Development of Automatic Process Planning System for Turning-Milling Center with 2 Turrets System *

Khusna DWIJAYANTI **, Hideki AOYAMA ***

Abstract

The objective of this study is to develop an automatic process planning system in a complex machining, specifically for a turning-milling center with 2 turrets system. The machining feature recognition is carried out based on delta volume decomposition and surface identification. The system is able to recognize the machining features with any type of surfaces such as planar, inclined planar, cylindrical, spherical, conical, and toroid. The SolidWorks API was used in the designed system for delta volume extraction; disassembly of the delta volume into simple machining features, surface's parameter identification, machining feature recognition, sequence determination, and prediction of processing time. Furthermore, the process planning system is able to generate all possible machining solutions, evaluate the machining plan and choose the appropriate machining plan based on the user's evaluation criteria. At this stage, the developed system is able to select the best machining process plan, based on shortest processing time. Finally, this paper proposes a new process planning method for turning-milling machining center with 2-turrets system, and presents the result of process planning simulation.

Key words: CAPP, Process Planning, Surface Identification, Machining Feature Recognition, Delta Volume Decomposition, Multi-Turrets System

1. Introduction

The turning-milling machining center with multi-turrets system is having high demand in the current manufacturing technology. The benefits of the multi-turrets machining are as follows: accelerate the machining process and cycle time; conduct parallel job in one machine; minimize the human error by changing turning milling; support the process of low batch and high variation of product. However, there are limited literatures in the process planning of multi-turrets machining.

In recent manufacturing technology it is important to create a process-planning system that can automatically determine the machining process, in order to shorten the manufacturing lead-time ⁴⁾. A machining feature can be regarded as the delta volume removed by a cutting tool. Recognition of machining features is a cornerstone of automatic machining ⁷⁾. Machining feature recognition is an important stage in process planning, and is required to identify the removal volume and the overall machining process. Machining sequence planning can be considered one of the most important functions of manufacturing process planning. However, little attention has been paid to the automation of this function in recent computer-aided process planning systems ¹⁾.

Many approaches have been reported for feature recognition in the literature, such as the feature topology, graph-based algorithm, hint-based geometric reasoning and volumetric decomposition ^{3) 10) 11)}. A machining feature recognition method based on delta volume decomposition with the SolidWorks API is introduced by Sriani ⁹⁾. However, this method is limited to 2D machining features, and cannot be applied to recognize 3D machining features.

Another delta volume decomposition method using XY, XZ, and YZ cutting planes are introduced ^{5) 6)}. However, the number of identified machining features is limited, and only focuses on 3-axes milling machines and could not be applied to turning-milling features.

In some research, the machining feature recognition process is conducted by evaluating the 3D-CAD data of the target shape ²⁾. However, this method identifies only the form features of the target shape, instead of recognizing the machining features.

Therefore, in this study, the process planning system has been developed based on machining feature recognition for the turning-milling machine. The machining feature recognition is conducted, based on delta volume decomposition. The main idea of the disassembly method in this paper is using all of delta volume's surfaces as a cutting plane. This research has been carried out as part of a continuous piece of work from the author's previous research ¹⁾, with additional analysis of other identified machining features such as inclined holes, spherical and conical features. The various alternative machining plans can be generated automatically from the delta volume. The sequence analysis and evaluation method for all machining plans are provided. The best machining plan is selected based on the shortest processing time. Finally, the proposed process planning method for 2-turrets system is presented.

2. Development of Automatic Process Planning System by Surface Recognition

This research introduces a new approach to machining feature recognition specifically for turning-milling machining, based on the delta volume's surface detection by using the API of SolidWorks 2013 with Visual Basic Application language. By accessing the API Objects, the detailed parameters of each surface in each body element can be obtained automatically to recognize the machining features. A diagram of the automatic surface identification and machining feature recognition methodology is shown in Fig. 1.

* Received 2 October 2014

Accepted 29 January 2015

** School of Integrated Design Engineering, Keio University, Japan, E-mail: khusna@ddm.sd.keio.ac.jp

*** Department of System Design Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa, 223-8522, Japan. E-mail: haoyama@sd.keio.ac.jp

Fig. 1 Diagram of automatic surface recognition process and machining feature identification

The recognition method used in this study involves recognition of a machining feature based on delta volume decomposition. This research develops a feature recognition algorithm based on the surface identification of the delta volume. Author's previous study proposed the detection of simple machining primitive shape based on API dimension table¹⁾. However, this study proposed machining feature recognition by using automatic surface identification system. The proposed machining feature identification method is shown in Table 1. The method is based on number of open and closed surfaces and identified parameters of surfaces.

By using the SolidWorks API developed with the Visual Basic language, the developed system is able to detect the parameters of the surface automatically, as shown in Table 2. For instance, the parameters of the surface are type of surface, normal value, rootpoint, axis, radius, number of edges, type of edge, vertex number and vertex coordinate. The angle of inclination plane can also be obtained automatically.

There are 5 target shapes (TS) present in this paper. The 1st and 2nd target shapes are simple parts with spherical and conical feature, as shown in Figs. 2 and 3. The automatic surface identification and feature recognition for the 1st delta volume (DV) is shown in Table 3. The summary of 2nd DV recognition is shown in Fig. 4. The Solidworks API Interface Objects to access the surface information are shown in Fig. 5.

The 3rd target shape is one which has an inclined surface and inclined holes, as shown in Fig. 6. The surface identification and inclined angle detection are presented. The 4th target shape is one which has an complex features in six-sides, including inclined surface and inclined holes, as shown in Fig. 7.

2.1. Development of machining feature recognition program

The delta volume disassembly and machining feature recognition process in the developed program consists of several steps, as follows:

- ✓ Step 1. Identify the delta volume's surfaces parameters.
- ✓ Step 2. Perform split operation to cut delta volume.
- ✓ Step 3. Identify simple elements for the machining features and determine the machining sequence.
- ✓ Step 4. Identify the target shape's surfaces parameters.
- ✓ Step 5. Compare the surface of the machining feature element and the target shape.
- ✓ Step 6. Determine the number of open and closed faces.
- ✓ Step 7. Determine the machining features and sequences.
- ✓ Step 8. Repeat the step no. 2-7 by the different cutting planes to generate all possible machining plan candidates.

2.1.1. Step 1 Identification of the delta volume's surfaces

The delta volume automatic surface identification consists of several steps as follows:

- Subtract target shape and raw material to get delta volume.
- Count the number of delta volume surfaces.
- Identify the type of each surface: planar, cylindrical, spherical, conical or toroidal.
- Identify the parameters of each surface, such as: Normal XYZ, root point XY, radius, minor radius, major radius, angle of inclined surface, number of edges, edge type, loop type, loop number, vertex coordinates.
- Set or give a name to each surface using a unique name. For example: surface DV S1, DV S2, and DV S3.
- Transfer and write all the identified parameters automatically to the MS. Excel table by integrating Excel API application to the SolidWork API application.

Table 1 Proposed machining feature identification method based on number of open-closed and type of surfaces

Example of Removal Shape	No	Removal Shape	Surface Data		No.Open Face	No.Closed Face	Machining Feature	Cutting Tool	Machining Type
			No	Type
(a).Cuboid	1	Cuboid	6	6 planar	1 planar	5 planar	Closed Pocket	End Mill	Milling
	2	Cuboid	6	6 planar	3 planar	2 planar	Open Pocket	End Mill	Milling
(b).Cylinder	3	Cuboid	6	6 planar	2 planar	4 planar	Closed Slot	End Mill	Milling
	4	Cuboid	6	6 planar	3 planar	3 planar	Open Slot	End Mill	Milling
(c).Cylinder hollow	5	Cuboid	6	6 planar	5 planar	1 planar	Face	End Mill	Milling
	6	Cuboid	6	6 planar	4 planar	2 planar	Step	End Mill	Milling
(d).Cuboid with Circular hole	7	Cylinder	3	2 planar 1 cylindrical	1 planar	1 planar 1 cylindrical	Blind Hole	Drill	Milling/ Turning
	8	Cylinder	3	2 planar 1 cylindrical	2 planar	1 cylindrical	Through Hole	Drill	Milling/ Turning
(e).Cuboid with conical hole	9	Cylinder	3	2 inclined planar 1 cylindrical	1 inclined planar	1 incl. planar 1 cylindrical	Inclined Hole	Drill	Milling
	10	Cylinder	3	2 planar 1 cylindrical	1 planar 1 cylindrical	1 planar	Turning Face	Turning Tool	Turning
(f).Cuboid with rectangular hole	11	Cylinder Hollow	4	2 planar 2 cylindrical	1 planar	2 planar 2 cylindrical	Cylindrical pocket	End Mill	Milling
	12	Cylinder Hollow	4	2 planar 2 cylindrical	1 cylindrical	2 planar 1 cylindrical	Turning slot	Turning Tool	Turning
(g).Cuboid with spherical hole	13	Cylinder Hollow	4	2 planar 2 cylindrical	1 planar 1 cylindrical	1 planar 1 cylindrical	Turning step	Turning Tool	Turning
	14	Cylinder with Spherical hole	4	2 planar 1 cylindrical 1 spherical	2 planar 1 cylindrical	1 spherical	Sphere	Turning Tool	Turning
(h).Cuboid with circular and rectangular hole	15	Cuboid with Spherical Hole	7	6 planar 1 spherical	5 planar	1 planar 1 spherical	Spherical Boss	Ball End Mill	Milling
	16	Cylinder with Conical Hole	4	2 planar 1 cylindrical 1 conical	1 planar 1 cylindrical	1 planar 1 conical	Conical Boss	Turning Tool	Turning
(i).Triangle Boss	17	Triangle Boss	5	4 planar 1 inclined planar	4 planar	1 incl. planar	Chamfer	Chamfer Tool	Milling
	18	Fillet Boss	5	4 planar 1 cylindrical	4 planar	1 cylindrical	Fillet	Ball End Mill	Milling
(j).Fillet Boss	19	Torus	2	1 planar 1 toroid	1 planar	1 toroid	Toroid Feature	Ball End Mill	Milling
	20	Cuboid with Circular Hole	7	6 planar 1 cylindrical	1 planar	5 planar 1 cylindrical	Rectangular Pocket with Circular Boss	End Mill	Milling
(k). Torus	21	Cuboid with Conical Hole	7	6 planar 1 Conical	1 planar	5 planar 1 Conical	Pocket with Conical Boss	End Mill	Milling
	22	Cuboid with 2 Circular Holes	8	6 planar 2 cylindrical	1 planar	5 planar 2 cylindrical	Pocket with 2 Circular Boss	End Mill	Milling
(l). Cuboid with fillet	23	Cuboid with Rectangular Hole	10	10 planar	1 planar	9 planar	Pocket with Rectangular Boss	End Mill	Milling
	24	Cuboid with Rectangular Hole & Circular Hole	11	10 planar 1 cylindrical	1 planar	9 planar 1 cylindrical	Pocket with Rectangular & Circular Boss	End Mill	Milling
	25	Cuboid with fillet	18	6 planar 8 cylindrical 4 spherical	1 planar	5 planar 8 cylindrical 4 spherical	Closed pocket with fillet	Ball End Mill	Milling

2.1.2. Step 2 Split operations (cutting the delta volume based on combination of surfaces of the delta volume)

In this stage, the overall delta volume will be cut or decomposed to create simple machining features, such as cuboids cylinders, or any simple primitive shapes as shown in Table 2.

Before performing the split operation, the system will choose a surface of the delta volume randomly as a cutting plane to cut the delta volume. All of the delta volume surfaces are candidates for the cutting plane. The split program will choose the cutting plane randomly to create all possible machining plan candidates. The split operation consists of several steps, as follows:

➤ Set all of the delta volume surfaces as the cutting plane.

➤ Determine the number of combination.

➤ Choose several planes consecutively as the cutting plane.

➤ Perform pre-split operation.

➤ Set up the arrays for the body element.

➤ Perform cut operation.

➤ Perform the post-split operation.

➤ Identify the whole split body element.

➤ Save the split body element.

➤ Repeat the split step with the other cutting planes combination.

➤ Different combination of cutting planes used in cutting the delta volume will create different candidates of the machining features, as shown in the Fig.8.

Fig. 2 Spherical feature

Fig. 3 Conical feature

Table 2 Parameters of surface recognition

No	Type of Surface	Obtained Parameters
1	Plane (Planar)	1 Normal X
		2 Normal Y
		3 Normal Z
		4 Root Point X
		5 Root Point Y
		6 Root Point Z
2	Cylinder (Cylindrical)	1 Origin X
		2 Origin Y
		3 Origin Z
		4 Axis X
		5 Axis Y
		6 Axis Z
		7 Radius
3	Cone (Conical)	1 Origin X
		2 Origin Y
		3 Origin Z
		4 Axis X
		5 Axis Y
		6 Axis Z
		7 Radius
		8 Half Angle
4	Sphere (Spherical)	1 Center X
		2 Center Y
		3 Center Z
		4 Radius
5	Torus (Toroid)	1 Center X
		2 Center Y
		3 Center Z
		4 Axis X
		5 Axis Y
		6 Axis Z
		7 Major Radius
		8 Minor Radius

Table 3 Automatic machining feature recognition (DV1)

DV	Planar 1	Planar 2	Planar 3	Planar 4	Planar 5	Planar 6	Spherical
	-1	0	1	0	0	0	0
	0	0	0	0	-1	-1	0.02
	0	1	0	-1	0	0	0
	-0.06	0.06	0.06	0.06	0	0	0.025
	0.05	0.05	0.05	0.05	0.05	0.02	
	-0.045	0.045	-0.045	-0.045	0	0	
TS	Planar 1	Planar 2	Planar 3	Planar 4	Planar 5	Planar 6	Spherical
	0	-1	0	1	0	0	0
	-1	0	0	0	0	-1	0.02
	0	0	1	0	-1	0	0
	0	0.06	-0.06	-0.06	-0.06	0	0.025
	0.02	0.02	0.02	0.02	0.02	0	
	0	0.045	-0.045	0.045	0.045	0	
Comp.	DV S1	DV S2	DV S3	DV S4	DV S5	DV S6	DV S7
TS S1	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	EQUAL	NOTequal
TS S2	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal
TS S3	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal
TS S4	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal
TS S5	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal
TS S6	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal
TS S7	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	NOTequal	EQUAL
Bool Value	0	0	0	0	0	1	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	1
Result	0	0	0	0	0	1	1
Status	Open	Open	Open	Open	Open	Closed	Closed
sum0	5 5 planar						
sum1	2 1 planar, 1 spherical						
Machining Feature = Spherical Boss							

Surface Data

Face 1
Type = Planar
Normal = (0, -1, 0)
Root = (0, 30, 0)

Face 2
Type = Conical
Origin = (0, 30, 0)
Axis = (0, 1, 0)
Radius = 10
Half angle = 20 degrees

Surface Attribute Recognition:
Closed Face Count = 2
Face 1. Planar Surface
Face 2. Conical Surface
Open Face Count = 5
Face 3. Planar Surface
Face 4. Planar Surface
Face 5. Planar Surface
Face 6. Planar Surface
Face 7. Planar Surface

Machining Feature:
Conical Boss

Fig. 4 Conical feature recognition (DV2)

Solidworks API Interface Objects Hierarchy

Simplified API tools to access the surface information:

1. IBody2::GetBody
2. IFace2::GetSurface
3. ISurface::GetSurfaceType
4. ISurface::GetParameter
5. IEdge::GetVertex
6. IVertex::GetStartVertex

Fig. 5 SolidWorks API Objects used in the designed system

2.1.3. Step 3 Identify all of the body elements surfaces parameter & determine machining sequence

After conducting the split operation, the program will evaluate each split body element and determine the sequence:

- Access each body element.
- Determine the number of split body elements.
- Evaluate each body element's surface parameters.
- Determine the mass property of each body: center of mass, mass value, volume.
- Compare the top surface height value of each body element to arrange the machining sequence, from the highest value.
- Compare the volumes of the body elements to arrange the sequence.

2.1.4. Step 4 Identify all target shape's surface parameters

Target shape identification is used to recognize all the surfaces of the target shape and its parameters, as follows:

- Count the number of target shape surfaces.
- Identify the type of each surface: planar, cylindrical, spherical, and conical.
- Determine the parameters of each surface, such as:
Normal XYZ, root point XY, radius, minor radius, major radius, angle of inclined surface, number of edges, edge type, loop type, loop number, vertex coordinates.

- Set or give a name to each target shape's surface, using a unique name. For example: surface TS S1, surface TS S2, and surface TS S3.
- Transfer and write all the identified parameters automatically to the MS. Excel table by integrating Excel application to the SolidWorks API application.

2.1.5. Step 5 Compare the surfaces of each body element of the delta volume and all target shape surfaces

In this stage, the developed program will compare each surface parameter of the split-body-element of the delta volume with the surface parameters of the target shape. If the surface comparison result is equal, it means that the surface is facing the target shape surface, or a closed surface.

The next process is to apply surface attribute data to every surface of each simple removal shape. The system uses binary values to represent surface attribute data. A zero (0) value means the surface is in contact with the air; this is also known as an open face. A value of one (1) means that the surface is in contact with the target object; this is also called a closed face. By establishing the value, the system can obtain information about closed or open boundaries on each surface of each simple body element of removal volume. Therefore, by calculating the number of open faces and closed faces, the simple removal shape can be determined as a machining feature by the system, as described in Table 3.

Fig. 6 Output of machining feature recognition for inclined surface and holes

Fig. 7 Complex delta volume extraction (subtraction of blank shape & target shape)

Fig. 8 Example of possible machining features candidates

The surface comparison step consists of several steps, as follows:

➤ Define the condition of equal range (equal surface parameter value), as follows:

- If the number of parameters are the same.
- If the value of each corresponding parameter is the same.

➤ Surface Parameter Comparison:

- Automatically compare the parameters of each surface.

➤ Apply Boolean values.

- If the ranges are equal: true (1), closed face.
- If the ranges are not equal: false (0), open face.

2.1.6. Step 6 Determine the number of open face and closed face

After comparing the surfaces, the program will automatically obtain the sum of the 0 values and 1 value in a single body element. Table 3 show the machining feature identification method, based on the number of open-closed surfaces, type of surfaces, and number of certain surface type in the open-closed boundaries.

2.1.7. Step 7 Determine the type of machining features and sequences.

By calculating the number of open faces and closed faces, and calculating the number of certain type of surface in the open faces and closed face, the simple removal shape can be recognized as a machining feature by the system, based on the rules described in the Table 1.

The identified machining feature has information about its entire surfaces. By comparing the surface's parameter data, the system obtains the height position of each surface and identifies the height value of the most upper surface of that machining feature. The system sorts the height data of each machining feature located in the same side of workpiece, from the highest to the lowest value. Then, the sequences of machining are automatically obtained.

2.2 Generation of Other Possible Machining Plan Candidates

In this study, the various methods to cut the delta volume are classified by the side order of cutting. Rules used in this stage are machining features on the upper part, front part, bottom part and the back part are machined sequentially. The left and right parts are also processed sequentially; these parts can be processed either at the beginning or at the end of the process¹⁾. By applying these rules, 8 combinations of basic order are obtained.

By creating four different orders in each of the 8 basic orders, 32 unique machining patterns are obtained. Hence, the system generates a total of 32 possible machining plans to machine the overall delta volume. Each machining plan has different shapes of removal volumes (manufacturing features). Figure 8 displays only 4 results from among the entire 32 machining orders due to space constraints. The next step, the program will repeat the recognition from step 3 to step 7, to recognize the simple machining features in each machining plan candidate.

Fig. 9 Example : Machining plan no. 4
16 machining features elements

Table 4 Machining feature recognition result (plan no.4)

Body	Removal Shape (delta volume)	Surface		Machining Feature	Operation Type
		Open	Closed		
1	Cuboid	5	1	Face	Milling
2	Cuboid	5	1	Face	Milling
3	Cuboid	5	1	Face	Milling
4	Cuboid	5	1	Face	Milling
5	Rectangular Boss	1	5	Rectangular Pocket	Milling
6	Cuboid	3	3	Open Slot	Milling
7	Cylinder	1	2	Blind Hole	Milling
8	Rectangular Boss	4	2	Inclined Step	Milling
9	Cylinder	1	2	Inclined Hole	Milling
10	Cylinder	1	2	Inclined Hole	Milling
11	Cuboid	5	1	Face	Milling
12	Cuboid	5	1	Face	Milling
13	Cylinder Hollow	1	3	Turning Slot	Turning
14	Circular Hole	5	2	Circular Boss	Milling
15	Circular Hole	5	2	Circular Boss	Milling
16	Circular Boss	1	2	Circular Pocket	Milling

Fig. 10 Example : Machining plan no. 8
19 machining features elements

Table 5 Machining feature recognition result (plan no.8)

Body	Removal Shape (delta volume)	Surface		Machining Feature	Operation Type
		Open	Closed		
1	Cuboid	4	2	Step	Milling
2	Cuboid	4	2	Step	Milling
3	Rectangular Boss	4	2	Inclined Step	Milling
4	Cylinder	1	2	Inclined Hole	Milling
5	Cylinder	1	2	Inclined Hole	Milling
6	Cuboid	5	1	Face	Milling
7	Rectangular Boss	1	5	Rectangular Pocket	Milling
8	Cuboid	5	1	Face	Milling
9	Circular Hole	5	2	Circular Boss	Milling
10	Cylinder	1	3	Turning Slot	Turning
11	Cuboid	5	1	Face	Milling
12	Cuboid	3	3	Open Slot	Milling
13	Cuboid	4	2	Step	Milling
14	Cylinder	2	1	Face	Milling
15	Cylinder	2	1	Face	Milling
16	Cylinder	1	2	Circular Pocket	Milling
17	Circular Hole	5	2	Circular Boss	Milling
18	Cylinder	2	1	Face	Milling
19	Cuboid	4	2	Step	Milling

Table 6 Evaluation method to eliminate unacceptable candidate

No	Elimination Rules						Score	Result	No	Elimination Rules						Score	Result
	a	b	c	d	e	f				a	b	c	d	e	f		
1	1	1	1	1	1	1	6	Acceptable	10	1	1	0	1	1	1	5	Eliminated
2	1	0	0	1	0	1	3	Eliminated	11	1	1	1	1	1	1	6	Acceptable
3	1	0	1	1	1	0	4	Eliminated	12	1	0	0	1	1	0	3	Eliminated
4	1	1	1	1	1	1	6	Acceptable	13	1	1	0	1	1	1	5	Eliminated
5	1	1	1	1	1	0	5	Eliminated	14	1	1	1	1	1	1	6	Acceptable
6	1	0	0	1	1	1	4	Eliminated	15	1	0	0	1	0	1	3	Eliminated
7	1	0	1	1	0	0	3	Eliminated	16	1	0	1	1	1	0	4	Eliminated
8	1	1	1	1	1	1	6	Acceptable	17	1	0	0	1	1	0	3	Eliminated
9	1	0	0	1	1	0	3	Eliminated	18	1	1	0	0	1	0	3	Eliminated

2.3 Result of Machining Feature Recognition

Figures 9 and 10 describe the results of different method to cut the delta volume. Different cutting plane in the split operation provide different candidate of machining features. For example, machining plan no. 4 has 16 machining feature elements, while machining plan no. 8 has 19 machining feature elements. The different results of delta volume disassembly create the large number of process plan candidates.

All bodies generated from the disassembly process of delta volume can be recognized as a machining feature. The results of machining feature recognition system of two different machining plan candidates in the Figs. 9 and 10 are shown in Tables 4 and 5 consecutively.

For example, in the Table 4, the result of feature recognition in the machining plan no 4, Bodies 1, 2, 3 and 4 are recognized as Faces. Body 5 is recognized as a closed rectangular pocket. Body 6 is recognized as open slots. On the other hand, in the Table 5, the result of feature recognition in the machining plans no 8 have different. Bodies 1 and 2 are recognized as Step. Body 3 is recognized as Inclined Step. Bodies 4 and 5 are recognized as Blind Holes.

The results of machining feature recognition from the delta volume decomposition create many different alternative of interpretation of machining feature. These different candidates of machining feature give the machining planner alternative and allow them to locate and approach the optimal solution.

2.4 Evaluation of Unacceptable Candidates

After determining all possible candidates of machining feature in the delta volume, the next step is evaluating the candidates based on machining rules. In this stage, unacceptable candidates are eliminated, and only several acceptable candidates will be chosen to the next evaluation process ¹⁾.

This method aims to eliminate the unacceptable machining sequences based on common machining rules. By applying the machining rules to each machining plan, the system evaluates each machining plan and eliminates those that do not fulfill the machining rules. Elimination of unacceptable machining patterns is done by applying several machining rules. The system uses two proposed machining rules and four common machining rules. In Table 6, the machining rules for evaluation are indicated by the letters a, b, c, d, e and f ¹⁾.

Table 7 Example of cutting tools installed in the system

Tool ID	Tool Type	Diameter (mm)
1	Face Mill	10
2	Face Mill	20
3	End Mill	3
4	End Mill	6
5	End Mill	10
6	End Mill	16
7	Drill	20
8	Drill	10
9	Drill	5
10	Facing Tool	10
11	Parting Tool	6
12	Ball End Mill	10
13	Ball End Mill	5
14	Chamfer Tool	10

The first proposed rule (a) is that a machining process should maintain the continuity of the object side to be processed. For example, after processing the upper part, the next portion to be processed should be either the front part or the back part. This rule is related to the efficiency of workpiece rotation in the X axis direction during the machining process. Second, as rule (b), the order for processing machining features is based on the object side ⁸⁾. For instance, the machining should not rotate the workpiece before finishing removal of machining features on one particular side. Other common machining rules used in this system are that the process machining starts from the highest Z level, as rule (c), from the largest volume, as rule (d), from the center, as rule (e) and cylindrical features are machined last, as rule (f) ⁸⁾.

2.5 Process Plan Evaluation

The sequence evaluation is carried out by providing the score for each machining rule in each machining plan. Scoring aims to give an assessment of the existing order sequence of each machining plan. Value 1 means qualified or fulfilling the requirement of a certain rule, while value 0 means not qualified or fails to comply a certain rule. Values 1 and 0 are applied to each machining plan corresponding to each machining rule. The resulting scores are then collected and summed as the final score ¹⁾.

The final score shows the fulfillment of the requirements of the machining rules. Score 6 means that the machining plan is meeting the requirements of all rules and the order of the machining sequence is good and acceptable. Then, the system eliminates those machining plans which have scored below 6, as shown in Table 6. As a result of the sequence evaluation, there are only 5 machining plans that have scores of 6. These machining plans meet the requirements of all machining rules and will be evaluated in the next stage.

3. Tool-path Length Calculation

The machining feature recognition system obtains the machining feature parameters such as surface, length, width, height, center, radius, axis, shape and name. The cutting tools selection method is based on machining feature name. In the

Fig. 11 Several toolpath patterns installed in the system**Table 8** Processing time comparison

Mach. Plan No.	Number of machining features	Productivity
		Time (min)
1	22	12.95
4	16	9.70
8	19	15.45
11	20	11.95
14	25	16.30

designed system, each specific machining feature corresponds to certain type of cutting tool. For example, an end mill for a closed pocket, and a drill for a hole, as shown in Table 1. The tool diameter is determined by considering the machining feature dimension. For toolpath selection, the system chooses the appropriate toolpath pattern which is valid to create shortest cutting time. As an example, for the removal of cuboid machining feature, the system utilizes the zig-zag toolpath.

The prediction of machining time for each machining feature is conducted by calculating the toolpath length of each machining feature based on the information of selected cutting tool and toolpath pattern, as shown in Table 7 and Fig.11 ¹⁾. The system generates toolpath for each machining feature in the delta volume and generates an NC program. Then the toolpath length and machining time for each machining feature can be obtained.

4. Processing Time Calculation

The total processing time for each machining plan can be obtained by summing the times needed for cutting all machining features, cutting tool changes, air cutting time, and time for workpiece rotation, as shown in Eqs. 1 and 2.

$$Tm = Ltp / F \quad (1)$$

$$T = \sum Tm + nTt + Ta + Tr \quad (2)$$

Notes :

T = Total machining time (min)

Tm = Cutting time for one particular feature (min)

n = Number of tool changes

Tt = Time for tool changing (min)

Ta = Air cutting time (min)

F = Feedrate (mm/min)

Ltp = Toolpath Length (mm)

Tr = Total workpiece rotation (min)

The air cutting time is a rapid motion of a cutting tool from one particular machining feature to the next machining feature according to machining sequence. In the designed system, the tool changing time is assumed to be 1 s, and the rotation time of workpiece is assumed to be 0.5 s, and the air cutting time is set equal to zero.

Fig. 12 One & two turrets system

Fig. 13 Complex target shape (mach. plan no.4)

Fig. 14 Simple turning-milling target shape

Table 9 Time prediction and machining sequence with 1-turret system (for machining plan no. 4)

Rot. No	Seq.	Removal Shape	Time	Process & Location MF
1	1	Cuboid	60 s	(M)Upper
2	2	Cuboid	56 s	(M)Front
3	3	Cuboid	54 s	(M)Bottom
4	4	Cuboid	57 s	(M)Back
5	5	Rectangular Boss	35 s	(M)Upper
	6	Cylinder	5 s	(M)Upper
	7	Cylinder	5 s	(M)Upper
6	8	Rectangular Boss	40 s	(M)Front
7	9	Cuboid	25 s	(M)Bottom
8	10	Cylinder	10 s	(M)Back
9	11	Cuboid	50 s	(M)Right
	12	Cuboid Hollow	40 s	(M)Right
	13	Cylinder Hollow	28 s	(T)Right
10	14	Cuboid	55 s	(M)Left
	15	Cuboid Hollow	40 s	(M)Left
	16	Cylinder Hollow	10 s	(M)Left
Cutting Time		570 s = 9.5 minutes		
		Rotations = 10 ; Sequences = 16 ; Tool changes = 7		
		Total processing time = 582 s = 9.7 minutes		

Table 10 Time prediction and machining sequence with 2-turrets system (for machining plan no. 4)

Rot. No	Seq.	Removal Shape	Turret 1 (Upper)		Removal Shape	Turret 2 (Bottom)	
			Time	Turret 1		Time	Turret 2
1	1	Cuboid	60 s	(M)Upper	Cuboid	54 s	(M)Bottom
	2	Rectangular Boss	35 s	(M)Upper	Cuboid	25 s	(M)Bottom
	3	Cylinder	5 s	(M)Upper			
	4	Cylinder	5 s	(M)Upper			
2	5	Cuboid	56 s	(M)Front	Cuboid	57 s	(M)Back
	6	Rectangular Boss	40 s	(M)Front	Cylinder	10 s	(M)Back
3	7				Cuboid	50 s	(M)Right
	8				Cuboid Hollow	40 s	(M)Right
	9				Cylinder Hollow	28 s	(T)Right
4	10	Cuboid	55 s	(M)Left			
	11	Cuboid Hollow	40 s	(M)Left			
	12	Cylinder Hollow	10 s	(M)Left			
Cutting Time			424 s = 7.06 minutes				
Rotations = 4 ; Sequences = 12 ; Tool changes 1= 5 ; Tool changes 2= 2							
Total processing time = 433 s = 7.21 minutes (Time reduction = 25%)							

For the air cutting time calculation, the system recognizes the distance between two sequential machining features. The distance is usually short and the tool motion is fast. Therefore, in the designed system, the air cutting time was ignored due to fast movement of cutting tool.

5. Processing Time Comparison

The total processing time for each machining plan can be obtained by summing the times needed for machining all of machining features, cutting tool changes, air cutting time, and time for workpiece rotation. After getting the total processing time for each machining plan candidate, the program will compare the processing time of each machining plan, and search for the best machining plan according to the user's evaluation criteria. In this stage, the user evaluation criterion is the shortest processing time.

The comparison of processing time can be shown in Table 8. Hence, the best sequence which has the minimum cutting time is machining plan no 4.

6. Proposed Automatic Process Planning System for 2 Turrets System

In the 2-turrets system, the workpiece is machined by two cutting tools. The 1st cutting tool is located in the upper turret and the 2nd cutting tool is located in the bottom turret, as shown in Fig. 12(b). These two cutting tools are operated at the same time to machine the upper machining features and the bottom machining features simultaneously. To move to the next process, the workpiece is rotated 90 degree along X axis, so that the front side machining features are facing the upper turret, and the back

side machining features are facing the bottom turret.

The proposed method for assigning the machining features to the 2-turrets system is as follows;

- The machining features in the particular machining plan candidate are divided based on the upper side and bottom side.
- The machining features on the upper side are assigned to tool 1 or turret 1.
- The machining features on the bottom side are assigned to tool 2 or turret 2.
- Rotation 90 degree of X axis is needed between each process to machine the machining features in the next side. In the Table 9, rotation number in the first column indicates the machining process in each particular side of workpiece. The letter (T) and (M) in the last column indicate the type of machining, (T) for Turning and (M) for Milling.
- The starting time of the tool 1 and tool 2 must be indicated in the beginning of process to get the two tools work simultaneously.
- In each process, the length of total machining time of the tool 1 and tool 2 might be different due to the difference type and number of the machining features on those two particular sides. As an example, in the Table 10, in process no.1, the tool 1 in the upper side has the longer machining time compared to the tool 2 in the bottom side.
- In each process, the tool which has longer time determines the total machining time in that particular process, while the tool which has shorter time will have an idle condition before move to the next process.

Table 11 Time prediction and machining sequence with 1 turret system (for simple target shape)

Rot. No	Seq.	Removal Shape	Time	Process & Location
1	1	Cylinder with Spherical hollow	20 s	(T)All
2	2	Spherical boss	10 s	(M)Right
3	3	Spherical boss	10 s	(M)Upper
4	4	Spherical boss	10 s	(M)Front
5	5	Spherical boss	10 s	(M)Bottom
6	6	Spherical boss	10 s	(M)Back
7	7	Cylinder	5 s	(M)Upper
	8	Cylinder	5 s	(M)Upper
8	9	Cylinder	5 s	(M)Front
	10	Cylinder	5 s	(M)Front
9	11	Cylinder	5 s	(M)Bottom
	12	Cylinder	5 s	(M)Bottom
10	13	Cylinder	5 s	(M)Back
	14	Cylinder	5 s	(M)Back
11	15	Spherical boss	10 s	(M)Left
Cutting Time		121 s = 2.01 minutes		
Rotations = 11 ; Sequences = 15 ; Tool changes = 3				
Total processing time = 128.5 s = 2.14 minutes				

Table 12 Processing time prediction and machining sequence with 2 turrets system (for simple target shape)

Rot. No	Seq.	Removal Shape	Turret 1 (Upper)		Removal Shape	Turret 2 (Bottom)	
			Time	Turret 1		Time	Turret 2
1	1	Cylinder with Spherical hollow	20 s	(T) All			
2	2				Spherical boss	10 s	(M)Right
3	3	Spherical boss	10 s	(M)Upper	Spherical boss	10 s	(M)Bottom
4	4	Spherical boss	10 s	(M)Front	Spherical boss	10 s	(M)Back
5	5	Cylinder	5 s	(M)Upper	Cylinder	5 s	(M)Bottom
	6	Cylinder	5 s	(M)Upper	Cylinder	5 s	(M)Bottom
6	7	Cylinder	5 s	(M)Front	Cylinder	5 s	(M)Back
	8	Cylinder	5 s	(M)Front	Cylinder	5 s	(M)Back
7	9	Spherical boss	10 s	(M)Left			
Cutting Time			81 s = 1.35 minutes				
Rotations = 7 ; Sequences = 9 ; Tool changes 1= 2 ; Tool changes 2 = 3							
Total processing time = 86.5 s = 1.44 minutes (Time reduction = 32%)							

Table 13 Comparison of program's execution time for the process planning system of 1-turret and 2-turrets system for complex turning-milling target shape

No	Process	1 Turret	2 Turrets
1	Subtract the target shape and the raw material to get the total delta volume (TDV)	7 s	7 s
2	Identify each surface's parameters of TDV	10 s	10 s
3	Identify each surface's parameters of target shape.	30 s	30 s
4	Generate the variation of cutting planes by permutation of all TDV surfaces. Each surface of TDV is a cutting plane candidate.	60 s	60 s
5	Generate all possible solution of machining plan candidates by cutting the TDV based on the variation of cutting planes.	80 min	50 min
6	Compare each surface of a simple machining feature shape in each machining plan candidate with each surface of the TDV	30 min	15 min
7	Determine the name of each machining feature contained in a machining plan candidate.	10 s	10 s
8	Apply elimination rules to each machining plan candidate.	28 min	14 min
9	Eliminate the unacceptable machining plan candidates.	55 min	28 min
10	Evaluate the acceptable machining plan candidate; choose the cutting tool, choose the toolpath type, calculate the toolpath length, compare the processing time, and get the best machining plan candidate.	50 min	20 min
Total program executing time: for computer specification : Intel (R) core (TM) i-7-2600 CPU @3.4 GHz 3.4 GHz RAM 4 GB		3.9 hours	3 hours

➤ The total machining time of the particular machining plan candidate is obtained by summing the longer machining time in each process, as shown in red color in the Table 10.

➤ The number of sequences of machining is smaller due to parallel work between tool 1 and tool 2.

The total machining time of the particular machining plan candidate is obtained by summing the longer machining time in each process, as shown in red color in the Table 10.

➤ The number of sequences of machining is smaller due to parallel work between tool 1 and tool 2.

6.1. Comparison of Sequence and Processing Time for 1-Turret and 2-Turrets System

This section describes the comparison of processing time prediction and the sequence differences of machining features of one machining plan candidate in 1-turret and 2-turrets system,

For the complex turning-milling target shape, as shown in Fig. 13, the prediction of processing time for 1-turret system is 9.7

minutes, while for 2-turrets system is 7.21 minutes. The difference of sequence and machining time can be seen in Tables 9 and 10. The time reduction by using 2-turrets system is 25%.

For the simple turning-milling target shape, as shown in Fig. 14, the prediction of processing time for 1-turret system is 2.14 minutes, while for 2-turrets system is 1.44 minutes. The difference of sequence and machining time can be seen in Tables 11 and 12. The time reduction by using 2-turrets system is 32%.

6.2. Comparison of Program Execution Time for 1-Turret and 2-Turrets System

The automatic process planning program of 1 turret and 2-turrets system for the complex turning-milling target shape in the Fig. 13 provide a different length of computation time, as shown in Table 13. The program for 2-turrets system has shorter computation time due to less number of sequences in each possible machining plan candidates, compared to 1-turret system.

7. Conclusion

In conclusion, this research develops an automatic process planning system based on machining feature recognition for turning-milling machine. The proposed machining feature recognition system is based on the delta volume decomposition and automatic surface identification by using the API of SolidWorks 2013 with Visual Basic Application language. The system is able to recognize the machining features with any type of surfaces such as planar, inclined planar, cylindrical, spherical, conical, and toroid.

The system provides automatic decomposition of the delta volume, surface identification of simple machining feature element, machining feature determination, sequence determination, operation selection and prediction of processing time. This system is able to generate the possible machining candidates, to evaluate the acceptable machining plan by several machining rules, and to select the best machining plan based on user evaluation point, such as shortest processing time. Hence, this system can help the machining operator by providing the information of all possible machining plan candidates and comparing the result before the real machining.

Finally, this study proposes a process planning method for 2-turrets machining system and compares the result with 1-turret system. Based on the simulation of machining process, the 2-turrets system creates shorter machining time than 1-turret system.

References

- 1) Dwijayanti, K., Aoyama, H., 2014, Basic Study of Process Planning System on Turning-Milling Center Based on Machining Feature Recognition. JSME Journal of Advance Mechanical Design, Systems, and Manufacturing. Vol 8, No.4, 2014, pp 1-14.
- 2) Hamada, D., Nakamoto K., Ishida, T., and Takeuchi, Y., Development of CAPP System for Multi-Tasking Machine Tool, JSME Series C, Vol.78, No.791(2012), pp.2698-2709.
- 3) Han, J.H., Pratt, M., Regli, W.C., Manufacturing feature recognition from solid models: A status report, IEEE Transaction on Robotics and Automation, Vol.16, No.6(2000), pp.782-796.
- 4) Kubota, K., Kotani, T., Nakamoto, K., Ishida, T., 2010, Development of CAM System for Multi-Tasking Machine Tools. Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol 4, No.5, 2010, pp 816-826.
- 5) Morinaga, E., Yamada, M., Wakamatsu, H., Arai, E., Flexible Process Planning for Milling, International Journal of Automation Technology, Vol. 5, No. 5 (2011), pp. 700-707.
- 6) Nakamoto, K., Shirase, K., Wakamatsu, H., Tsumaya, A., Arai, E., Automatic Production Planning System to Achieve Flexible Direct Machining, JSME International Journal, Series C, Vol. 47, No.1 (2004), pp. 136-143.
- 7) Sheen, B.T., You, C.F., 2006, Machining Feature Recognition and Tool-Path Generation for 3-Axis CNC Milling, Elsevier Journal of CAD 38, pp.553-562.
- 8) Shirase, K., Nakamoto K., 2013, Simulation Technique for the Development of an Autonomous and Intelligent Machine Tools, International Journal of Automation Technology, Vol 7, No , pp.6-15.
- 9) Sriani, T., Aoyama, H., 2010, Novel Tool Design Method for Orbiting Electrical Discharge Machining, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol 4, No.7, pp 1182-1191.
- 10) Tseng, Y.J., Joshi, S.B., 1994, Recognizing Multiple Interpretation of Interacting Machining Feature, Elsevier Journal of CAD, Vol 26, pp.667-688.
- 11) Yan, X., Yamazaki, K., Liu, J., Recognition of machining features and feature topologies from NC programs, Elsevier Journal of CAD, Vol.32 (2000), pp. 605-616.