Basic study on process planning for Turning-Milling Center based on machining feature recognition

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Abstract
This research aims to develop an automatic process planning system based on the machining feature recognition in the complex machining for Turning-Milling Center. The previous studies on the machining feature recognition are briefly discussed. In this study, the machining feature recognition is conducted based on the delta volume decomposition to achieve optimal result of process planning. The complex delta volume is cut or disassembled to generate simple machining features. Each surface of the delta volume is the candidate of the cutting plane. By this disassembly method, various possible candidates of machining features for process planning are obtained from the delta volume. The Solidworks API has been used in the designed system for automatic disassembly of the delta volume into simple machining features, feature recognition, tool-path length calculation, sequence determination, process selection and prediction of processing time. In this research, a new approach to machining feature recognition has been developed based on a design table and surface comparison method. Further analysis to select the best candidate of machining features are done automatically by applying several machining rules. This process planning system is able to evaluate all possible machining solutions and sequences, and determine the machining plan which has the shortest machining time.

Key words: Process planning, Feature recognition, Machining feature, Multi-tasking machining, CAPP

1. Introduction

Recognition of machining features is a cornerstone of automatic machining (Sheen and You, 2006). Machining feature recognition is an important stage in process planning, and is required to identify the removal volume and 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 automate this function in recent computer-aided process planning systems. This paper presents a basic study on process planning for Turning-Milling part based on machining feature recognition. In the process planning system developed in this paper, various alternative machining plans can be generated automatically from the delta volume. This research develops a method to recognize machining features and provides a sequence analysis as an evaluation method for all machining plans. The best machining plan is selected based on the shortest machining time.

Feature recognition has been developed for two decades. 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 (Yan et al., 2000, Han et al., 2000, Morinaga et al., 2011). The recognition process produces multiple interpretations for feature identification, but the multiple interpretations of features do not always meet the needs of the machining process (Tseng and Joshi, 1994). According to the design perspective, the more features are decomposed from the overall delta volume, the more freedom of design change is permitted. However, from the machining perspective, the burr and machining time increases with more decomposed features (Sheen and You, 2006). Accordingly, specific development of machining feature recognition is necessary.

A Turning-Milling Center is a machine tool which has both of milling and turning function. Another study describes this machine as a multi-tasking machine. The multi-tasking machine tool has a variety of machining functions, which may lead to the reduction in machining time and the machining with high quality, and they have the growing availability. On the other hand, the use of multi-tasking machine tool causes the long process planning due to the functional complexity (Hamada, et al., 2012).
A machining feature can be defined as a volume swept by a cutting tool. The machining features are extracted from the total delta volume, which is the volume obtained by subtracting the target shape and blank shape. In some research, the machining feature recognition process is conducted only based on the form feature data, by evaluating the 3D-CAD data of the target shape (Hamada, et al., 2012). The machining features recognition method is not conducted based on the machining features from the total delta volume. Thus, the number of possible candidates of machining plan is very limited and it leads to difficulty in finding the optimal process planning solution. Therefore, in this study, the machining feature recognition is conducted based on the delta volume decomposition, to achieve optimal result of process planning.

In the disassembly method of the total delta volume, a concavity based division method has been proposed to avoid merging process and to lower the computational load (Morinaga, et al., 2011). Furthermore, automatic process planning and operation planning for milling machine have been proposed (Nakamoto, et al., 2004). Both of researches proposed the machining feature recognition methods from delta volume, and provided the disassembly method by cutting the total delta volume to get the simple machining primitive candidates. However, the target shape is a non-complex shape and their methods could not be applied to the turning-milling machine. Furthermore, their disassembly methods use the cutting plane which is perpendicular to the particular axis. The previous methods could not identify the inclined cutting plane of a machining feature which has inclined surface. The determination of machining feature type is based on the manual identification of open and closed surfaces. The numbers of identified features are also limited to the cuboid and cylindrical machining primitive candidates. Therefore, the designed system can be applied to disassembly of the total delta volume by any angle position of cutting plane or surface which the delta volume has. The identification of machining feature’s type is done automatically by comparing all surfaces of simple machining primitive with all surfaces of target shape. The recognition system automatically provides information about the open and closed surfaces, and identifies the machining feature type.

This paper presents the automatic process planning system based on machining feature recognition for the turning-milling machine. The various machining plans candidates are generated automatically from the delta volume. The new approach in automatic machining features recognition is proposed. Furthermore, this paper presents the case study on process planning system of a complex target shape. The sequence determination, tool-path length calculation, process selection and the evaluation method for all possible machining plans are presented. The system determines the best machining plan candidate based on shortest machining time. Finally, the advantages and disadvantages of the designed process planning system are discussed.

2. Proposed Machining Feature Recognition Method

This research introduces a new approach in machining feature recognition based on an API Solidworks design table and the surface comparison created by Solidworks 2013 using the Visual Basic Application language. A diagram of the feature recognition methodology is shown in Figure 1. The recognition method used in this study involves the recognition of a machining feature based on delta volume decomposition. By using API Solidworks, a table called a design table can be obtained automatically. This table contains important information such as names of the feature, dimension name, dimension value, surface parameters and surface attribute data that are used as input data in the algorithm.
A design table recognition method has been used by Sriani and Aoyama (2010). However, that method was mainly designed to detect 2D features, and cannot be applied to detect 3D machining features. Therefore, in order to fill this gap, this research develops a feature recognition algorithm based on the Solidworks API design table to recognize 3D machining features.

2.1 Proposed Method of Total Delta Volume Disassembly

There are many ways to disassemble or cut a total delta volume to generate simple machining primitives shape such as cuboids, cylinders, and other simple machining feature shapes. In the previous research, simple machining primitives or machining features are generated by dividing the total delta volume by these following rules (Nakamoto, et al., 2004, Shirase, et al., 2013):

1. Divide by the xy plane,
2. Divide by the xz plane,
3. Divide by the yz plane,
4. Divide by the plane which includes a surface that the delta volume also has.

In the disassembly method, the previous research used the cutting planes which are perpendicular to the particular axis. This study proposed a new approach of the decomposition of a total delta volume. The cutting planes used in the decomposition method covers all surfaces of a total delta volume, including cylindrical, spherical, planar or any type of surface that the total delta volume has. The developed system is able to identify any type of surfaces or cutting planes of the total delta volume, except freeform surface. The system generates the variation of cutting planes by permutation rule of all total delta volume surfaces, and then generates all possible solution of machining plan candidates by cutting the total delta volume based on the variation of cutting planes. Different cutting planes selection for cutting the delta volume produce different shapes of machining feature. Furthermore, a different order in cutting each side of a delta volume also generates a totally different machining plan candidates.

2.2 Proposed Simple Machining Feature Recognition Based on API Dimension

The recognition process is started by disassembling the overall delta volume as described in section 2.1 to create simple machining features such as cuboids, cylinders, and other machining feature shapes as shown in Fig. 2. The next process is identifying the various simple machining features created by the previous process by using an API dimension table, as shown in Table 1. Each shape has a unique dimension name as shown in Fig. 3, which describes the shape’s parameters such as length and diameter. Example of unique dimension name in the table is D1@Sketch1, it refers to the first dimension at the first sketch in the CAD data. The API dimension table is generated automatically by using...
Solidworks API. After the table generated, the algorithm developed in this system reads the unique dimension name and recognizes the shape. The result of dimension table recognition is the identification of simple shapes of manufacturing features such as cuboid, cylinders, cylinders with cylindrical holes, cuboids with cylindrical holes, and cuboids with rectangular holes.

### 2.3 Proposed Machining Feature Recognition System Based On Surface Comparison

This section describes the proposed machining feature recognition method based on the identification of open and closed faces. This method is done automatically based on surfaces parameter comparison by Solidworks API table. The machining feature identification method based on the number of open or closed faces can be seen in Table 2.

Figure 4 is an example of simple target shape or form feature obtained from CAD data. By the extraction of blank shape and target shape, the total delta volume or machining feature is obtained, as shown in Fig. 5. This delta volume is a simple delta volume, which has only one simple primitive shape. The shape information of the simple delta volume can be identified automatically by the API design table as described in section 2.2. As the result, this unknown simple delta volume shape is recognized as a cuboid type by the system, as it has 6 numbers of planar faces, with certain length, width and height value as shown in Table 3.

In the next process, the system identifies the type of machining feature for this simple-cuboid-type-shape based on automatic surface comparison. This process determines the type of the machining feature, such as face, pocket, slot, step or another machining feature, based on the shape type and the number of open and closed faces. The system automatically recognizes the detailed parameter of each surface of the delta volume (cuboid shape), such as normal value and root point of the plane and write the result to the API Table as shown in Table 4. Then, the system also recognizes the parameter of each surface of the target shape automatically, as shown in Table 5. Next, the system conducts the automatic comparison of surface parameter of the delta volume and target shape.

The comparison is done automatically by comparing the parameters of 6 delta volume’s surfaces and 10 target shape’s surfaces, as shown in Table 6. If the parameters of a particular delta volume’s surface are equal to the parameters of a particular target shape’s surface, then both of surfaces are indicated as a same surface, or a closed face. For example, the parameters of surface number 4, 5 and 6 of the delta volume are equal to the target shape surfaces, and then these surfaces are recognized as closed faces. Hence, delta volume has 3 closed faces and 3 open faces.

The system applies an attributes data to every surface of each simple shape. The system uses binary values to represent surface attribute data. 0 value means the surface is in contact with the air; this is also known as an open face. The 1 value means the surface is in contact with the target object; this is also called closed face.

![Unrecognize Target Shape or form feature obtained from CAD data.](image1)

![Delta Volume (DV) or removal shape. Machining feature obtained by the system.](image2)

| Parameters      | Value   |
|-----------------|---------|
| Y max surface   | Surface 3 |
| Y value max     | 0.05    |
| Body Name       | DV      |
| Surface Number  | 6       |
| Body Type       | Cuboid  |
| Length X        | 0.02    |
| Length Z        | 0.05    |
| Height Y        | 0.01    |
| WidthMF         | 0.02    |
| Max Tooldiam    | 0.02    |
| nPlanar         | 6       |
| nCylindrical    | 0       |
| nSpherical      | 0       |
| nToroidal       | 0       |
| nInclined planar| 0       |

Table 3  Delta volume’s surface data.

The most upper surface is surface 3.

The altitude value for the sequence determination is 0.05.
Table 4  Delta volume’s surface recognition. The surface position based on normal direction can be seen in Fig. 6.

| Parameters      | Surface 1 | Surface 2 | Surface 3 | Surface 4 | Surface 5 | Surface 6 |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Normal.X        | -1        | 0         | 0         | -1        | 1         | 0         |
| Normal.Y        | 0         | 0         | 1*        | 0         | 0         | -1        |
| Normal.Z        | 0         | 0         | 0         | 0         | 0         | 0         |
| RootPoint.X     | -0.025    | -0.025    | 0         | -0.01     | 0.01      | 0         |
| RootPoint.Y     | 0.05      | 0.05      | 0.05**    | 0.04      | 0.04      | 0.04      |
| RootPoint.Z     | -0.025    | 0.025     | 0         | 0.025     | 0.025     | 0         |
| Surface Type    | planar    | planar    | planar    | planar    | planar    | planar    |

Inclined Angle 0 0 0 0 0 0

Note:
- **Surface 3**
  - The most upper surface (Ny = 1).
  - **Altitude value:** 0.05

By reading the normal value and root point, the system obtains the altitude position of each surface and identifies the most upper surface of each particular machining feature for sequence determination.

Table 5  Target shape’s surface recognition.

| Parameters      | Surface 1 | Surface 2 | Surface 3 | Surface 4 | Surface 5 | Surface 6 | Surface 7 | Surface 8 | Surface 9 | Surface 10 |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|
| Normal.X        | 0         | -1        | 0         | 1         | 0         | 0         | -1        | 1         | 0         |            |
| Normal.Y        | -1        | 0         | 0         | 0         | -1        | -1        | 0         | 0         | -1        |            |
| Normal.Z        | 0         | 0         | 1         | 0         | -1        | 0         | 0         | 0         | 0         |            |
| RootPoint.X     | 0         | 0.025     | -0.025    | -0.025    | -0.025    | 0         | 0         | -0.01     | 0.01      | 0          |
| RootPoint.Y     | 0.05      | 0.05      | 0.05*     | 0.05      | 0.05      | 0         | 0.04      | 0.04      | 0.04      |            |
| RootPoint.Z     | 0         | 0.025     | -0.025    | 0.025     | 0.025     | 0         | 0         | 0.025     | 0.025     | 0          |
| **Inclined Angle** | 0         | 0         | 0         | 0         | 0         | 0         |          |           |            |            |

Table 6  Comparison result of delta volume’s surfaces and target shape’s surfaces, and machining feature determination

| **DV TS** | 6 Surfaces of Delta Volume (DV) |
|-----------|---------------------------------|
|           | 1                               | 2 | 3 | 4 | 5 | 6 |
| 10 Surfaces of Target Shape (TS) | NOT equal | NOT equal | NOT equal | NOT equal | NOT equal | NOT equal. |
| Conversion into Boolean Value | 1 | 0 | 0 | 0 | 0 | 0 |
| | 2 | 0 | 0 | 0 | 0 | 0 |
| | 3 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 0 | 0 | 0 | 0 | 0 |
| | 6 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 0 | 0 | 0 | 0 | 0 |
| | 8 | 0 | 0 | 0 | 0 | 0 |
| | 9 | 0 | 0 | 0 | 1 | 0 |
| | 10 | 0 | 0 | 0 | 0 | 1 |

**Sum** | 0 | 0 | 0 | 1 | 1 | 1 |

**Detected Face**
- Open
- Closed

**Machining Feature**
- Open Slot

By reading the normal value and root point, the system obtains the altitude position of each surface and identifies the most upper surface of each particular machining feature for sequence determination.

![Fig. 6 Recognized machining feature. Based on the comparison of surface in Table 6. The cuboid has 3 open and 3 closed surfaces. Hence, the machining feature type is an open slot.](image-url)
By establishing the value, the system can obtain information about closed or open boundaries on each surface of simple removal volume. Therefore, by calculating the number of open faces and closed faces, the simple removal shape can be recognized as a machining feature by the system. Table 6 describes the result of automatic surface comparison method to identify the open and closed face, converts the surfaces equality information into Boolean, and provides the result of machining feature detection, an open slot. Figure 6 describes the result of the recognized machining feature.

Thus, the identification process of machining feature’s type is done automatically by comparing all surfaces of simple machining primitive with all surfaces of a target shape. Hence, the system provides automatic identification of open and closed faces, counts the total number of open and closed faces, and identifies the machining feature type. The automatic identification process is done in the Solidworks API design table as shown in Table 6.

3. Proposed Process Planning Strategy

After determining the machining feature type in the machining recognition system, the system creates the process plans for each set of machining feature in the machining plan candidates. In this paper, the process planning strategies to generate the best machining plan candidate are proposed in this section. The method is described by Dwijayanti and Aoyama (2013) as follows:

(1). Generate all possible solutions of machining feature candidate by the various ways in disassembly the total delta volume.

(2). Determine the machining sequence by identifying the altitude data of the most upper surface of each primitive machining feature, as shown in Table 4 and Fig. 6. The system sorts the altitude data from the highest to the lowest value. Then, the sequence of machining in particular machining plan candidate is automatically obtained.

(3). Recognize the numerous machining features contained in each possible machining plan candidate.

(4). Eliminate the unacceptable machining patterns by applying common machining rules;

   a. Features with a higher altitude should be machined first,

   b. On the same altitude, features with higher volume should be machined first,

   c. Machining should start from the center,

   d. Cylindrical features should be machined at the end, as described by Shirase, et al., (2013).

(5). Select the cutting tool type, diameter and toolpath type for each machining feature in each machining plan candidates. The toolpath length is calculated based on each machining feature’s toolpath type and the selection of cutting tool type.

(6). Simulation of machining process of the selected machining plan candidates.

(7). Compare the productivity time and obtain the machining plan candidate that requires minimum machining time.
4. Results of Process Planning System (Case Study)

The target shape in this study is a turning-milling part which has many machining features on each side, as shown in Fig. 7. On the target shape, there are six sides to be machined, classified as the upper part, front part, bottom part, back part, right part and left part. Each side has different machining features to be processed. The total delta volume extraction process is shown in Fig. 8. Hereinafter, the cross-sectional view of the total delta volume will be used for further discussion.

4.1 Generation of All 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 process. By applying these rules, 16 combinations of basic order are obtained.

By creating four different orders in each of the 16 basic orders, 64 unique machining patterns are obtained. Hence, the system generates a total of 64 possible machining plans to machine the overall delta volume. Each machining plan has different shapes of removal volumes (manufacturing features). Figure 9 displays only 28 results from among the entire 64 machining orders due to space constraints.

Fig. 9  Result of machining plan candidates (machining pattern) generated by the system. By creating various different orders in cutting the delta volume in each side, 64 unique machining patterns are obtained. This figure displays only 28 results from among the entire 64 machining orders due to space constraints.
Fig. 10 Different way of cutting the delta volume produces different candidates of machining features. Figure 10(a) and 10(b) show different shape and number of machining feature in the two example of machining plans created by the system.

Table 7 Machining feature recognition result (Plan no.1)

| Body | Removal Shape | Surface | Machining Feature | Operation Type |
|------|---------------|---------|-------------------|----------------|
| 1    | Cuboid        | Open    | Face              | Milling        |
| 2    | Cuboid        | Closed  | Closed Pocket     | Milling        |
| 3    | Rectangular Hole | 2       | 4     | Rectangle Boss  | Milling        |
| 4    | Cylindrical Hole | 2       | 1     | Cylinder Boss   | Milling        |
| 5    | Cuboid        | 5       | 1     | Face            | Milling        |
| 6    | Cuboid        | 3       | 3     | Open Slot       | Milling        |
| 7    | Cuboid        | 3       | 3     | Open Slot       | Milling        |
| 8    | Cuboid        | 5       | 1     | Face            | Milling        |
| 9    | Cylinder      | 1       | 2     | Blind Hole      | Milling        |
| 10   | Cuboid        | 5       | 1     | Face            | Milling        |
| 11   | Cuboid        | 4       | 2     | Step            | Milling        |
| 12   | Cuboid        | 4       | 2     | Step            | Milling        |
| 13   | Cuboid        | 5       | 1     | Face            | Milling        |
| 14   | Cylindrical Hole | 2       | 1     | Cylinder Boss   | Milling        |
| 15   | Cylinder Hollow | 1       | 3     | Turning Slot    | Turning        |
| 16   | Cuboid        | 5       | 1     | Face            | Milling        |

Table 8 Machining feature recognition result (Plan no.3)

| Body | Removal Shape | Surface | Machining Feature | Operation Type |
|------|---------------|---------|-------------------|----------------|
| 1    | Cuboid        | Open    | Face              | Milling        |
| 2    | Rectangular Hole | 2       | 4     | Rectangle Boss  | Milling        |
| 3    | Cuboid        | 5       | 1     | Face            | Milling        |
| 4    | Cuboid        | 3       | 3     | Open Slot       | Milling        |
| 5    | Cuboid        | 3       | 3     | Open Slot       | Milling        |
| 6    | Cuboid        | 5       | 1     | Face            | Milling        |
| 7    | Cylinder      | 1       | 2     | Blind Hole      | Milling        |
| 8    | Cuboid        | 5       | 1     | Face            | Milling        |
| 9    | Cuboid        | 1       | 5     | Closed Pocket   | Milling        |
| 10   | Cuboid        | 4       | 2     | Step            | Milling        |
| 11   | Cuboid        | 5       | 1     | Face            | Milling        |
| 12   | Cylindrical Hole | 2       | 1     | Cylinder Boss   | Milling        |
| 13   | Cylinder Hollow | 1       | 3     | Turning Slot    | Turning        |
| 14   | Cuboid        | 5       | 1     | Face            | Milling        |
| 15   | Cuboid        | 4       | 2     | Step            | Milling        |
| 16   | Cuboid        | 4       | 2     | Step            | Milling        |
| 17   | Cuboid        | 5       | 1     | Face            | Milling        |
| 18   | Cuboid        | 1       | 5     | Closed Pocket   | Milling        |
| 19   | Cuboid        | 5       | 1     | Face            | Milling        |

4.2 Machining Sequence Determination

Since the target shape is a 6-sided complex features, the sequence determination is classified by the side order of total delta volume. For each set of machining plan candidate generated, its machining sequence is determined by several rules. The surfaces to be machined are divided into 2 groups. The 1st group consists of 4 sides: Upper (U) - Front (F) - Bottom (Bo) - Back (B) sides. The machining features on the upper part, front part, bottom part and the back part are machined sequentially. The removal process for the machining feature of the 1st group can be done by choosing any side as the starting point of machining. After removing all machining features on that particular side, the next machining features to be removed are the machining features on the next side, which required 90° rotation of the workpiece along the X-axis. The 2nd group consists of 2 sides: Right (R) - Left (L) sides. The machining process in this group required changing of clamping system. The machining features on the left and right sides are processed sequentially. The machining of the 2nd group can be processed either at the beginning or at the end of the process.

For the machining features in each particular side, the machining sequence determination is done by identifying the altitude data of the most upper surface of each primitive machining feature. The system sorts the altitude data from the
highest to the lowest value. Then, the sequence of machining in a particular machining plan candidate is automatically obtained. The others machining sequence rules used in this system are: the process machining starts from the largest volume, from the center, and cylindrical features are machined last. The detailed rules will be described in section 4.4.

4.3 Machining Features Recognition in Each Machining Plan Candidate

The recognition process is done by the machining recognition system as described in section 2. The example of recognition result are shown in Fig. 10(a) and Fig. 10(b). A different way of cutting the delta volume produces different candidates of machining plan. Each machining plan candidate contains a different pattern of machining features. Table 7 and 8 show different result of machining feature in the two examples of machining plans created by the system.

4.4 Proposed Machining Plans Evaluation System

After searching all possible candidates of machining feature from the total delta volume, the system evaluates the candidates based on common machining rules. In this stage, unacceptable candidates are eliminated. The acceptable candidates will be chosen for the next evaluation process.

The system generates 64 possible machining plan candidates to machine the delta volume, as shown in Fig. 9. Every single machining plan candidate has different shape of simple machining features and a distinct machining pattern. This unique shape is due to the various orders for cutting the delta volume in each machining plan.

There are many possibilities for the machining sequence in each of the machining plan candidates. Therefore, an
Table 10  Prepared cutting tools

| 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           | 10            |
| 8       | Drill           | 20            |
| 9       | Facing Tool (Turning) | 10   |
| 10      | Parting Tool    | 10            |

\[
T_m = \frac{L_{tp}}{F} \quad \text{(1)}
\]

\[
T = \sum T_m + nT_t + T_a \quad \text{(2)}
\]

**Note:**
- \(T_t\) = Time for tool changing (min)
- \(T_a\) = Air cutting time (min)
- \(F\) = Feedrate (mm/min)
- \(L_{tp}\) = Toolpath Length (mm)

appropriate sequence evaluation method to choose only acceptable machining plans is needed. 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 9, the machining rules for evaluation are indicated by the letters a, b, c, d, e and f. Letter S means the score.

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. For instance, the machining should not rotate the workpiece before finishing removal of machining features on one particular side. In line with Shirase, et al., (2013), 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).

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.

The final score shows the fulfillment of the requirements of the machining rules. Score 6 means that the machining plan candidate 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 9. As a result of the sequence evaluation, there are only 16 machining plan candidates that have scores of 6. These machining plans meet the requirements of all machining rules and will be evaluated in the next stage. The next evaluation processes are calculating the machining time and enumerating the total number of cutting tool changes.

**Fig. 11** Toolpath and time calculation interface.
4.5 Cutting Tool Selection, Toolpath Calculation and Time Evaluation

The prediction of machining time for each machining feature is conducted by calculating the calculated toolpath length and feedrate data of the selected cutting tool, as shown in Fig.11 and Table 10. Then the total processing time for the machining plan can be obtained by summing the times needed for processing all machining features, air cutting and cutting tool changes, as described in Eq.1 and Eq. 2.

Fig. 12 Result of machining feature recognition (machining plan 1). This figure shows the types of machining features obtained from the recognition process. The features contain both of turning and milling features.

Fig. 13 The simulation of removal process. This figure describes the order of the removal process from blank shape to target shape based on machining plan 1. The removal sequence is obtained automatically from the system.
Overal Delta Volume
Upper Face Pocket with Cylinder & Rectangle Boss
Front Face Open Slot
Bottom Face Hole
Back Face Step
Right Face Cylinder Boss
Left Face Cylinder Boss
Hole with Cylinder Boss
Turning Slot

Fig. 14 Overall machining features based on depth of cut. The individual machining feature shapes are cut in each layer based on the desired depth of cut.

Fig. 15 Structure of overall machining features. This diagram describes the detail structure of machining feature in each side of delta volume.

4.6 Simulation of Machining Process on the Selected Machining Plan Candidate

The detailed process in machining plan no.1 that is shown in Fig. 12 is simulated in the system. The order in which the surfaces are machined is upper-front-bottom-back-right-left. First, the cutting tool will cut the machining feature on the upper part. Machining starts by removing a large cuboid to create a face on the upper part, as shown in Fig. 13(a). After processing a face, the workpiece is as shown in Fig. 13(b). The next machining features to be removed are small cuboids with a rectangular hole and a cylindrical hole to create a pocket with a rectangular boss and a cylindrical boss. The results are as shown in Fig. 13(c).

After removing all machining features on the upper part, the next process is removing the machining features in the front part. A 90° rotation of the workpiece along the X-axis is needed. By this rotation, the front side of the workpiece becomes the upper position, as shown in Fig. 13(d). Then, the first process is to remove a large cuboid to create a face, as shown in Fig. 13(e). The next machining features to be removed are two pieces of long narrow cuboids to create two open slots, as shown in Fig. 13(f) and Fig. 13(g).

The next process is removing the machining features in the bottom part. A 90° rotation of the workpiece along the X-axis is carried out. By this rotation, the bottom side of workpiece has moved into the upper position, as shown in Fig. 13(h). Then, the first process is to remove a large cuboid to create a face, as shown in Fig. 13(i). The next machining feature to be removed is a cylinder to create a blind hole, as shown in Fig. 13(j).

To process machining features on the back part, a 90° rotation of the workpiece along the X-axis is carried out. By this rotation, the back side of the workpiece has moved into the upper position, as shown in Fig. 13(k). Then, the first process is to remove a large cuboid to create a face, as shown in Fig. 13(l). The next machining features to be removed are two cuboids to create two steps, as shown in Fig. 13(m) and Fig. 13(n).

Machining feature removal for the right part can be done directly without rotation of the workpiece as it is clamped by the left side fixture. The first process is removing a cuboid to create a face. The result is shown in Fig. 13(o).

| Mach Plan | Productivity Time (min) |
|-----------|-------------------------|
| 1         | 7.525                   |
| 2         | 8.125                   |
| 3         | 8.000                   |
| 4         | 7.850                   |
| 5         | 8.100                   |
| 6         | 8.100                   |
| 7         | 8.575                   |
| 8         | 8.575                   |
| 9         | 8.125                   |
| 10        | 8.250                   |
| 11        | 8.275                   |
| 12        | 8.575                   |
| 13        | 8.200                   |
| 14        | 8.299                   |
| 15        | 8.625                   |
| 16        | 8.850                   |

Table 11 Productivity comparison (processing time) of each acceptable machining plans.
Table 12  The data of program execution time. The generation of all possible machining plan candidates requires the longest computation time.

| No | Process                                                                 | Time  |
|----|-------------------------------------------------------------------------|-------|
| 1  | Subtract the target shape and the raw material to get the total delta volume (TDV) | 7 s   |
| 2  | Identify each surface’s parameters of TDV                                | 10 s  |
| 3  | Identify each surface’s parameters of target shape.                     | 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  |
| 5  | Generate all possible solution of machining plan candidates by cutting the TDV based on the variation of cutting planes. | 1.5 hours |
| 6  | Compare each surface of a simple machining feature shape in each machining plan candidate with each surface of the TDV | 30 min |
| 7  | Determine the name of each machining feature contained in a machining plan candidate. | 10 s  |
| 8  | Apply elimination rules to each machining plan candidate.               | 28 min|
| 9  | Eliminate the unacceptable machining plan candidates.                   | 55 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|

Total program executing time: 
for computer specification: Intel (R) core (TM) i-7-2600 CPU @3.4 GHz 3.4 GHz RAM 4 GB = 4.06 hours

The next machining feature to be removed is a cuboid with a cylindrical hole to create a cylinder boss, as shown in Fig. 13(p). Then, a cylinder with a cylindrical hole is removed to create a hole with a cylindrical boss, as shown in Fig. 13(q).

The next process is removing the machining features in the left part. For this step, the clamping of the workpiece must be changed to the right side fixture. The result is shown in Fig. 13(r). Then, the first process is removing a cuboid to create a face. The result is shown in Fig. 13(s). The next machining feature to be removed is a cuboid with a cylindrical hole to create a cylinder boss, as shown in Fig. 13(t). The last process is removing a cylinder with a hole to create a turning slot. The result is shown in Fig. 13(u). All processes are carried out by milling, except the turning slot, the last feature in the left part, which is machined by turning.

4.7 Machining Time Comparison

The comparison of machining time for each machining plan candidate can be seen in Table 11. This table describes the prediction of processing time for each machining plan candidate. Based on this productivity comparison, the system can select the optimum machining pattern and sequence which has the minimum processing time, as shown in Fig. 13. Hence, the best machining plan which has the minimum cutting time is machining plan 1. The overall machining features based on depth of cut can be seen in Fig. 14 and the details of the machining features structure can be seen in Fig. 15.

5. The Advantages and Disadvantages of the Designed Process Planning System

In this research, the developed system consists of machining feature recognition system and process planning system has several advantages and disadvantages. The advantages for the system are listed as follows;

(1). Initial form feature identification of the target shape is not necessary.

(2). Machining features are determined automatically from the delta volume.

(3). Various candidates of machining feature are obtained by cutting the delta volume.
(4). The system searches all possible candidates of machining features.
(5). The unacceptable candidates are eliminated automatically by applying several machining rules.
(6). The system is able to select the best candidate of machining features based on user evaluation points, in this stage the evaluation point is the shortest processing time.
(7). Different evaluation point produces a different pattern of machining plan candidates.
(8). The system is able to give suggestion to the user (machining operator) to select the best machining plan based on the evaluation points.

However, the developed system also has several disadvantages. The disadvantage is related to the long computation time, as follows;
(1). Generation of all possible of machining plan candidates requires the longest computation time among other steps in process planning system, as shown in Table 12.
(2). Due to the complexity of target shape, approximately 4.06 hours were required for all of the computation process to generate the machining plan candidates, evaluate the acceptable machining plan candidates and compare each machining time, as shown in Table 12.

6. Conclusion

In conclusion, Solidworks API has been used in the designed system to create an automatic process planning system for Turning Milling parts based on machining feature recognition. The machining feature candidates are obtained by cutting the overall delta volume. The system provides automatic disassembly of the delta volume into simple machining features, feature recognition, tool-path length calculation and prediction of processing time. In this study, a new approach to automatic machining feature recognition has been developed based on a dimension table and surface comparison of the delta volume. The process planning system is able to generate 64 alternative machining plans, to evaluate all possible machining sequences by several machining rules, and to identify the machining plan which has the shortest processing time.

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