STEP based Finish Machining CAPP System

Arivazhagan Anbalagan, Mehta NK, Jain PK

***Abstract*—**This research paper presents various methodologies developed in a STEP based Computer Aided Process Planning (CAPP) system named "Finish Machining – CAPP" (FM-CAPP). It is developed to generate automatic process plans for finish machining prismatic parts. It is designed in a modular fashion consisting of three main modules, namely (i) Feature Recognition module (FRM) (ii) Machining Planning Module (MPM) and (iii) Setup Planning Module (SPM). The FRM Module analyses the geometrical and topological information of the inputted part in STEP AP 203 / AP214 formats, and generates a text file with full dimensional details of features and machinable volumes. It is then passed on to the MPM for the selection of best suited machining process. Here, the selection is based on a 7 stage elimination strategy considering major manufacturing factors. After machining planning, the task of selecting the best suited setup is implemented in the SPM module. When these tasks are completed, the system generates the process-planning sheet containing the details of feature, finish cut machinable volume, machining processes with the cutting tool/ media, process parameters and the setup required for machining

Keywords **—** CAPP, Syntactic Pattern Recognition, Feature Recognition, Machinable Volumes.

I. INTRODUCTION

DUE to growing competition in the global market, manufacturing industries are striving to increase productivity by eliminating manual procedures followed in Process Planning (PP) and automating the activities with the help of computers. Generally, process planning is a task aimed at translating part design specifications from an engineering drawing into manufacturing operation instructions. Conventionally, an experienced process planner carries out this task manually and the output is in the form of planning sheets. The process planner studies the engineering drawing in respect of features, dimensions, tolerances, surface finish, material and production volume etc. and then decides the manufacturing processes, machine(s), tool(s), machining parameters, fixture(s) and sequence of operations. The manual process planning approach depends heavily on the experience of process planner. In all cases, the activity is highly subjective, cumbersome and tedious. Therefore, it requires personnel who are well trained and experienced in the manufacturing practices. Computer Aided Process Planning (CAPP) which is considered as a link between design (CAD) and manufacturing (CAM) is the new form of process planning technology. CAPP is defined as a coded form of process planner's knowledge to recognize the manufacturing features and selecting the suitable machine tools, machining parameters and setups for automatic generation of process plans [1, 2, and 3].

Arivazhagan Anbalagan is with the Indian Institute of Information Technology Design and Manufacturing, Kancheepuram, Centre of Excellence, MHRD Govt of INDIA, Melakottayur, Chennai - 600127 (phone: 91-44-27476358; fax: 91-44-27476358; e-mail: arivazhagan.a@iiitdm.ac.in).
Mehta NK, is with Indian Institute Technology Roorkee, Roorkee-247667, Uttarakhand, INDIA. (e-mail: mehtafme@iitr.ernet.in).
Jain PK is with Indian Institute Technology Roorkee, Roorkee-247667, Uttarakhand, INDIA. (e-mail: pjainfme@iitr.ernet.in).

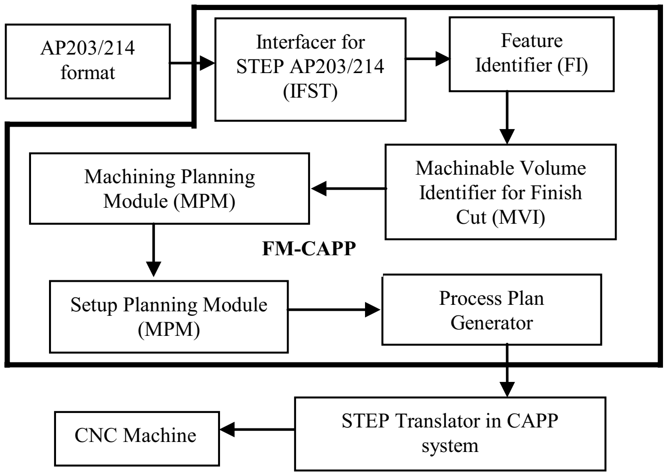

Fig.1 Schematic representation of FM-CAPP System

In the present work, a STEP based Computer Aided Process Planning system named "Finish Machining – Computer Aided Process Planning system" (FM-CAPP) has been developed for finish cuts to generate process plans automatically for prismatic parts (Fig.1). It consists of three modules, namely (i) Feature Recognition module (FRM) (ii) Machining Planning Module (MPM) and (iii) Setup Planning Module (SPM). The input to the FRM is through STEP AP 203 / AP214 formats. This module contains three sub modules for processing the information from the STEP formats. They are (i) Interfacer developed for STEP AP203/214 formats (IFST) (ii) Feature Identifier (FI) and (iii) Machinable Volume Identifier for Finish cut (MVI). In this research, a total of 276 features grouped under four hierarchical levels of 'feature-characteristics' have been considered for generation of process plans. They are (i) feature class (ii) nature of feature (iii) feature shape and (iv) type of taper. Of the 276 features 30 are normal and 246 are tapered. The tapered features that are considered have the following nine types of taper: (i) feature having taper at the top face of the part (ii) feature having taper at the base of the feature (iii) feature having taper at the base of the part (iv) feature having tapered walls in the feature (right wall, left wall and both) (v) feature having chamfer tapering towards the end (vi) feature having fillet tapering towards the end (vii) feature having taper at the side face of the part (right face ,left face and both) (viii) feature narrowing at the end (tapering at the base & tapering at the walls) and (ix) feature having more than one of the above individual tapered features.

When the data stored in the STEP format is inputted to the FRM, the sub module IFST gets activated, producing an B-Rep output file which contains the coordinate information related to the model. The sub module FI uses the B-Rep details extracted from STEP format to recognize the manufacturing features in the prismatic part. Initially, the FI adopts the syntactic pattern recognition technique to recognize the possible 'feature-characteristics' by matching the standard pattern strings developed for every feature. Using these strings the types of faces on the prismatic part are determined and edge loops are constructed.

The edge loops describe a feature by the information implicit in the details of the edges, vertices, coordinate points and directions. Using the edge loops and by checking the presence of similar edge loops on parallel faces, connectivity of faces between parallel edge loops the possible category of a feature is identified. Finally, IF-THEN rules developed for each 'feature-characteristics' are used to finalize the feature. The developed methodology identifies interacting, tapering, interacting-tapering, curved base features and tapering cross sections. Next, to calculate the machinable volumes of manufacturing features the sub module MVI utilizes the output of the feature recognizer which contains the information about the dimensional details, edge loops, edges, vertices, coordinate points and location planes of the features to calculate the machinable volumes.

For the 276 features considered in this research, generalized methodologies are developed for 17 basic 'feature-types' each consisting of a varying number of specific features. Initially, the pattern strings are generated for the front and back faces of the rough machined feature and final feature. Then MVI uses the pre-defined syntactic pattern strings stored in the strings data base and checks with the generated strings of the feature to determine the shape of the machinable volume. After determining the shape, one relevant methodology or more than one methodology (for features having combination of more than one taper) are selected from among the 17 'feature-type' - specific methodologies developed for finish cut machinable volume identification. The final output from this module is stored as a text file with full dimensional details of machinable volumes and passed on to the Machining Planning Module (MPM).

The MPM selects the best machining plan in terms of best suited machining processes along with the cutting media/tool and cutting conditions by analyzing the various parameters such as process capability, surface finish, production rate, cost, etc. associated with the prismatic part. For this, complete process capability details of traditional as well as 16 non traditional methods were compiled in a data base which is used for identification of all the relevant machining processes. The selection of the best machining processes from among the list of identified ones is based on an elimination strategy which is implemented step-wise considering 7 manufacturing factors.

After machining planning, the task of selecting the best suited setup is implemented in the SPM module. The setup planning approach adopted in this research consists of two stages namely (i) setup grouping and (ii) setup sequencing. In the first stage, setups are arranged based on features possessing a common tool approach direction and datum. The second stage arranges the features in each setup in the correct order by performing two checks namely (i) feature interaction (ii) datum and reference requirements. In this stage, the machining processes and operations linked with each setup are also sequenced based on the priority of the setups. Finally, an output, is generated which contains the best-suited setups for machining the features with their datum and tool approach direction. When these tasks are completed, the FM-CAPP system generates the process-planning sheet. The generated process planning sheet contains the details of feature, finish cut machinable volume, machining processes with the cutting tool/ media, process parameters and the setup required for machining. The following sections present step by step explanations to all the methodologies adopted in the FM-CAPP system.

II. Literatures related to Computer Aided Process Planning / Feature Recognition / Setup / Fixture Planning

Xionghui et al. [4] presented an approach to integrate CAD and CAPP using commercial systems. They focused on 5 key techniques to integrate CAD/CAPP/CAM, namely (i) feature parameters and constraints extraction (ii) feature precedence tree reconstruction (iii) technical information processing (iv) automatic process marking and (v) 3D material stock geometric model generation. Ismail et al. [5] presented a new algorithm to recognize features called edge boundary classification technique for recognition of conical features, through and blind holes, bosses and internal undercut. Jung and Aristides [6] developed a feature recognizer named If^2 that can interpret the part in terms of machining features by characterizing them as slot, step, V-groove etc. Hint based reasoning approach was used to recognize these features. Three implemented parts were explained to show the working logic of feature recognizer. Hebbal and Mehta [7-9] developed a feature recognition system for the CAPP system named CAPPS_PRINTER to identify prismatic parts and to calculate rough machinable volumes. He recognized primitive features of depression and protrusion type having both planar and inclined surfaces, certain complex features arising from interaction between primitive features and wide ranges of interacting features such as slot intersecting a slot, pocket in a step, pocket in a slot and blind step interacting with a through step. He adopted syntactic pattern recognition technique to develop methodologies for identifying primitive features (such as blind slot, through slot, blind step, w-slot etc.) and interacting features. The concept of edge loops has been used to check whether the feature is blind or through or interacting. Jain and Sharavan Kumar [10] identified the machining features from DXF format by using syntactic pattern recognition approach. An algorithm was developed and the working logic that calculates the size, location and shape of features present in prismatic part was presented. Jain [11] presented an approach to identify volumetric features from three-dimensional wire frame models for prismatic parts. In his system volumetric features such as slot, step, holes and interacting features such as slot in slot, slot in step combinations are identified. Jatinder Madan et al. [12] recognized protrusion / depression machining features for a die casted part from a CAD model using STEP format. In their work, they adopted geometric reasoning technique to recognize features and developed an automated parting direction and determined the parting line required for the process. Dereli and Filiz [13] used STEP AP-203 protocol for identifying the features from prismatic parts. In their approach, they first validated the models by means of Euler's law and derived a relation matrix. Attributed adjacency relationship graphs were used for identifying the faces of the part. After identification, they have considered roughness and tolerance specifications required for the finishing operations. In their publication, feature recognition was made for the whole CAD model. Jian and Sreedharan [14] have proposed an optimal volume segmentation approach for extracting features. The material to be removed from a blank known as elementary volume was grouped into manufacturing features and removed by a single tool path. Gao et al. [15] presented a feature based CAD/CAM integration system and discussed the difficulties faced during the integration. They focused on the hole-series features that are present in the gear box components. In their system they developed an approach to convert the design feature model into the machining feature model in order to realize the interest of feature based CAD and CAPP activities. Finally, they converted the whole data into a STEP format (AP224) and tested it with a CAPP system. Sharma and Gao [16] proposed a system for evaluating manufacturing related costs and time resources. The system incorporates STEP AP 224 for deciding these factors. They evaluated the design with respect to the available manufacturing processes and provided an option to create a feature library specific to a particular application or a part. Li et al. [17] developed a feature recognition processor to recognize manufacturing features from a design model. The processor recognized most of the features including protrusive features and bosses defined in STEP AP224 protocol with their rough machinable volumes.

Jain VK et al. [18] developed an interactive CAPP system for electric discharge machining process. In their system, they developed three modules to generate process plans for prismatic parts. The modules developed are (i) database module, which contains the details about various EDM machines (ii) component representation module where the size and shape of the blank and features are represented and (iii) planning module, where the operation to be carried out, dielectric supply at desired pressure and passes with fixtures are decided. An approach has been proposed by Chen et al. [19] to carry out setup planning for prismatic parts to be machined on a 3-axis vertical machining centre using hopfield neural net coupled with simulated annealing. In another work, Hebbal [20] carried out setup & fixture planning, grouping of setups from machining and fixturing viewpoints for the traditional machining processes namely drilling, milling, slotting and shaping .

Zhou et al. [21] developed an interfacing application to integrate a setup planning system with a feature based CAD system. Ong & Chew [22] presented an approach on setup planning for evaluating manufacturability of machined parts. They developed a Machinability and Fixturability Evaluation System (MFES) to derive quantitative machinability and fixturability for the part. The setup plan evaluation is performed considering the machining and setting up times and tool changes for the setups. Ming & Mak [23] presented an approach to identify setups automatically using neural networks. Kohnen-Self organizing neural network is utilized according to the nature of the different steps in setup planning to generate setups in terms of the constraints of fixtures/jigs, approach directions, feature precedence relationships & tolerance relationships. Then the operations sequence problem and the setup sequence problem are mapped onto the traveling sales man problem and solved by Hopfield neural networks.

A tolerance normalization approach has been presented by Hang & Liu [24] to provide an accurate means for direct comparison of different geometrical and dimensional tolerances. The different types of geometrical tolerances considered are parallelism, perpendicularity, angularity, position, concentricity, symmetry, run out (circular and total) and profile tolerances such as profile of a line and profile of a surface. Setup planning has been carried out by Huang et al. [25] for rotational parts by following a graph based theoretical approach using tolerance analysis. Initially the design specification of a part is represented as a graph. Then the problem of identifying the optimal setup plan is transformed into a graph search problem. One more approach to automate setup planning is presented by Wu & Chang [26] using tolerance analysis. An object oriented fuzzy set based approach is presented by Wu & Zhang [27] for carrying out set up planning in prismatic parts. Contini & Foli [28] proposed a near-optimal setup plans for prismatic work pieces having multiple parts to be mounted on the same pallet in machining centers. In their approach, setups are determined by considering accessibility of machining direction of the work piece and the technological constraints among the required operations.

III. INTERFACER DEVELOPED FOR STEP AP203/214 FORMATS

Extraction of necessary B-Rep data required for feature recognition is considered as one of the main task while integrating Computer Aided design (CAD) with Computer Aided Process Planning (CAPP). This section concentrates on developing a standard interfacing methodology for a standard neutral format known as Standard for Exchange of Product Data (STEP).

The flow diagram of the Interfacer for STEP AP203/214 formats as developed in the present work is shown in Fig. 2. It contains a main module comprising AP203/214 Database

(APD), Hierarchy Tree Tracer (HTT), Hierarchy Tree Database (HTD), STEP file ID storage (SIS), STEP File ID Access Module (SIDA) and Temporary Storage (TS). Six hierarchical modules (Hierarchical Level I-VI) with the separate sub modules serve to extract the geometrical and topological ID's from the STEP formats. The interfacer works on the principle of subdivision and extraction of entities present in the STEP file for the recognition of manufacturing features. The details of various modules developed are based on the geometrical and topological entities present in the STEP formats. Already the details for these entities and extraction procedures are easily available in many handbooks [29]. Hence, the outputs of various modules that are accessed and used in IFST are presented separately under in the section 5.

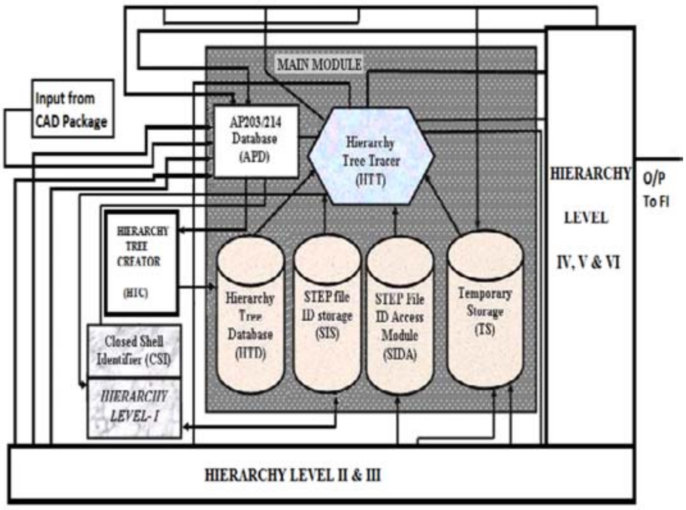

Fig.2. Interfacer for STEP AP203/214 formats (IFST)

After the extraction of necessary data from the STEP formats, the IFST passes the information to the next sub module FI for identification of the features with normal, tapered and curved base cross sections. The next section explains how the data is utilized to identify the features using the syntactic pattern recognition methodology.

IV. FEATURE RECOGNITION OF PRISMATIC PARTS WITH NORMAL, TAPERED AND CURVED BASE CROSS SECTIONS

The initial implementation to develop a feature recognizer has been already completed by [5] for rough machining by adopting a DXF format. The rough machined part and the final part details from the STEP AP203/214 formats extracted by the interfacer (IFST) described in previous section are inputted to the feature recognizer, which adopts the syntactic pattern recognition technique to recognize the part features present in the rough machined part and final part.

In this research, a feature recognizer has been developed which is capable of identifying the combinations of different shapes of features differentiated on the basis of slot, step and pocket/hole. The feature recognizer is capable of recognizing 30 normal features and with 9 types of tapers. The names of 30 normal features and 9 types of tapers are coined by following the schematic representation given in Fig. 3. The schematic representation of the normal features is already given in [20] and can be seen from standard sources [30].

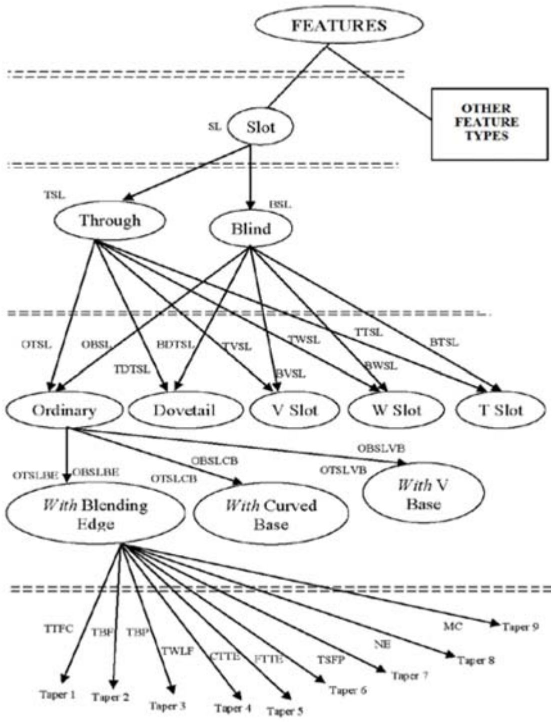

Fig. 3 Schematic representation of hierarchy tree of features

V. CONCEPTS ADOPTED FOR FEATURE RECOGNITION

A brief overview of all the basic concepts adopted for feature recognition of prismatic parts has already been presented by Hebbal S & Mehta NK [7]. Moreover, all these standard concepts such as pattern primitives and strings are well known and can be referred from standard handbooks [30]. In this section the IF THEN rules that are framed to determine the four different levels of feature characteristics are presented. These rules frame the base to differentiate the features and its characteristics.

Logic for IF THEN rules to determine the feature class

IF (L1 = L2, OH1 = OH2, W1 = W2, OW1 = OW2, OL1 = OL2, H1 = H2, and R1 & R2 > 0 or LW1 & LW2 > 0 or CP1 & CP2 > 0 or W1 & UW1 > 0 or W2 & UW2 > 0 or BW1 & BW2 > 0) THEN (Feature Class = Slot Class)

IF (L1 = L2, OH1 = OH2, W1 = W2, OW1 = OW2, OL1 = OL2, H1 = H2 and BFH1 & BFH2 > 0 or IWW1 & IWW2 > 0 or R1 & R2 > 0 or IFH1 & IFH2 > 0 or BW1 & BW2 > 0)

THEN (Feature Class = Step Class)

IF (OL1 = OL2, OH1 = OH2, OW1 = OW2 and W1 & W2 > L1 & L2 or W1 & W2 = 0, L1 & L2 = 0, R1 & R2 > 0)

THEN (Feature Class = Pocket / Hole Class)

Logic for IF THEN rules to determine the nature of feature

Slot Class & Step Class

IF (L1 & L2 = OL1 & OL2) THEN (Feature Type =

Through)

IF (L1 & L2 < OL1 & OL2) THEN (Feature Type = Blind)

Pocket / Hole Class

Rectangular Shape:

IF (H1 & H2 = OH1 & OH2) THEN (Feature Type = Through)

IF (H1 & H2 < OH1 & OH2) THEN (Feature Type = Blind)

Circular Shape:

IF (H1 & H2 = OH1 & OH2) THEN (Feature Type = Through)

IF (H1 & H2 < OH1 &OH2) THEN (Feature Type = Blind)

Logic for IF THEN rules to determine the feature shape

Slot class

1. IF (L1 = L2, OH1 = OH2, W1 = W2, OW1 = OW2, OL1 = OL2, H1 = H2, R1 & R2 = 0, LW1 & LW2 = 0, CP1 & CP2 = 0, W1 = UW1, W2 = UW2, BW1 & BW2 = 0 and L1 & L2 = OL1 & OL2) THEN (Feature Shape = Ordinary Through Slot – OTSL)

1.1 IF (R1 & R2 > 0) THEN (Feature Shape = Ordinary Through Slot with Curved Base – OTSLCB)

1.2 IF (BW1 & BW2 > 0, W1 > W2) THEN (Feature Shape = Ordinary Through Slot with Blending Edge – OTSLBE)

1.3 IF (BW1 = BW2 & W1 & W2 = UW1 & UW2, CP1 & CP2 = OW1 / 2 & OW2 / 2) THEN (Feature Shape = Ordinary Through Slot with V Base – OTSLVB)

2. IF (L1 = L2, OH1 = OH2, W1 = W2, OW1 = OW2, OL1 = OL2, H1 = H2, R1 & R2 = 0, LW1 & LW2 = 0 , CP1 & CP2 = 0, W1 = UW1 , W2 = UW2, BW1 & BW2 = 0 and L1 & L2 < OL1 & OL2) THEN (Feature Shape = Ordinary Blind Slot – OBSL)

3. IF (W1 < UW1, W1 < UW2, BW1 & BW2 = 0 and L1 & L2 = OL1 & OL2) THEN (Feature Shape = Through W-Slot – TWSL)

Pocket / Hole Class

1. IF (W1 = W2, H1 = H2, L1 = L2, OH1 = OH2, OW1 = OW2 and H1 & H2 = OH1 & OH2) THEN (Feature Shape = Through Rectangular Pocket / Hole – RTPH)

2. IF (W1 = W2, H1 = H2, L1 = L2, OH1 = OH2, OW1=OW2 and H1 & H2 < OH1 & OH2) THEN (Feature Shape = Blind Rectangular Pocket / Hole – RBPH)

3. IF (R1 = R2, OH1 = OH2, OW1 = OW2, H1 = H2, W1 & W2 = 0, L1 & L2 = 0 and H1 = OH1 & OH2) THEN (Feature Shape = Through Circular Hole / Pocket – CBHP).

VI. METHODOLOGY TO DETERMINE NORMAL AND TAPERED FEATURES

The methodology to determine the normal and tapered is a general 3 step procedure where the points are projected towards their parallel faces and the collinearity is calculated. Then the decision is made as tapered if the points are not collinear. The concept has already been given in [31] and can be deducted from standard mathematical text books. The steps followed are given here:

Step 1: Project the point on the face to the parallel edge loop

Step2: Match the Points with the parallel face / edge loops

Step 3: Find the collinearity between points to confirm the normal or tapered feature by the following equation:

Three or more points P1, P2, P3,... are said to be collinear, if they satisfy the following equation of straightness:

$X_2 - X_1 : Y_2 - Y_1 : Z_2 - Z_1 = X_3 - X_1 : Y_3 - Y_1 : Z_3 - Z_1 \ldots$ (1)

If the condition is satisfied then the feature is a normal feature, otherwise it is a tapered feature.

Logic for IF THEN rules to determine the type of taper

1. IF (OH1 < OH2 & H1< H2) THEN (Type of Taper = feature having taper at the top face of the part – TTFC)

2. IF (H1 > H2, L1 = L2) THEN (Type of Taper = feature having taper at the base of the feature – TBF)

3. IF (OH1 > OH2, H1 = H2) THEN (Type of Taper = feature having taper at the base of the part – TBP)

4. IF (W1 > W2, L2 = L1) THEN (Type of Taper = feature having tapered walls in the feature (right wall, left wall and both) – TWLF)

5. IF (CH1 > CH2, H1 > H2, W1 > W2) THEN (Type of Taper = feature having chamfer tapering towards the end – CTTE)

6. IF (W1 >W2, W1+R1 = UW1, OW1 = OW2) THEN (Type of Taper = feature having fillet tapering towards the end – FTTE)

7. IF (OW1 > OW2, W1=W2) THEN (Type of Taper = feature having taper at the side face of the part (right, left and both) – TSFP)

8. IF (W1 > W2, H1 > H2) THEN (Type of Taper = feature narrowing at the end (tapering at the base & at the walls) – NE)

9. IF (any of the above combinations occur) THEN (Type of Taper = feature having more than one of the above individual tapered features – MC).

By using these methodologies, the Feature Identifier (FI) generates the data in the text file and passes the information to the next module namely the Machinable Volume Identifier for Finish cut (MVI) for further processing. In the next section the general steps followed by the feature recognizer is summarized.

VII. GENERAL STEPS FOLLOWED BY THE FEATURE RECOGNIZER TO RECOGNIZE NORMAL AND TAPERED FEATURES

Step1: Input the data (extracted by the interfacer (IFST)) of the rough machined part and the final part to the feature identifier.

Step2: View the part from XY, YZ & ZY directions and identify the faces parallel to these planes.

Step3: Identify the type of faces on these planes by adopting the standard pattern strings developed for the purpose. Then group the faces either as face with edge loops or face without edge loops.

Step4: Implement the concept of edge loops and identify the manufacturing features.

Step5: Match the parallel edge loop in the same plane and recognize the possible category for the first three hierarchical levels of 'feature-characteristics'

Step6: Implement the IF-THEN rules to make the final confirmation for the first three hierarchical levels of 'feature-categories'

Step7: Identify whether the feature is normal or tapered.

Step8: Implement the IF-THEN rules and confirm the type of taper belonging to the fourth hierarchical level of 'feature-characteristics'

Step9: Finally, calculate the taper angle

VIII. MACHINABLE VOLUME IDENTIFIER FOR FINISH CUT (MVI)

The output data of the feature recognizer in terms of edge loop data, edge and vertex data, coordinate points and plane information serves as the input for the MVI. While calculating machinable volumes, there may be many combinations of features in a prismatic part including those with interactions of normal features and tapered features. Hence, during this process, standard dimensional details are used to describe the volume. They are length (l), width (w), height (h) and thickness (t).

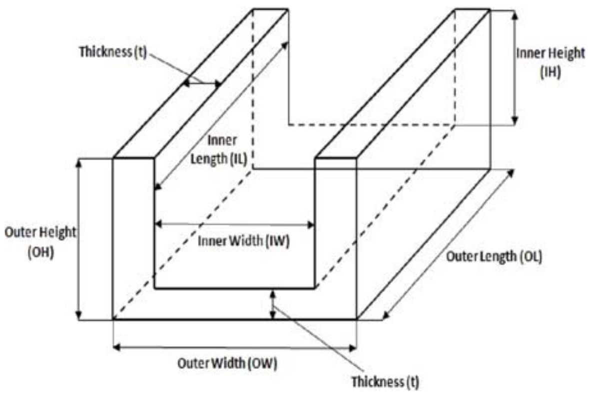

Fig. 4 Machinable volume details for a through slot

TABLE I
CHARACTERISTIC OF '5' OUT OF 17 'FEATURE-TYPES'

S.No	Name of the 'feature-type' and number of applicable features	Characteristic parameters : (edges (e) , face (f), parallel face (pf), radius (r), fillet radius (fr), curved base (cb), curved corners (cc), chamfer (c))
1	Through step - 21	e - 4
2	Through slot - 21	e - 6
3	Blind step - 21	e - 3; pf - 1
4	Through slot with filleted corners - 6	e - 6; fr - 4
5	Through slot with blending edge - 14	e - 10

Further to describe the machinable volume's inner and outer dimensions the following notations has been introduced: (i) Outer Length (OL) and Inner Length (IL) (ii) Outer Width (OW) and Inner Width (IW) (iii) Inner Height (IH) and Outer Height (OH) and (iv) Thickness (t) is the value obtained by deduction of the rough machined part from the final part. Figure 4, shows the schematic representation of these dimensional details. Basically, there are 17 basic 'feature-types' methodologies which are able to identify all the features considered in this research. Table I shows '5' basic 'feature-types' from a list of '17' to identify the finish cut volume.

IX. GENERAL METHODOLOGY TO IDENTIFY THE FEATURES AND CALCULATION OF FINISH CUT MACHINABLE VOLUME

The steps applicable to the present work are discussed below:

Steps for calculation of finish cut machinable volume

Step 1: Identify the shape of the finish cut machinable volume by separating the information of rough machined part and final part.

Step 2: Identify whether the features are interacting or non-interacting

Step3: Reconstruct the interacting feature as a sum of the constituent features.

Step 4: Calculate the finish cut machinable volume by identifying the suitable 'feature type' specific methodology based on the number of edges, faces, fillet radius, chamfer radius etc.

Step5: Display the final results with the dimensional details of the machinable volumes.

X. DESCRIPTION OF 'FEATURE-TYPE' SPECIFIC METHODOLOGIES FOR FINISH CUT CALCULATION

Feature-type: through slot with curved base: This section presents the details of finish cut machinable volume calculation for one sample feature type "Through Slot with curved base" from among the '5' listed in Table I.

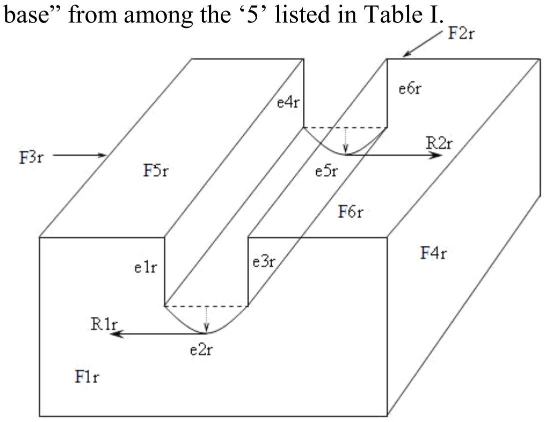

Fig. 5 Rough machined part

Fig 5 represents a rough machined part by means of edge loops and faces. The final part is not shown as it contain the same shape but including the finish cut volume and with a sub script 'f'. The machinable volume contains the following dimensions to represent the volume: length (l) width (w), thickness (t) & height (h). The methodology adopted to calculate these details for the feature type 'though slot with curved base' is as follows:

Initially the strings are generated for the front and back face by following the predefined vector as shown Fig.6. The generated string for this feature type is "BIDCBJDC". The details of machinable volume and the pre-defined vector direction are also shown Fig.6.

Height (h): From the above figure the height (h) of the machinable volume is calculated in a similar procedure of slot class features, the difference is that by including the radius of the base of the slot. The edges e1r, e2r, e3r of edge loop EL1r and e4r, e5r, e6r of edge loop EL2r and edges e1f, e2f, e3f of edge loop EL1f and edges e4f, e5f, e6f of edge loop EL2f are considered.

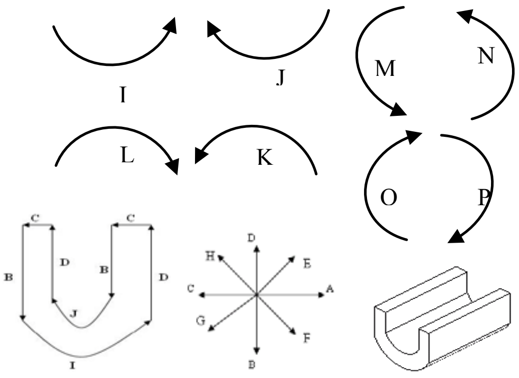

Fig. 6 Pre-defined vector & machinable volume for through slot with curved base

Calculation of height for rough machined part:
Height (h) = e1r + Radius of Curve R1r = [(X0r, Y0r, Z0r) – (X1r, Y1r, Z1r)] + R1r = IH
e3r + R1r = [(X2r, Y2r, Z2r) – (X3r, Y3r, Z3r)] + R1r = IH
e4r + R2r = [(X4r, Y4r, Z4r) – (X5r, Y5r, Z5r)]+R2r = IH
e6r + R2r = [(X6r, Y6r, Z6r) – (X7r, Y7r, Z7r)] + R2r = IH
Calculation of height for final part:
Height (h) = e1f + Radius of Curve R1f = [(X0f, Y0f, Z0f) – (X1f, Y1f, Z1f)] + R1f = OH
e3f + R1f = [(X2f, Y2f, Z2f) – (X3f, Y3f, Z3f)] + R1f = OH
e4f + R2f = [(X4f, Y4f, Z4f) – (X5f, Y5f, Z5f)] + R2f = OH
e6f + R2f = [(X6f, Y6f, Z6f) – (X7f, Y7f, Z7f)] + R2f = OH
Length (l): To calculate length (l), the edges e1r, e4r, of EL1r & EL2r and edge se3r, e6r of EL1r & EL2r and the edges of the final feature e1f, e3f, e4f, e6f of EL1f & EL2f are considered.
Calculation of height for rough machined part:
L = e1r – e4r = [(X0r, Y0r, Z0r) (X1r, Y1r, Z1r) – (X4r, Y4r, Z4r) (X5r, Y5r, Z5r)] = IL
e3r – e6r = [(X2r, Y2r, Z2r) (X3r, Y3r, Z3r) – (X6r, Y6r, Z6r) (X7r, Y7r, Z7r)] = IL
Calculation of height for final part:
e1f – e4f = [(X0f, Y0f, Z0f) (X1f, Y1f, Z1f) – (X4f, Y4f, Z4f) (X5f, Y5f, Z5f)] = OL
e3f – e6f = [(X2f, Y2f, Z2f) (X3f, Y3f, Z3f) – (X6f, Y6f, Z6f) (X7f, Y7f, Z7f)] = OL

Width (W): In these type of feature the width is directly taken as the twice of the radius of the base curve obtained from the feature recognizer
Calculation of width for rough machined part:
W = R1r * 2 and R2r * 2 = IW
Calculation of width for final part:
W =R1f *2 and R2f * 2 = OW
Thickness (t): To find the thickness, edge loops EL1r, EL2r and EL1f, EL2f are considered. The vertex points of edges from rough to final are deducted.
EL1r- EL1f = [(e1r, e2r, e3r) – (e1f, e2f, e3f)]
[(X0r, Y0r, Z0r) (X1r, Y1r, Z1r), (X1r, Y1r, Z1r) (X2r, Y2r, Z2r) (R1r), (X2r, Y2r, Z2r) (X3r, Y3r, Z3r)] – [(X0f, Y0f, Z0f) (X1f, Y1f, Z1f), (X1f, Y1f, Z1f) (X2f, Y2f, Z2f) (R1f), (X2f, Y2f, Z2f) (X3f, Y3f, Z3f)]
EL2r- EL2f = [(e4r, e5r, e6r) – (e4f, e5f, e6f)]
[(X4r, Y4r, Z4r) (X5r, Y5r, Z5r), (X5r, Y5r, Z5r) (X6r, Y6r, Z6r) (R2r), (X6r, Y6r, Z6r) (X7r, Y7r, Z7r)] – [(X4f, Y4f, Z4f) (X5f, Y5f, Z5f), (X5f, Y5f, Z5f) (X6f, Y6f, Z6f) (R2f), (X6f, Y6f, Z6f) (X7f, Y7f, Z7f)].

XI. MACHINING PLANNING MODULE (MPM)

The next task after calculating the finish cut machinable volumes is to select the best suited machining processes with their cutting media/tool and cutting conditions. This is done by analyzing the various parameters such as process capability, surface finish, production rate, cost, etc. associated with the prismatic part. Then based on these parameters, a final machining plan is created. To create a best machining plan by considering all the above constraints, complete process capability details of both the traditional and non-traditional methods are compiled. In the process capability study the details of Tolerance IT grades & Surface Finish are compiled for both rotational and flat surfaces from standard sources. With these data as the base for this work, a seven level elimination strategy has been created to shortlist the best suited machining process. They are:
(i) compatibility of the previous machining process for finish machining (to reduce the number of setup and the manufacturing time) by considering the required surface finish and tolerance of the features
(ii) volume of material to be removed to decide the type of operation
(iii) previously adopted machining processes
(iv) features to be machined (based on feature class and code)
(v) work piece material
(vi) suitability of economic and environmental aspects and
(viii) effects of surface integrity alterations.

The MPM shortlists and passes on the information to the next module 'SPM' through a text file for generation of best suited setup.

XII. SETUP PLANNING MODULE (SPM)

After machining planning, the task of selecting the best suited setup is carried out by the Setup Planning Module

(SPM) to machine the features in the part. The next section explains the general methodology adopted in setup planning.

XIII. GENERAL METHODOLOGY ADOPTED IN SETUP PLANNING

Setup grouping

The grouping of setups is carried out in the following steps:

Step1: Identify the location plane for each feature.

While carrying out setup planning the location plane of the feature should be identified. The location plane is determined by considering the feature edges in the respective faces of the part.

Step2: Identify the datum for each feature.

After identifying the location of the feature, the datum is determined. Here the face of the part parallel to the floor of the feature is taken as the datum.

Step3: Identify the tool approach direction and separate the features having a common tool approach direction. This step is implemented through the following sub steps:

Step4: Identify the features possessing a common datum.

Here, from step 2 the features having the common datum are identified.

Step5: Group the features having common tool approach direction and datum into a setup.

In this stage, the features having the common tool approach direction and datum are grouped into a single setup. Likewise all the features are grouped into setups.

Setup Sequencing

After grouping, the setups have to be sequenced so that the machining is conducted in a proper manner. While sequencing two checks namely (i) feature interaction and (ii) datum and reference analysis are performed. The forthcoming sections provide the general methodology for performing these checks.

Step 6: Identify the interacting features and group them separately accordingly to the number of interactions.

Step 7: Analyze the datum and the reference dimensions linked with the prismatic part and group the features into setups.

Step 8: Finally, group the features into separate setups as per the above sequence of interaction and reference requirements and create the final process plan.

XIV. CASE STUDY

The prismatic part shown in Figures.7 (a) and (b) contains eight features namely (i) Blind Dovetail Slot Narrowing at the End [BDSLNE] – FT1 (ii) Through W Slot Narrowing at the End [TWSLNE] – FT2 (iii) Through Circular Pocket Narrowing at the End [TCPNE] – FT3 (iv) Ordinary Through Step with Blending Edge Narrowing at the End [OTSBENE] – FT4 (v) Ordinary Through Slot Narrowing at the End [OTSLNE] – FT5 (vi) Blind Circular Hole /Pocket [BCHP] – FT6 (vii) Through Rectangular Pocket Narrowing at the End [TRPNE] – FT7 and (viii) Ordinary Through Slot with Curved Base Narrowing at the End [OTSLCBNE] – FT8. The features FT1, FT4, FT7, and FT8 are tapered features, which are narrowing at the end. It means that these features have a tapering base and tapering walls both. The feature FT5 has a tapered base towards the end, while FT6 is an ordinary straight feature.

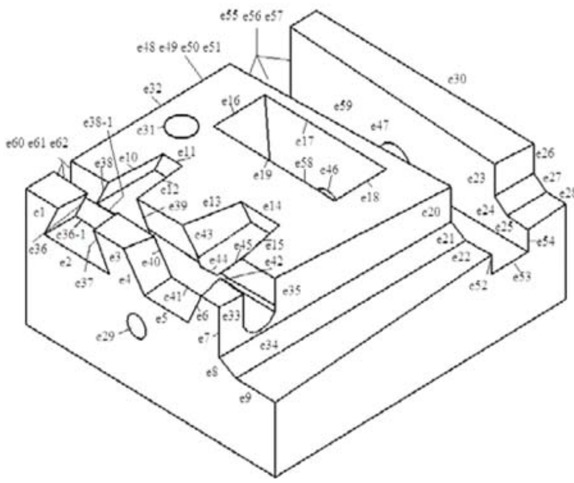

Fig. 7 (b) Prismatic part showing the details of edges

Sub Step 1.3: The location of edges representing the features FT1, FT2, FT3 and FT4 is identified in XY plane.

Sub Step 1.4: finally, the plane location for the features FT1, FT2, FT3 and FT4 is identified as XY plane. The details of other features when viewed from YZ and ZX directions are given in Table II.

Step 2: Identify the datum for each feature

Sub Step 2.1: The edges representing the base of the features FT1, FT2, FT3 and FT4 are identified as e2, e5 and e9.

Sub Step 2.1: Initially, for the feature, the face connecting the parallel edges of the base is identified. Then the face of the part parallel to the face connecting the parallel edges of the base of the feature is identified.

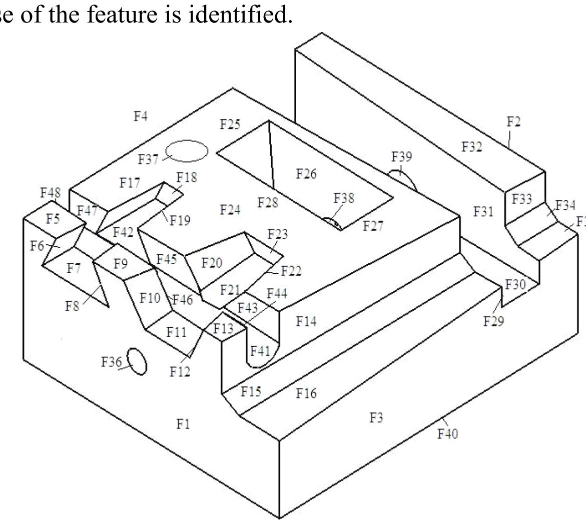

Fig. 7 (c) Prismatic part showing the details of faces

For the given part, the datum of each feature with its plane location is given below: (i) For FT1: Connecting faces: F7, F42; Parallel face of the part: F40; Plane: XZ (ii) For FT2: Connecting faces: F11, F21; Parallel face of the part: F40; Plane: XZ (iii) For FT3: Connecting face: F16; Parallel faces of the part: F3 & F4 ; Plane: XY (iv) For FT4: Connecting face: F16; Parallel faces of the part: F40 & F24; Plane: XZ

Step 3: Identify the tool approach direction and separate the features having a common tool approach direction.

The tool approach direction of each feature is determined by seeing direction of the tool access on front or back faces of feature parallel to the XY plane. The tool approach direction of these features is either in +Z or –Z directions. Further, in this step the perpendicularity and parallelism constraints that should be maintained while tool is approaching the feature(i) Face F3 – YZ plane ║to Face F4 – YZ plane, Face F4 – YZ plane ┴ to F1 F2, Face F3 – YZ plane ┴ to Faces F1& F2 (ii) Face F1 – XY plane ║ to Face F2 – XY plane, Face F1 – XY plane ┴ to Faces F3 & F4(iii) Face F40 – XZ plane ║ Face F24, Face 40 – XZ Plane ┴ with Faces F3 & F4.

The features that have common tool approach directions are: (a) FT1, FT2 and FT4 having +Z, -Z and +Y as their tool approach directions (b) FT6, FT7 having +Y, -Y as their tool approach directions (c) FT5, FT8 having +X, -X, +Y as their tool approach directions and (d) FT3 having +Z, -Z as tool approach direction. The features that have common tool approach directions are: (a) FT1, FT2 and FT4 having +Z, -Z and +Y as their tool approach directions (b) FT6, FT7 having +Y, -Y as their tool approach directions (c) FT5, FT8 having +X, -X, +Y as their tool approach directions and (d) FT3 having +Z, -Z as tool approach direction.

TABLE II
DETAILS FROM THE FEATURE RECOGNITION MODULE

S.No	Feature Name	Location in the Plane	Thickness of Finish Cut Machinable Volume (mm)
1	Blind W Slot Narrowing at the End [BWSLNE] – FT2	XY Plane	h= 28.93, 11.93, 24.89, 8.35; w = 45.22, 22.78, 41.32, 19.58; l = 101.93, t = 3.2
2	Blind Dovetail Slot Narrowing at the End [TDSLNE] – FT1	XY Plane	h= 28.93, 17.72, 25.87, 13.87; w = 67.19, 39, 63.37, 34.37; l = 82.16, t = 2.8
3	Through Circular Pocket Narrowing at the End [TCPNE] – FT3	XY Plane	l = 300; t=1.8
4	Ordinary Through Step with Blending Edge Narrowing at the End [OTSBENE]- FT4	XY Plane	h= 51.33, 33.95, 47.35, 30.87, t=2.8, l= 300, w= 58.29, 33.19, 55.65, 30. 45

Step 4: The features possessing a common datum in the same plane are (i) FT1, FT2, FT4, FT6, FT7, FT5, FT8: Face F40 – XZ Plane (ii) FT3: Face F1–XY Plane,

Step 5: Features having common tool approach directions & datum are:

(i)FT1, FT2, FT4 (ii) FT6, FT7 (iii) FT5, FT8 and (iv) FT3

Setup sequencing

After grouping, the setups have to be sequenced so that the machining is conducted in a proper manner. While sequencing two checks namely (i) feature interaction and (ii) datum and reference analysis are performed. The forthcoming section provides the details of all these checks. Finally, the through circular hole (FT6) and tapered through rectangular pocket (FT7) are machined.

TABLE III
A PARTIAL LIST OF PROCESS PLAN GENERATED FOR THE CONSIDERED PART

S.No	Feature Name & Feature Code	Details of Finish Cut Machinable Volume (mm)& Setup details	Best Suited Machining Processes & Details of Machine Type / Sequence of Operations with other details
1	Blind W Slot Narrowing at the End [BWSLNE]	h= 28.93, 11.93, 24.89, 8.35; w = 45.22, 22.78, 41.32, 19.58; l = 101.93, t = 3.2; Setup 1 FT2	Electro discharge machining (EDM) Charmilliesus Roboform 2400QCRi **Semi Finishing:** Pressure, psi: 5 – 8; Capacitance μF: 5 – 24; Frequency: kHz: 16- 20; Voltage (open circuit), V: 15-40; Avg.Current, A: 5-10; **Preferred Finishing :** Pressure, psi: 8 – 9; Capacitance μF: 24- 28; Frequency: kHz: 20-100; Voltage (open circuit), V: 40 - 70; Avg.Current, A: 10-25; **Super Finishing :** Pressure, psi: 9 – 10; Capacitance μF: 28- 56; Frequency: kHz: 100- 250; Voltage (open circuit),V: 70-80; Avg.Current, A: 25-30; Polarity on Electrode : negative; **Dielectric type :** Texaco 499, Eloxal Oil, Spray Flushing Hansvedt SE-290 Oil, **Electrode material:** Copper Tungsten, Silver Tungsten, Tungsten, Tungsten Carbide, steel
2	Blind Dovetail Slot Narrowing at the End [BDSLNE]	h= 28.93, 17.72, 25.87, 13.87; w = 67.19, 39, 63.37, 34.37; l = 82.16, t = 2.8; Setup 1 FT1	
3	Ordinary Through Step with Blending Edge Narrowing at the End [OTSBENE]	l = 300; t=1.8; Setup 1 FT4	
4	Ordinary Through Slot with Curved Base Narrowing at the End [OTSLCBNE]	h= 51.33, 33.95, 47.35, 30.87, t=2.8, l= 300, w= 58.29, 33.19, 55.65, 30. 45; Setup2 FT8	
5	Through Rectangular Pocket / Hole Narrowing at the End [TRPHNE]	h= 70.51, 56.97, 68.21, 54.39, t=1.3, l= 257.53, w= 62.53, 37.79, 60.71, 35.41; Setup 3 FT7	

The orders of features after analyzing the datum, reference and tolerances are (i) Tapered Through Step (FT4) (ii) W-Slot (FT2) (iii) Dovetail Slot (FT1) (iv) Tapered Through Circular Hole (FT3)(v) Tapered Through Slot with Curved Base (FT8) (vi) Tapered Through Slot (FT5) (vii) Through Circular Hole (FT6) (viii) Tapered Through Rectangular Pocket (FT7).

Final setups with the features to be machined:

(i) Setup 1: (with Face F40 – XZ Plane); Features FT4, FT2 and FT1 (ii) Setup2: (with Face F40 – XZ Plane); Features FT5, FT8 (iii) Setup 3: (with Face F40 – XZ plane as datum); Features FT6, FT7 (iv) Setup4: (with Face F2 – XY Plane as datum); Feature FT3

After deciding the final setup the machining plan is incorporated with the setups and is reproduced in Table III as the final process plan.

XV. Conclusions

In this work a CAPP system named FM-CAPP system containing three modules has been developed to generate process plans for finishing operations. These modules impart to the developed FM-CAPP system, the capability to deal with the whole gamut of aspects of process planning starting from feature recognition to setup planning, unlike most of the existing systems whose scope is restricted. The salient features are summarized in the form of following concluding remarks:

(i) The FRM module interlinks the CAD package with the CAPP system through a standard product data exchange (STEP) by identifying new complex features (having normal, tapered, curved base and their interaction) and to calculate the finish cut machinable volume.

(ii) The machining planning module (MPM) selects the best suited machining process based on a seven level elimination strategy to perform finish machining operations on the prismatic parts

(iii) By adopting a new approach on setup grouping, setup sequencing the SPM module identifies the best suited setups for finish machining the prismatic part.

All these methodologies are coded in C / C++ languages and more than 70 CAD models are tested and validated. The process plan generated from the FM-CAPP system is tested in a CNC machine by generating G&M codes. It is found that the final machined prismatic part is error free and is having the proper dimensions seen in the drawing sheet.

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Arivazhagan Anbalagan is a Assistant Professor at IIITD&M, Kancheepuram, Chennai, INDIA. He did his graduation in Mechanical Engineering from University of Madras in 2001, Masters in CAD/CAM from Vellore Institute of Technology in 2001 and Ph.D from IIT Roorkee in 2008. He worked as an Engineer / Technologist from 2008-2009 in GE, JFWTC, Bangalore, India and has high exposure over the CAD/ CAM techniques involved in the manufacturing of various industrial components. He is a young scientist holding projects from DST, Govt of India, and published/reviewed research works in journals/ conferences of international repute.

Mehta Narinder Kumar (Mehta NK) is a Professor emeritus who has been serving the Department of Mechanical and Industrial Engineering at IIT Roorkee for the past 38 years in different teaching and administrative positions. He obtained Bachelor’s degree from Agra University in 1964, M.Sc. and Ph.D. in Mechanical Engineering from P.F University, Moscow, Russia during 1970 and 1979 respectively. Prof Mehta was a ‘Scientific Attaché’, at Indian Embassy in Moscow, Russia for 3 years, and coordinated Indo-Russia bilateral Science & Technology Programs.

Jain Pramod Kumar (Jain PK) is a Professor who has been serving the Department of Mechanical and Industrial Engineering at IIIT Roorkee for the past 20 years in different teaching and administrative positions. He obtained Bachelor’s, Master's and Ph.D degrees from University of Roorkee during 1987,1989 and 1996. He has many projects from DST, CSIR Govt of India, and published/reviewed his research work in journals/ conferences of international repute. He has also reviewed technical papers in many international journals.