Development of a CAPP system for multi-tasking machine tools to deal with complicated machining operations

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Abstract
There is always strong impetus to shorten the manufacturing lead-time of mechanical products. Seeking higher efficiency through multi-tasking machine tools has attracted attention for its many advantages in the field of machining. There are a lot of different kinds of multi-tasking machine tool structures that have both turning and milling functions. Therefore, the machining operations are generally complicated, and it takes a great deal of time and labor to generate numerical control (NC) programs. To reduce preparatory time, computer aided process planning (CAPP) systems are needed to automatically determine machining process parameters such as machining sequence, cutting tool, cutting conditions. This study aims to develop a CAPP system for multi-tasking machine tools with two confronting spindles to deal with complicated machining operations. Chucking switch for a workpiece between two confronting turning spindles is introduced to realize 6-face machining of a complex target shape. A workpiece shape and target shape are divided into two domains related to the main turning spindle side and sub turning spindle side, respectively. Then, the machining features can be recognized from each domain according to the assumed spindle side. Moreover, parallel machining using plural functions of turning and milling can be achieved by recognizing machining features that are simultaneously machined by the same machining method. The results of case studies confirmed that the developed CAPP system is effective for NC program generation of complicated machining operations on multi-tasking machine tools.

Keywords: CAPP, Process planning, Multi-tasking machine tool, Machining feature, Complicated operation

1. Introduction

Manufacturing industries have tended towards high-mix low-volume production in recent years. As a result, there is strong impetus to shorten the manufacturing lead time of mechanical products. Gaining higher efficiency by using multi-tasking machine tools has attracted attention due to its many advantages in the field of machining. Typical multi-tasking machine tools have both turning and milling functions, where various machining processes have been integrated to cope with the increased demand for a small quantity of parts with complex geometry, that can be produced with high accuracy in a short machining time. In addition, some characteristic abilities, such as chucking switch of a workpiece, can be realized between two confronting turning spindles to remove manual setting operations. However, such machining operations are generally complicated because of the highly flexible functions and abilities. Thus, it takes a great deal of time and labor to generate the numerical control (NC) program for multi-tasking machine tools.

Computer aided manufacturing (CAM) systems and related technologies such as collision avoidance and machine simulation are necessary to operate multi-tasking machine tools effectively. To perform highly efficient machining, CAM systems are expected to minimize the effort required for NC program generation. Although some commercial CAM systems have been designed for multi-tasking machine tools, they commonly require long operating times to manually assign machining methods, allocate target parts, and generate tool paths. From a practical point of view, further efforts are needed to improve these technologies.

In this study, a computer aided process planning (CAPP) system is developed for multi-tasking machine tools to
deal with the complicated machining operations. The system reduces the preparatory time on CAM systems by automatically determining machining process parameters. Moreover, it helps to accomplish the chucking switch of a workpiece between two confronting turning spindles, and parallel machining using plural functions of turning and milling simultaneously. In order to confirm the system’s feasibility, case studies are conducted by assuming complex parts machining. The results indicate that the developed CAPP system is effective for NC program generation of complicated machining operations on multi-tasking machine tools.

2. Computer aided process planning system

In order to reduce the preparatory time on a CAM system, a CAPP system is expected to automatically determine machining process parameters such as machining sequence, cutting tool, cutting conditions (Sugimura, 2006). Feature recognition has been considered as a key technology in the development of CAPP systems. Machining feature means a characteristic shape pattern that can identify the specific machining operation. Many feature recognition methods have been already proposed, and they treat a target shape as an object to be recognized (Wang et al., 2010; Woo et al., 2005; Hamada et al., 2016). However, machining features should be recognized from the removal volume in nature, because that volume changes depending on workpiece shapes. Although some researchers have attempted to recognize machining features from the removal volume (Morinaga et al., 2011, 2014; Nishida and Shirase, 2018a, 2018b), multi-tasking machine tools are not assumed as the utilized machine tool. On the other hand, few feature recognition methods proposed for multi-tasking machine tools (Dwijayanti and Aoyama, 2014; Ueno and Nakamoto, 2015) have considered complicated machining operations and complex target shapes adequately.

In this study, a CAPP system is developed to deal with complicated machining operations and complex target shapes using the novel machining features proposed in the authors’ previous study (Ueno and Nakamoto, 2015). Machining primitives are first obtained from the removal volume. Then, machining features are recognized by allocating a machining sequence for each machining primitive. The proposed machining features can be assigned to several alternative machining methods, and contribute directly to allocation of the machining sequence. Thus, process planning would be conducted based on the respective machining strategy depending on available cutting tools and the structure of machine tools. Because a machining operation varies according to the recognized machining features, including cutting tools and cutting conditions, a prediction method for process evaluation indices has also been also devised (Koremura et al., 2017).

CAD models of a workpiece shape and target shape are prepared as input information for proposed machining feature recognition. In order to obtain machining primitives, the removal volume is divided by faces that are created by extending their own boundary faces, as shown in Fig. 1. The boundary face is determined to be the face where the

![Fig. 1 Acquisition of machining primitives. It is possible that some collections of machining primitives will occur according to the division pattern. Machining primitives are obtained by dividing a removal volume by some extended boundary faces.](image-url)
removal volume and target shape come into contact. Then, the machining sequence is allocated based on the information of the newly generated surface, volume of machining primitives, and so on. Finally, machining features are recognized according to the number of generated surfaces and a circle edge. Figure 2 shows the proposed machining features in the previous study (Ueno and Nakamoto, 2015). Machining features (A)–(D) are made from a cylindrical machining primitive, and (a) is integrated into the above machining features to add a hole as needed. Similarly, machining feature (E)–(L) are made from a rectangular machining primitive, and (b) is integrated into the above machining features to add a hole as needed.

3. Complicated machining operations

In the authors’ previous study (Inoue and Nakamoto, 2017), target shapes are limited to cuboids on the assumption that a 3-axis controlled machining center is utilized. Thus, when a multi-tasking machine tool is assumed as the utilized machine tool, target shapes can be expanded to complex geometry parts including cylindrical shapes. In this system, a complex target shape is first approximated, and the machining features are recognized from the removal volume. In the case where chucking switching is necessary, a workpiece shape and target shape are divided into two domains related to the main turning spindle side and sub turning spindle side, respectively. Moreover, available machining features are detected to accomplish parallel machining using plural functions of turning and milling simultaneously on the multi-tasking machine tool. Simple Modeler (AIKOKU ALPHA Corp.) is used as a CAD software, and the API functions of Simple Modeler and C# are used to develop a CAPP system.

3.1 Feature recognition for complex target shape

Specific areas such as chamfer and fillet parts should be identified before recognizing machining features because they are usually machined at the final dedicated operation. Therefore, a target shape is modified to remove the specific areas, as described in the authors’ previous study (Inoue and Nakamoto, 2017). As shown in Fig. 3, the face of a machining primitive is detected as a chamfer part by comparing the distances and lengths of long edges. Then, the target shape is approximated to remove the chamfer part by creating a new edge. Similarly, a target shape with a fillet part is also approximated for filleting. The difference between the approximated target shape and the original one is obtained as a special machining primitive. In this study, not only planar and cylindrical faces but also conical and torus faces are considered to detect the candidates for chamfer and fillet parts.

A machining feature is recognized depending on the number of newly generated surfaces and the shape, while the machining sequence of each machining primitive is allocated. However, machining features cannot be directly recognized when machining primitives are not simple shapes such as a cylinder or a cuboid. On the other hand, it is not...
practical to define an infinite number of machining features corresponding to various shapes of machining primitives. Therefore, complex machining primitives are simplified. A shape having a tapered or conical face is converted to a cylinder, and other shapes are converted to a cuboid, as shown in Fig. 4. Moreover, the properties of generated surfaces are succeeded to a converted machining primitive from an original machining primitive. Then, one of the previously proposed machining features is recognized for each simple machining primitive. Finally, the simple machining primitive is restored to the complex machining primitive to determine machining process parameters and process planning can be conducted by selecting suitable machining method, cutting tools, cutting conditions, and so on.

### 3.2 Workpiece chucking switch

There is a wide variety of multi-tasking machine tools in the industry. Among them, a type with two confronting turning spindles is common and suitable for the creation of complex target shapes by lathe turning and 6-face machining. In order to introduce a workpiece chucking switch for 6-face machining, a workpiece shape and target shape are separated by a dividing face into two domains that are chucked by either the main turning spindle or the sub turning spindle. However, there are many candidates of dividing faces based on prepared machine tools, cutting tools, and so on. In addition, the workpiece chucking switch can be carried out when the machining primitive adjacent to the dividing face is not simplified. In this study, therefore, whole faces whose normal vectors are parallel to turning spindles are firstly acquired from the target shape. Then, the face that has the largest area of the circumscribed rectangular is detected as the dividing face. The separated workpiece shape at the side of the main turning spindle and the separated target shape at the side of the sub turning spindle are merged and treated as a new target shape to recognize machining features for machining operations using the main turning spindle as shown in Fig. 5. In the same
3.3 Parallel machining

Multi-tasking machine tools have both turning and milling functions. Thus, parallel machining is expected to improve machining efficiency by using these plural functions simultaneously. In order to achieve parallel machining, two machining features with a successive machining sequence that are machined by either turning or milling are detected. When they do not overlap in the vertical direction of the center axis of the turning spindle, the two machining features are machined simultaneously. After recognizing the machining features of each turning spindle side, the workpiece chucking switch is introduced between the respective machining operations in the developed CAPP system.

Fig. 6 Detection of machining features for parallel machining. In serial machining, each machining feature is machined in order from sequence 1 to 3. In parallel machining, two machining features such as sequences 2 and 3, can be machined simultaneously, because these machining features do not overlap in the vertical direction of the center axis of the turning spindle.
features are assumed to be machined simultaneously. Figure 6 shows an example of machining features that are candidates for parallel machining. The machining features of machining sequences 1 and 2 cannot be machined simultaneously because they overlap in the vertical direction of the turning spindle. On the other hand, the machining features of machining sequences 2 and 3 can be machined simultaneously because they do not overlap in the vertical direction of the turning spindle after the machining feature of machining sequence 1 is removed.

4. Case study

Case studies are conducted to confirm that the developed CAPP system is useful to automatically determine the machining process parameters of complex parts machining by multi-tasking machine tools. Moreover, the feasibility is confirmed to deal with complicated machining operations on multi-tasking machine tools.

The assumed multi-tasking machine tool has a milling function with 5-axis control, two confronting spindles and a lower turret with plural cutting tools. In terms of the cutting tools, a turning tool, cut-off tool, three types of square end mills (6, 12 and 30 mm in diameter) and two types of drills (4 and 8 mm in diameter) are prepared. The recommended cutting conditions for the carbon steel of the workpiece material are adapted based on the tool catalog. Machining features are recognized and machined first on the main turning spindle side. A turning operation is selected for a machining primitive when both turning and milling operations are available.

The machining sequence gives priority to operations by considering the ease of tool approach. Thus, the machining primitive with the smallest number of generated surfaces is machined first. When the generated surface is a cylindrical surface excluding (a) Boss C and (b) Boss P, the number of generated surfaces is varied from 1 to 4 to match the machinability with a plane; for example, the number of generated surfaces becomes 4 in case of a cylinder. In addition, the machining primitive with the largest total area of generated surfaces is given priority when there are machining primitives with the same number of generated surfaces.

Although the turning tool is selected to machining features of the cylinder type when the machining method is turning, the cut-off tool is applied for grooving in the case of neither a straight turning nor an end-face turning. The drill is applied to machining features of the cylinder type when the tool diameter is the same as the diameter of the machining feature. Square end mills are adopted for the other machining features, and the largest tool is used within the smallest distance between confronting generated surfaces and the diameter of the rounded corner parts. The tool axis is decided based on the normal vector of the largest generated surface such that the normal vector does not intersect the target shape.

4.1 Case study for determining machining process parameters

In this case study, the workpiece shape and target shape shown in Fig. 7, respectively, are prepared. Machining process parameters are determined for a multi-tasking machine tool using the developed CAPP system.

Table 1 summarizes the recognized machining features, machining process parameters, and tool paths generated by a commercial CAM system (ESPRIT 2015, DP Technology Corp.). Eleven machining primitives are obtained, and 6 kinds of machining features are recognized from the removal volume. Regarding the machining sequence, for example, the machining primitive of machining sequence 3 is set to be machined prior to the machining primitive of machining sequence 6 because the numbers of generated surfaces are 2 and 5, respectively. Tool paths are generated according to

Fig. 7 Input data of case study for determining machining process parameters.

(a) Workpiece shape

(b) Target shape
the machining process parameters, including selected tools, machining method, and so on. In machining sequences 1 and 2, the turning tool is selected for these machining features because the machining method is turning. In machining sequences 3–7, milling is assigned as the machining method for machining features. For machining sequences 3 and 4, the square end mill with 30 mm in diameter is selected because the smallest distance exceeds 30 mm. On the other hand, in machining sequence 5, the square end mill with 12 mm in diameter is selected because the smallest distance is 17.5 mm. In machining sequences 6 and 7, the square end mill with 30 mm in diameter is again selected because no drills have the same diameter as the machining feature, and the smallest distance exceeds 30 mm. For machining sequences 8 and 9, the drill with 8 mm in diameter is applied to these machining features because the machining features are cylinder type, and the drill has the same diameter. For machining sequences 10 and 11, the square end mill with 6 mm in diameter is selected because the corner diameter is 10 mm.

From the results, it is found that the developed CAPP system can determine the machining process parameters of complex parts machining on a multi-tasking machine tool.

Table 1  Recognition of machining features and determination of machining process parameters. Eleven machining primitives are obtained, and 6 kinds of machining features are recognized. Symbols in the table follow Fig. 2. Tool paths are generated by using a commercial CAM system.

| Machining sequence 1 | Machining sequence 2 | Machining sequence 3 |
|----------------------|----------------------|----------------------|
| Type of machining feature: (B) | Type of machining feature: (B) + (a) | Type of machining feature: (K) |
| Tool primitive | Tool path | Tool path | Tool path |
| Tool | Turning tool | Turning tool | Square end mill (ϕ 30 mm) |
| Cutting speed | 200 m/min | 200 m/min | Speed |
| Feed rate | 0.3 mm/rev | 0.3 mm/rev | Feed |
| Depth of cut | 5 mm | | Depth of cut |

| Machining sequence 4 | Machining sequence 5 | Machining sequence 6 |
|----------------------|----------------------|----------------------|
| Type of machining feature: (J) | Type of machining feature: (K) + (b) | Type of machining feature: (C) |
| Tool | Square end mill (ϕ 30 mm) | Tool | Square end mill (ϕ 12 mm) | Tool | Square end mill (ϕ 30 mm) |
| Speed | 300 min⁻¹ | Speed | 750 min⁻¹ | Speed | 300 min⁻¹ |
| Feed | 75 mm/min | Feed | 125 mm/min | Feed | 125 mm/min |
| Depth of cut | 5 mm | Depth of cut | 2 mm | Depth of cut | 5 mm |

| Machining sequence 7 | Machining sequence 8 | Machining sequence 9 |
|----------------------|----------------------|----------------------|
| Type of machining feature: (A) | Type of machining feature: (C) | Type of machining feature: (C) |
| Tool | Square end mill (ϕ 30 mm) | Tool | Drill (ϕ 8 mm) | Tool | Square end mill (ϕ 6 mm) |
| Speed | 300 min⁻¹ | Speed | 3600 min⁻¹ | Speed | 1500 min⁻¹ |
| Feed | 75 mm/min | Feed | 720 mm/min | Feed | 100 mm/min |
| Depth of cut | 5 mm | Depth of cut | 1 mm | Depth of cut | 1 mm |
4.2 Case study for verifying complicated machining operations

In this case study, three process patterns (A, B, C) are supposed using the workpiece shape and target shape shown in Fig. 8 to verify the feasibility of workpiece chucking switch and parallel machining. In Pattern A, neither workpiece chucking switch nor parallel machining are assumed. In Patterns B and C, the workpiece chucking switch is introduced, parallel machining is also utilized in Pattern C.

Table 2 summarizes the machining features according to the allocated machining sequence in Pattern A. Fifteen machining primitives are obtained, and 6 kinds of machining features are recognized. Regarding the machining sequence, for example, the machining primitive of machining sequence 6 is set to be machined prior to the machining primitive of machining sequence 8 because the numbers of generated surfaces are 2 and 3, respectively. Furthermore, such as machining sequence 10, the machining primitive having small area of generated surfaces is machined later. In this pattern, machining features are recognized only from the main turning spindle side, because neither workpiece chucking switch nor parallel machining are assumed. On the other hand, a dividing face is detected from the target shape to assume the workpiece chucking switch in Patterns B and C. As shown in Fig. 9, the workpiece shape and target shape are divided into two domains to recognize the machining features from the main turning spindle side and the sub turning spindle side, respectively.

![Fig. 8 Input data of case study for complicated machining operation.](image_url)

(a) Workpiece shape  
(b) Target shape

| Machining sequence 1 | Machining sequence 2 | Machining sequence 3 | Machining sequence 4 | Machining sequence 5 |
|---------------------|---------------------|---------------------|---------------------|---------------------|
| (B) + (a)           | (B) + (a)           | (B) + (a)           | (B) + (a)           | (B) + (a)           |
| Machining sequence 6 | Machining sequence 7 | Machining sequence 8 | Machining sequence 9 | Machining sequence 10 |
| (K)                 | (B) + (a)           | (D) + (a)           | (J)                 | (D) + (a)           |
| Machining sequence 11| Machining sequence 12| Machining sequence 13| Machining sequence 14| Machining sequence 15|
| (G)                 | (A)                 | (G)                 | (A)                 | (G)                 |

Table 2 Recognition results of machining features in Pattern A. Fifteen machining primitives are obtained, and 6 kinds of machining features are recognized. Symbols in the table follow Fig. 2.
Table 3 summarizes the machining features according to the allocated machining sequence in Pattern B. In this pattern, only the workpiece chucking switch is assumed. Unlike Pattern A, the workpiece shape and target shape are divided into two domains for recognition of machining features. Twelve machining primitives are obtained and 6 kinds of machining features are recognized at the main turning spindle side. Similar to above case studies, the machining primitive of machining sequence 4 is set to be machined prior to the machining primitive of machining sequence 6 because the numbers of generated surfaces are 2 and 3, respectively. Moreover, 4 machining primitives are obtained and 2 kinds of machining features are recognized at the sub turning spindle side. The workpiece chucking switch is carried out between machining sequences 12 and 13.

Table 4 shows the machining features according to the allocated machining sequence in Pattern C. As with pattern...
B, the workpiece chucking switch is introduced. Twelve machining primitives are obtained and 6 kinds of machining features are recognized at the main turning spindle side. 4 machining primitives are obtained and 2 kinds of machining features are recognized at the sub turning spindle side. In this pattern, machining sequence 5 is integrated to simultaneously machine two machining features by one turning operation and machining sequence 9 is integrated to simultaneously machine two machining features by one milling operation. Thus, parallel machining is available and the total number of sequences is reduced compared to Patterns A and B.

The machining time is estimated by generating tool paths using a commercial CAM system (ESPRIT 2015, DP Technology Corp.) for the three patterns. Table 5 summarizes the estimated machining time, not including the time for tool changes, workpiece transfer, and chucking switch. It is found that machining time decreased in order from A to C. Machining time for Pattern A is the longest of the three because the cutting distance is longer due to some recognized machining features that required grooving operations, as shown in Fig. 10(a). On the other hand, machining times are shorter for Patterns B and C because a turning operation with the sub turning spindle after the workpiece chucking switch is decided for the same area, as shown in Fig. 10(b). In addition, realizing parallel machining in Pattern C decreased the number of machining sequence, as shown in Fig. 11.

From the results of this case study, it is found that the developed CAPP system is helpful for dealing with complicated machining operations such as workpiece chucking switch and parallel machining. Moreover, different process planning parameters can be presented to operators according to the priority to allocate machining sequence in the proposed CAPP system. Thus, operators can obtain appropriate machining process parameters depending on their own machining strategy by comparing the selected cutting tools, the required machining time, and so on.

Table 4  Recognition results of machining features in Pattern C. As with Pattern B, machining features are recognized at each turning spindle side. Moreover, machining features of sequences 5 and 9 are integrated on the assumption of parallel machining. As a result, the total number of machining sequences are decreased.

| Main turning spindle side | Machining sequence 1 | Machining sequence 2 | Machining sequence 3 | Machining sequence 4 |
|---------------------------|----------------------|----------------------|----------------------|----------------------|
| (B) + (a)                 | (B) + (a)            | (B) + (a)            | (K)                  |
| Machining sequence 5 (Parallel machining) | (B) + (a) | (D) + (a) | (J) |
| Machining sequence 8      | (A)                  | (G)                  | (A)                  | (G)                  |
| Sub turning spindle side  | Machining sequence 11 | Machining sequence 12 | Machining sequence 13 | Machining sequence 14 |
| (B) + (a)                 | (B) + (a)            | (B) + (a)            | (D) + (a)            |
5. Conclusions

This study aims to develop a CAPP system for multi-tasking machine tools with two confronting spindles to deal with complicated machining operations. The developed CAPP system automatically recognizes machining features through allocating the machining sequence to each machining primitive. In order to determine machining process parameters for multi-tasking machine tools, the previously proposed method is expanded to treat target shapes with

Table 5 Machining time estimated by a commercial CAM system for the three patterns. Machining time for Pattern A is the longest due to the long cutting distance. Machining time is shorter by adapting workpiece chucking switch for Pattern B and also is the shortest of the three by using workpiece chucking switch and parallel machining in Pattern C.

| Pattern | w/o chucking switch | w/ chucking switch | W/ parallel machining |
|---------|---------------------|--------------------|----------------------|
| A       | 74.57               | 59.45              | 59.02                |
| B       |                     |                    |                      |
| C       |                     |                    |                      |

Fig. 10 Different tool paths in the same area. (a) shows a grooving operation assigned using a cut-off tool. (b) shows a turning operation allocated for the same area by the sub turning spindle after the workpiece chucking switch.

Fig. 11 Parallel machining using plural cutting tools in Pattern C. (a) shows that a parallel turning operation is allocated to two machining features of successive machining sequences in new machining sequence 5. (b) shows that parallel milling operation is allocated to two machining features of successive machining sequences in new machining sequence 9.
complex geometry parts including cylindrical shapes. Chucking switching of a workpiece between two confronting turning spindles is introduced to realize 6-face machining of complex shapes. A workpiece shape and target shape are divided into two domains related to the main turning spindle side and the sub turning spindle side, respectively. Then, machining features are recognized from each domain according to the assumed spindle side. Moreover, parallel machining using plural functions of turning and milling is achieved by recognizing machining features that can be simultaneously machined by the same machining method. From the conducted case study, it is confirmed that the developed CAPP system is effective for NC program generation of complicated machining operations on multi-tasking machine tools.

A workpiece shape and target shape are separated into two domains by a dividing face having the largest area of the circumscribed rectangular in this study. Therefore, a suitable dividing face would be decided considering the target shape and its chucking based on the prepared machine tools, cutting tools, jigs, etc. in future research.

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