should be required for the maintenance of the fixture.

5) Life in Service:

- The service life of the product should be comparable to that of the milling machine.
- Life in service should be assessed against the criteria outlined in the Performance and Environment categories.

6) Target Costs:

- The total cost of raw material and parts for manufacture should be less than the cost of standard fixture.

7) Environment:

- Exposure to adequate volumes of lubricant.
- The fixture should resist corrosion through the use of special materials and/or surface protection methods such as coating.

8) Safety:

- The fixture should never be manually adjusted during a machining operation.
- Tool paths should be simulated to ensure no threat of collision between the fixture and the cutting tool.

9) Aesthetics:

- The proposed device should be easily operated with its form and function.
- The fixture should look attractive and well finished.

10) Ergonomics:

- Operation of the multipurpose fixture should require only a single person.
- A minimal range of tools should be necessary for assembly and disassembly.

11) Quality and Reliability:

- Aspects of the performance criteria for the design must not significantly deteriorate over its life in service if routine maintenance is performed.

12) Installation:

- The fixture is to be installed according to the instructions for mounting a new work holder as specified in the selected machine user manual.

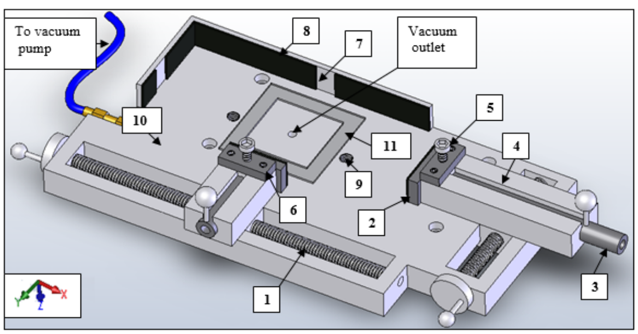
3. Evaluation of Alternative Designs

3.1 Rating/Weighting Matrix

Alternative designs were evaluated against critical elements of the product design specifications as stated earlier and other favourable criteria using a Rating/Weighting method (as shown in Table 1). Each evaluation criterion was allocated a weight factor on a scale of 1-5. The higher the number assigned, the greater the importance of the respective criterion. The alternative designs were then rated against the evaluation criteria on a scale of 1-5. Likewise, the higher the rating the better the alternative satisfied the criterion. Finally, rating and weight factors were multiplied and summed to obtain a total score for each alternative. The highest score was taken to reflect the strongest alternative design. As indicated in Table 1, the highest scoring design is alternative design E, with a total of 128. Consequently, the final design was modelled based on this concept.

3.2 Development of the Selected Design

The design, illustrated in Figure 2, utilises two mutually perpendicular clamp assemblies driven by independent power screws (1). Both clamps (2) are also adjustable perpendicular to the direction of travel along these screws by varying the position of a push rod/clamp shaft (3) within the clamp housing (4). This position can be maintained with ease using a single quick release screw (5) and threaded locking-bracket (6).



Legend: 1. Power screw; 2. Clamps; 3. Push rod/clamp shaft; 4. Clamp housing; 5. Quick release screw; 6. Threaded locking bracket; 7. Fixed locator; 8. Neoprene rubber; 9. Internally threaded holes; 10. Fixture base; and 11. Vacuum gasket tape

Figure 3. The Selected Alternative Design E for Development

The design of this clamping mechanism again allows varied sizes of regularly shaped parts to be easily accommodated (up to 280 mm in X-direction). The fixed locator (7), and the clamps themselves, are padded with a thin layer of Neoprene rubber (8) to minimise surface marring of the workpiece. Two internally threaded holes (9) are also incorporated into the design, allowing the Kistler type 9272 dynamometer to be bolted directly to the fixture base (10). A vacuum work holding system is integrated within the base of the apparatus as well. Utilising zero creep vacuum gasket tape, or an appropriate substitute (11), free form bodies with at least one sizeable flat surface can be held with the aid of a suitable vacuum pump.

4. Discussion

4.1 Effectiveness of Integrated Approach

A multipurpose milling fixture was designed using an integrated Pugh's CC approach combined with virtual prototyping process. Attributes of the new design include:

- An increased work holding capacity of the fixture, with a limit of 280 mm in the X-axis, optimising the available maximum travels of the milling machine.
- Facilitation of the mounting of the Kistler dynamometer, introducing the option for the gathering of data on cutting forces and torques generated throughout milling cycles.
- The possibility for securing work without the application of significant holding force from any clamp. This effectively reduces the likelihood of part deformation and part wastage.
- The added capacity for location of cylindrical workpieces around their circumference with the use of chuck-like jaws, and
- A vacuum system that can allow free-form objects with one substantial flat surface to be located and held.

4.2 Features of Final Design

The final design will be based on alternative design E and will function with the use of two mutually perpendicular clamp assemblies both manually driven by independent power screws. These screws will convert

Table 1. Rating/Weighting Matrix for Selection of Multi-purpose Milling Fixture

Criteria	Weight Factor	Rating					Weight Factor × Rating				
		A	B	C	D	E	A	B	C	D	E
Overall work holding flexibility	5	2	5	3	4	5	10	25	15	20	25
Ability to house dynamometer	5	5	5	5	5	5	25	25	25	25	25
Potential to reduce part deformation	4	3	4	2	3	4	12	16	8	12	16
Ease of manufacture	4	3	3	4	2	3	12	12	16	8	12
Low manufacturing cost	4	4	2	3	3	4	16	8	12	12	16
Ease of part location (ability to reduce setup time)	4	4	3	4	4	4	16	12	16	16	16
Ergonomics	3	3	3	3	3	3	9	9	9	9	9
Maintenance	3	3	4	3	3	3	9	12	9	9	9
		Total					109	119	110	111	128

rotational motion to linear translation. This independent clamping system aims to eliminate part deformation as well as securely locate regular-shaped workpieces of various sizes. Moreover, the multi-purpose fixture base will be made of plain carbon steel. Each power screw incorporates square threads for increased sturdiness. The clamp housings will be constructed of aluminum which has a high strength to weight ratio. The clamps, clamp sliding supports, clamp shafts and locking screw brackets will be fabricated from mild steel stock.

The rear fixed locator will be made of aluminum and can be padded with a 2mm layer of Neoprene rubber to reduce the likelihood of surface marring to any workpiece. In addition to the rear fixed locator, there is also a set of fixed locators. These can be bolted to the fixture base to permit the fixing of tiny work pieces, as the individual travels of the long and short clamp shafts (140mm and 65mm respectively) are limited by space restrictions within the selected CNC milling machine. Each clamp shaft knob will be fabricated of aluminum. All clamps and the removable locators can be padded with a layer of Neoprene. The Kistler dynamometer can be mounted with the use of two 1¼-inch long, 7/16-inch diameter hexagonal bolts.

A vacuum clamping system is also integrated to the fixture base. Using a single ¼-inch brass nipple, the fixture can be coupled to an electric vacuum pump. Zero creep vacuum gasket tape or an appropriate substitute will be applied between the fixture and the work to maintain the vacuum. The essential purpose of this vacuum system is to locate free form bodies with at least one sizeable flat surface.

This integrated approach facilitates effective concept selection by combining the powerful design tools of Pugh's CC method and virtual prototyping. Using this method, concepts with useful features are combined and improved, thus strengthening the concept pool and ensuring that the final chosen concept is of the highest quality. Moreover, the presented approach can be used as an example of the implementation of Pugh's CC method and concept generation and selection. In the future, this approach can be applied to the design of other mechanical devices and components to strengthen and support the effectiveness of the presented approach.

5. Conclusion

An integrated approach for the design of a multipurpose milling machine fixture was presented which featured Pugh's Controlled Convergence and virtual prototyping process. PDS were used to develop alternative designs, the best of which was selected by applying the method of CC. It was shown that the proposed integrated approach was successful in the design of a multipurpose milling machine fixture and in future can be applied to design of other products to further test the efficacy of the approach.

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