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An approach towards fully integration of CAD and CAM technologies

M. Tolouei-Rad *
School of Mechanical Engineering, Shahid Rajaee University, Tehran. Iran
* Corresponding author: E-mail address: mtrad@srttu.edu

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Analysis and modelling

ABSTRACT

Purpose: An integrated CAD/CAM system for milling operations has been developed which helps designers to solve machining problems at the design stage.
Design/methodology/approach: A methodology has been employed which provides all necessary information for machining products automatically. Use of these system results in reduced machining leadtimes and cost through designing machinable components; using available cutting tools; improving machining efficiency. The system is menu driven with a user friendly interface.
Findings: Different components for developing such a system have been identified and various problems that arose in the development of this system have been dealt with The system developed leads to an adequate basis for fully integration of CAD and CAM technologies in one system. It allows simultaneous generation of all information required to satisfy machining requirements of the design such as its machinability and availability of the required tooling resources.
Research limitations/implications: Different components required for developing such systems have been identified and various problems that arose in the development of these systems have been dealt with, leading to an adequate basis for complete integration of CAD and CAM technologies. Although much of the work described here goes beyond the scope of published literature, however, it should be noted that the system developed couldn't be considered as a complete solution to the CAD/CAM integration problem. Further work requires including other manufacturing activities that are considered in concurrent engineering concept. In this direction, further integration of the system developed with systems such as MRP, MRP II and assembly sequence planning packages are highly desirable.
Originality/value: CAD/CAM integration is regarded as a solution for bridging the gap between design and manufacturing, one of the ultimate goals for concurrent engineering. Since the advent of CAD and CAM numerous attempts have been made to integrate these technologies; however, a full CAD/CAM integration is not yet achieved. In addition, most of the systems developed focus only on turning, leaving room for further investigation on other machining operations including milling. This paper goes one step closer towards achieving a full CAD/CAM integration for milling operations.
Keywords: CAD/CAM; Integration design; Manufacturing; Machinability

1. Introduction

Industrial world has witnessed significant improvements in product design and manufacturing since the advent of computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies. Although CAD and CAM have been significantly developed over the last three decades, they have traditionally been treated as separate activities. Many designers use CAD with little understanding of CAM. This sometimes results in design of non-machinable components or use of expensive tools and difficult operations to machine non-crucial geometries. In many cases, design must be modified several times, resulting in increased machining lead times and cost. Therefore, great savings in machining times and costs can be achieved if designers can solve machining problems of the products at the design stage. This can only be achieved through the use of fully integrated CAD/CAM systems.

The need to integrate CAD and CAM has long been recognised and many systems have been developed. Kalta and Davies [1] developed an IGES pre-processor to integrate CAD and CAPP for turned components. In a different work, a rule-based system was developed for converting engineering drawings into numerically controlled machine programs for two dimensional punch objects [2]. Lye and Yeo [3] and Thakar et al. [4] developed integrated CAD/CAM systems for design and manufacture of turned components. Bidanda and Billo [5] reported the development of a system for generation of NC programs for producing countersink cutting tools.

Feature recognition and feature based design have been used as by most researchers to bridge the gap between CAD and CAM. Many used feature extraction method. Examples are rule based [6] and syntactic pattern based [7] feature recognition. Development of domain specific feature modeling systems has also been reported. Examples include OMEGA [8], PRISPLAN [9], CFACA [10], VITool [11], IFPP [12]. OMEGA uses production rules to define operation sequences that are then subsequently grouped into set-ups based on the nature of the tolerances. PRISPLAN, CFADA and IFPP focus on generating NC programs for machining centers.

Developments of such systems have also been reported by others [13-19]. However, a fully CAD/CAM integration is not yet achieved. The process of integration of CAD and CAM has been relatively slow in comparison with the developments made in each of these technologies. Researchers believe that the slowness of the integration over the recent decades is essentially attributable to the incompatibility of database formats and the lack of common languages. The developed systems can only be considered as *islands of integration* and still there is a missing link fully integrating these two technologies.

In most of the systems developed, user still must determine crucial manufacturing parameters such as cutting tools, cutting speeds, feed rates, cutting depths, etc., requiring expertise and considerable amount of time. In addition, contributions made to integrate CAD and CAM systems for milling operation are very limited, while this operation forms a considerable amount of machining operations. This paper describes development of an integrated CAD/CAM system for milling operations. It has been proven that the use of this system would help reduce machining leadtimes and cost, and it is believed that this system goes one step closer towards achieving fully integrated CAD/CAM systems.

2. System developed

An integrated CAD/CAM system for milling operations has been developed which helps designers to solve machining problems at the design stage. A methodology has been employed which provides all necessary information for machining products automatically. Use of these system results in reduced machining leadtimes and cost through (1) designing machinable components; (2) using available cutting tools; (3) improving machining efficiency. The system is menu driven with a user friendly interface. As shown in Figure 1, the system is composed of following components: design module, expert system, machining sequence planning module, optimisation module, manufacturing module, executive program.

3. Design module

The design module is developed based on feature-based design approach. It is implemented with AutoLISP programming language and uses AutoCAD's solid modeller to create product models. This module has a feature library that includes two groups of features, pre-defined and user-defined. Pre-defined features are divided into protrusions and depressions. Protrusions include cubic, rectangular, circular, polygonal, elliptical, semi-circular, semi-polygonal and semi-elliptical features. Depressions include pockets, holes, slots and steps. There could be different numbers and forms of islands inside pockets. Holes are composed of normal, counterbore, countersink and flat bottom ones. Slots have different shapes such as normal, round bottom, U, T and V shapes. Steps are divided into normal, round bottom and notches. User-defined features are complex features of common use for a manufacturing firm that can be created by any combination of pre-defined features, restored in the feature library, and used whenever required.

The relationship between different features is represented by use of a feature tree. This tree represents parent-child relationship between features where a feature forms its root and other features form its branches and leaves. A feature can be considered as the child of another when at least one of its imaginary faces is coincident with a real face of the parent feature. Feature A becomes a parent for feature B when there is no tool access to machine feature B before machining feature A. Each parent feature can have an unlimited number of child features and all features must have a parent feature except the root feature. The feature tree can be organised only when the product design is completed.

The design module uses different co-ordinate frames and datum points for placement of features in the design model. These can be defined as:

- *Global co-ordinate frame (GCF)* is the original or world co-ordinate frame of the component. There is only one GCF for each component.
- *Local co-ordinate frame (LCF)* is the user defined co-ordinate frame to design different features easier. There may exist no or several LCFs in the design and each LCF can be defined with respect to the GCF or another LCF.
- *Datum point (DP)* is the reference point of the feature and there is one DP for each feature. DP determines the position of the feature with respect to the current co-ordinate frame that can be either GCF or LCF. In other words, DP can be considered as a sub-LCF that determines the location of a feature with respect to the current co-ordinate frame having the same orientation.

When different co-ordinate frames are employed, the system must determine the position of each feature with respect to GCF when it is defined in a LCF and vice versa. It is known that one co-ordinate frame must be defined with respect to another. A new co-ordinate frame can be described with a matrix of vectors. In addition, the sequence of rotations and translations required to relocate from one co-ordinate frame to another must be described; this can be done with a transformation matrix. A matrix can be used to represent translation and rotation because a sequence of translations and rotations can be combined to produce a complex relocation more easily with matrix multiplication than with vector addition. For example, if $\mathbf{p_1}$ represents the DP of a feature with respect to the LCF, it can be represented by $\mathbf{p}$ with respect to GCF where:

$$\mathbf{p} = \mathbf{A}\,\mathbf{p_1} \tag{1}$$

when:

$$\mathbf{p} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \mathbf{A} = \begin{bmatrix} x_x & y_x & z_x & p_x \\ x_y & y_y & z_y & p_y \\ x_z & y_z & z_z & p_z \end{bmatrix}, \mathbf{p_1} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} \quad (2)$$

$$\mathbf{p_1} = \mathbf{A}^{-1}\,\mathbf{p} \quad (3)$$

where $\mathbf{A}$ is the general transformation matrix and $\mathbf{A}^{-1}$ represents the inverse of $\mathbf{A}$.

It is important to note that transformation matrix is composed of four vectors; the first three vectors represent the orientation of the three axes and the last vector represents the translation of the origin of the new co-ordinate frame, all with respect to the old co-ordinate frame.

In order to allow inversion of the 3x4 transformation matrix, an additional dummy row is introduced to it and additional fourth numbers are introduced to the point vectors, which have no effect on the matrix manipulations. Therefore they become:

$$\mathbf{p} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}, \mathbf{A} = \begin{bmatrix} x_x & y_x & z_x & p_x \\ x_y & y_y & z_y & p_y \\ x_z & y_z & z_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{p_1} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix} \quad (4)$$

When nested LCFs are defined, there will be more than one transformation matrix. In this case, to transform a point from a nested LCF to GCF, more than one transformation matrix should be employed. For example, in the component shown in Figure 2, LCF_1 is defined with respect to GCF, LCF_{11} is defined with respect to LCF_1 and the DP of counterbore hole is defined with respect to LCF_{11}. If $\mathbf{p_1}$ represents the DP of counterbore hole with respect to LCF_{11}, it can be represented by $\mathbf{p}$ with respect to GCF where:

$$\mathbf{p} = \mathbf{A_1}\,\mathbf{A_2}\,\mathbf{p_1} \quad (5)$$

where $\mathbf{A_1}$ and $\mathbf{A_2}$ represent transformation matrices to transform a point from LCF_1 to GCF and from LCF_{11} to LCF_1, respectively. Similarly, DP of the counterbore hole can be transformed from GCF to LCF_{11} where:

$$\mathbf{p_1} = \mathbf{A_1}^{-1}\ \mathbf{A_2}^{-1}\,\mathbf{p} \quad (6)$$

4. Expert system

In most machining activities, the selection of cutting tools and determining machining parameters are still carried out manually by expert operators using extensive searching through catalogues and manuals, which requires expertise and time. Therefore, automation of these functions can be considered as essential for developing fully integrated CAD/CAM systems. In this work, an expert system has been developed which is capable of performing the above-mentioned functions. It assists user in designing machinable components, selection of cutting tools considering available tools resources, and determining initial machining parameters at the design stage. To accomplish this task, the system uses information restored in a number of databases and a knowledge base. Totally seventeen databases have been developed. Of these, nine databases are devoted to restoring the information of different types of cutting tools (face mills, end mills, drills, etc.). The other eight databases restore appropriate machining parameters (cutting speeds, feed rates, depths of cut, cutting fluids, etc.) recommended by machining handbooks and based on the type of operation, quality of the cutting tool and quality of workpiece material. Use of these databases in the expert system has many benefits such as:

- A limited number of rules have been developed for the knowledge base. A large number of rules should have been developed to determine required cutting tools and machining parameters for the operations if there were no databases linked to the system.
- Decreased required time for developing the knowledge base.
- Decreased running time for the expert system.
- Readability and easy accessibility to the information restored in the databases for updating purposes. This is specially useful for updating the information of available cutting tools since some of those may not be available occasionally.

The input to the expert system includes geometric characteristics of the operation and mechanical characteristics of the workpiece material. Its output includes appropriate cutting tools and machining parameters for the operation such as cutting speed, feed rate, depth of cut, and appropriate type of cutting fluid if required. These parameters will be determined for each step of machining operation. When a non-machinable feature is placed on the design, the expert system uses technological expertise restored in the knowledge-base, and issues a warning message to the user. It also assists user to redesign the feature in order to make it machinable. An example of non-machinable features is a pocket with sharp corners. In this case the system warns the user and requests him/her to define a fillet radius for the pocket no smaller than the radius of the smallest available end mill that can machine the feature.

As shown in Figure 3, the inference engine plays a central role in the expert system developed. It uses backward chaining where it actively integrates expertise rules restored in the knowledge base as if-then rules, with tooling and machining information restored in the databases. In order to reach its goal, the inference engine systematically searches for new values to assign to appropriate variables that are present in the knowledge base. Therefore, it has the capability of adding to the known store of knowledge. Inference engine fires appropriate rules from the knowledge base and extracts necessary information from the databases to select appropriate cutting tools and determine machining parameters for the operations.

5. Optimisation module

For improving machining efficiency in this system, an optimisation module has been developed which determines optimum machining parameters for each step of machining operation. This module is activated only if user wishes to use optimum machining parameters rather than those recommended by handbooks. Cutting speed, feed rate and depth of cut have the greatest effect on the success of a machining operation. Accordingly, these parameters have been considered as variables in developing the optimisation models. The maximum profit rate has been selected as the default objective function in this work. Maximum machine power, required surface finish and maximum cutting forces have been considered as the constraints. These models and constraints have been programmed in FORTRAN, and the optimisation method of *feasible directions* has been used to solve the problems. It is noteworthy that details of the optimisation module developed and its models have been published elsewhere [20].

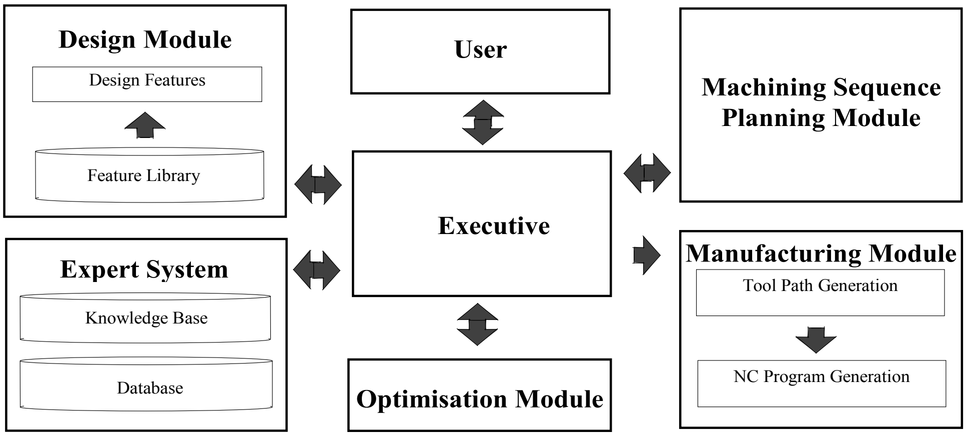

Fig. 1. Structure of the system developed

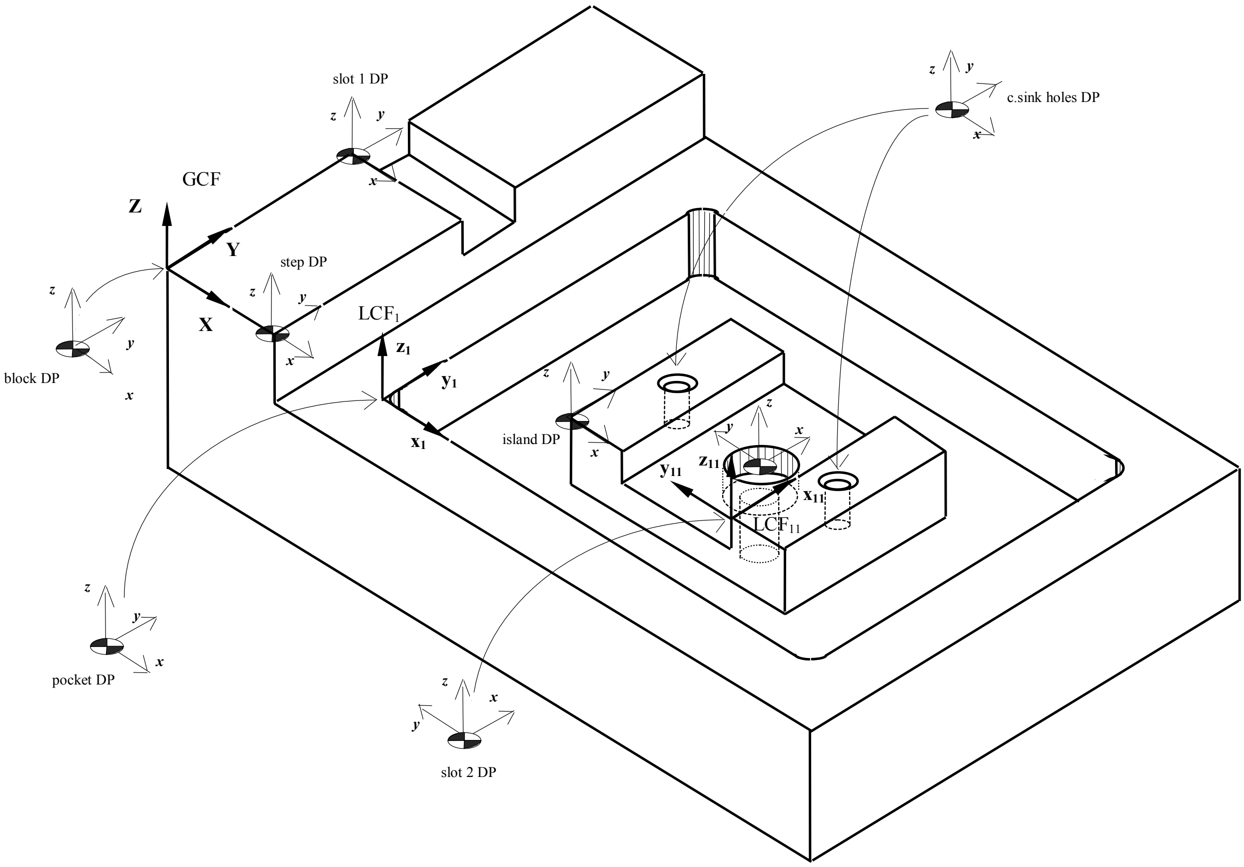

Fig. 2. The sample part

Optimum machining parameters resulted from this work have been put in practice and results showed to be satisfactory. It has been proven that the use of the optimum machining parameters significantly improves machining efficiency and reduces machining time and cost. This is of great importance where machining economy is of concern, specially when NC and CNC machines with high capital cost are in use.

6. Machining sequence planning module

Machining sequence planning is one of the most important functions in process planning activities. An algorithm has been developed for automatic machining sequence planning of the components designed by this system. The algorithm is based on the bilateral precedence between machining operations and generates feasible and optimal machining sequences, reducing machining cost and time. It puts machining operations in a definite order based on technological and geometric considerations such that the number of necessary tool changes becomes minimal. This algorithm has been described elsewhere [21].

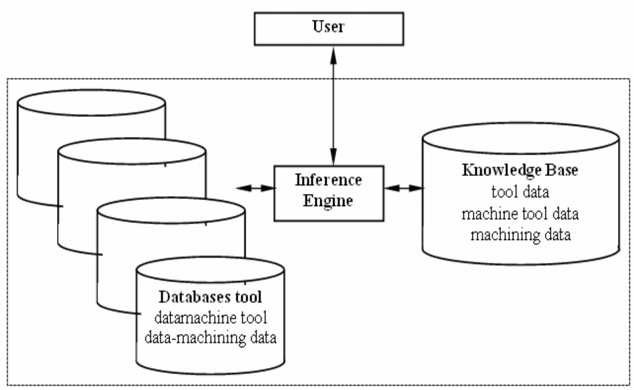

Fig. 3. Structure of the expert system

7. Manufacturing module

The system restores technological data determined by different components in the manufacturing data file (MDF) for use by the manufacturing module. MDF provides all necessary data for each step of machining operations that are required for NC program generation. An IGES file generated by the CAD system provides the geometric data. It is noteworthy that IGES is the most common method for data exchange in current CAD systems. Using these data, the manufacturing module generates required tool paths for each step of machining operation and determines all cutter locations. User can either accept generated tool paths or modify them. Upon confirmation of generated tool paths, the required NC program is generated using an existing post-processor. The NC machine to produce the product can then use the generated program.

8. Executive program

The executive program plays a central role in the system developed, as shown in Figure 1. The user is in touch with all components of the system only through this program. Upon running the system, user gets in touch with the executive program where he/she should determine the desired job from displayed menus. The executive program communicates with user and manages the operations of all components of the system, activates the design module for designing the product, and at the same time, helps the user in designing machinable features using the expertise rules restored in the knowledge base of the expert system. It also communicates with the expert system for determining cutting tools and initial machining parameters. Communication with the machining sequence planning module and optimisation module can be mentioned as other functions of the executive program. It collects data generated by all components of the system and restores them in a file using a specific format called ‘design representation scheme.’ This scheme is developed based on a group of LISP codes that represent mechanical components as a related set of features. Each component is represented using a group of pre-defined feature codes, together with mechanical information of the workpiece material, and geometric and topological information of its features in the following form:

```
(       (mechanical_data)
        (geometric_data)
        (co-ordinate_frames)
        (feature_tree)       )
```

This scheme gives a complete and unambiguous representation of the product that can be used for different purposes such as verification of generated process plans, NC program generation, fixture design and so on. Details of this representation scheme can be found elsewhere [19]. Based on the information restored in this file, the executive program generates the required MDF file to be used by manufacturing module for NC part program generation.

9. Case study

A number of test components have been designed and produced using the system developed. Results showed significant improvements in machining times and costs in design and machining of these components. For example, in producing the sample part shown in Figures 2 and 4 machining time and cost were reduced by 38% and 42% respectively. This resulted in a significant improvement in the total profit rate of about 350%, which increasing it from \$0.71/min to \$2.49/min.

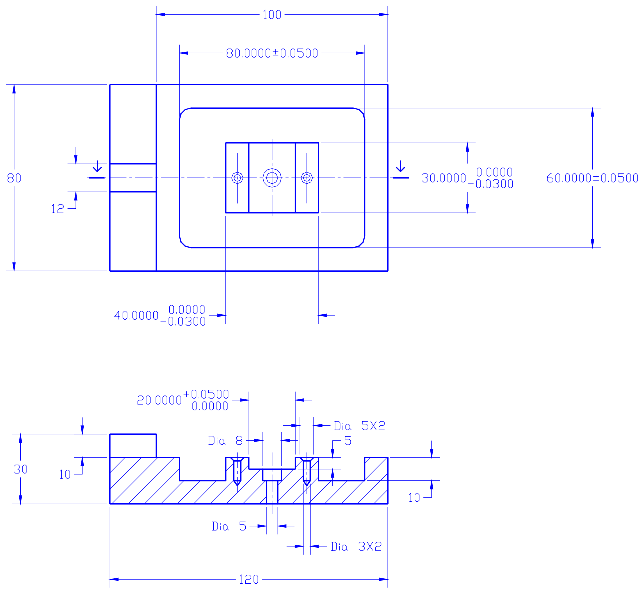

Fig. 4. The sample part dimentioned

10. Conclusions

In this work several goals have been achieved in the line of developing fully integrated CAD/CAM systems. Different components required for developing such systems have been identified and various problems that arose in the development of these systems have been dealt with, leading to an adequate basis for complete integration of CAD and CAM technologies. The system developed allows simultaneous generation of all information required to satisfy machining requirements of the design such as its machinability and availability of the required tooling resources. It thus integrates different areas of design and manufacturing, giving each area an appreciation of its role in the design process. It has been proven that use of this system results in considerable improvements in machining efficiency, time and cost.

Although much of the work described here goes beyond the scope of published literature, however, it should be noted that the system developed couldn't be considered as a complete solution to the CAD/CAM integration problem. Further work requires including other manufacturing activities that are considered in concurrent engineering concept. In this direction, further integration of the system developed with systems such as MRP, MRP II and assembly sequence planning packages are highly desirable.

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