Auto-recovery from Machining Stoppages Based on STEP-NC

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ABSTRACT

Machining stoppage occurs from time to time due to various reasons. For the current CNC system using G/M code as part program, to recovery from the stoppage, the operator needs to scroll the part program to find the specific lines where the stoppage happens and make changes to it, because the part program only contains low level machining information, i.e. tool-paths. This process highly relies on operator's experience and is time-consuming. STEP-NC as a new standard for part program defines the machining of a workpiece by workingsteps of machining features, which include geometry information and machining strategy for each feature. Helped by that information in STEP-NC part program, the system is able to plan the retracting toolpath, use different strategies to recover from the stoppage and even regenerate new toolpath for an alternative cutter if the same one is unavailable. When using traditional CNC system, the machining of unfinished workpiece cannot be resumed by another machine tool due to the G/M code's hardware dependency. However, the feature-level machining history information can be stored in STEP-NC file and transferred to another machine, which will be used for process planning and toolpath generation. After relocating the workpiece coordinate system in the alternative machine, the machining can be resumed.

1. INTRODUCTION

The Computer Numerical Control (CNC) machine tool plays an important role in manufacturing automation. Currently, nearly all CNC systems use G/M code as the basis of a part program, which defines very basic machining tool-paths (G code) and commands for programmable logic controls (PLC) (M code) [1]. The information flow of manufacturing a workpiece typically starts from Computer Aided Design (CAD), which provides geometric description, to Computer Aided Process Plan (CAPP) / Computer Aided Manufacturing (CAM) system, where G/M code is generated, and ends at CNC system, where tool-paths in part program are interpolated to generate commands to control the axis [2]. Apparently, after G/M code is generated, all high-level information of the workpiece is lost, making the information flow unidirectional. Apart from that, the G/M code is not only hard to read and modify by operator but also machine tool dependent, which increases lead time and cost [3].

As a new part programming interface, Standard for the Exchange of Product model data - Numerical Control (STEP-NC) defines features and corresponding strategies for machining the features. Workingstep is the basic execution elements instead of tool-path, which brings possibility to realize the data flow from CNC back to CAM [4]. STEP-NC part program is more portable and interoperable because it is no longer machine tool dependent, and there is no need for post processors [5].

Modern CNC machine tools advance in robustness and reliability, but machining stoppage still happens due to failures, such as tool failure, hardware and/or software error, communication error when using fieldbus, and etc. With the traditional CNC system using G/M code as part program, recovery from the stoppage of the machining process entails the operator's locating the specific line(s) where the stoppage happened, finding out the cutting parameters corresponding to the stoppage and eventually making necessary changes to the G/M code. If the cutter needs to be replaced and no cutter with the same parameter is available, it is likely that a new set of G/M codes is required to be regenerated by CAM system. To do this, operator's experience is a must and even so the task is normally very time-consuming. If the workpiece is dismounted from the machine tool, lost of coordinate systems' relation and lack of

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machining historical information make the recovery even harder. Often a simpler approach is taken, i.e. re-machining the half-finished part from the very beginning or simply discarding it, which leads to a waste of time and/or material.

There is numerous research focusing on machining monitoring system [6] and cutting tool monitoring system [7]. Many commercial cutting tool monitoring system are also available on the market [8]. Those system combine sensor technology and signal processing technology and develop strategies for decision making. Based on various tool failure situations, tool monitoring system gives different types of warnings or triggers emergency stop. As for recovering from failures, Moon and Moodie analyzed the cause of failure in manufacturing cells and presented the recovery strategy [9]. Kao proposed a framework of generating recovery strategies for assembly processes [10]. Berruet, Toguyeni, et al. presented recovery procedure for flexible manufacturing system which implemented a model applying graphic theory based algorithms [11]. However, the above mentioned papers deal with the recovery in the manufacturing system level and not focus on recovering machining. Some commercial CNC systems supporting interruption and customs macros make possible the auto recovery of tool failure [12]. Nevertheless, that practice is still highly machine tool dependent and cannot deal with unavailability of the same cutter.

In Section 2, a brief introduction to STEP-NC and an example demonstrating how manufacturing information is defined by attributes and entities are presented to facilitate the understanding of rest sections. After discussing about the action to take at the moment when stoppage incidents take place in Section 3, developed strategies for recovering from stoppage are presented in Section 4. In the last section, the method to relocate workpiece coordination system and the information needed for inter-machine recovery are demonstrated.

2. STEP-NC FEATURES

STEP-NC describes the machining of a workpiece by defining workplans and workingsteps for machining features. The data structures involved in the paper are defined by ISO14649-1 [13], which defines fundamental principles, ISO14649-10 [14], which defines manufacturing features of the workpiece, and ISO14649-11 [15], which defines processes for milling indicating how the workpiece should be machined. STEP-NC complies with STEP in describing data structure by standard data modeling language EXPRESS and standard graphical notion EXPRESS-G supporting a subset of EXPRESS. To illustrate an example how machining information is defined by a STEP-NC part program, a Unified Modeling Language (UML) object diagram is shown in Figure 1, which is obtained by a mapping from EXPRESS [16].

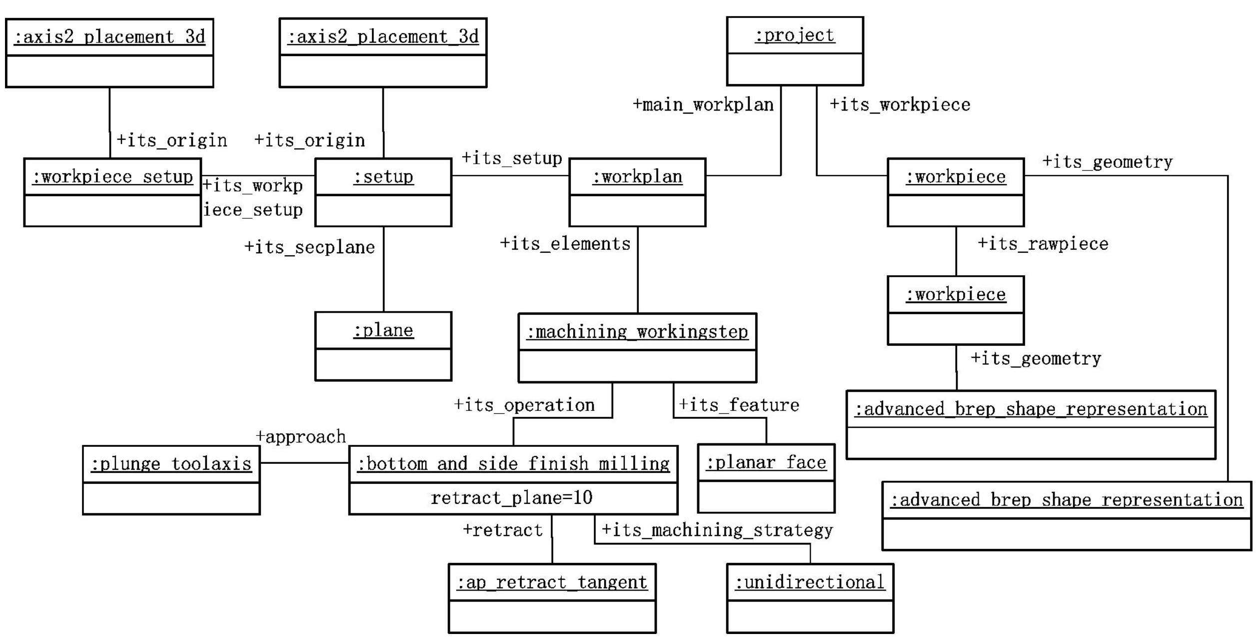

Figure 1. Example of information defining by ISO14649.

The top-level entity called Project is mandatory for ISO14949 based data model. It defines its_workpiece as the identification of workpiece to be machined and main_workplan as a top-level workplan. The information stored by its_workpiece includes descriptions of raw piece (its_rawpiece) and exact final geometry (its_geometry) of the workpiece. It is worth to note that the description of raw piece is in the same type as the workpiece.

The top-level workplan defines its_setup, which defines global security plane (its_secplane), setup origin in machine coordinate system (its_origin), and workpiece setup (its_workpiece_setup) e.g. workpiece origin in setup coordination system (its_origin) and its_elements, which is a list of executables. The executables is an abstract entity which means it must be inherited. In this example, the machining_workingstep is the inherited subtype describing a specific machining process which defines the feature to be machined (its_feature), which is of abstract Type manufacturing_feature, and the corresponding operation (its_operation). This paper mainly focuses on the 2.5D feature defined by two5D_manufacturing_feature which is the subtype of manufacturing_feature. Subtype of two5D_manufacturing_feature includes planar_face, pocket, slot, step, round_hole, toolpath_feature, profile_feature, boss, spherical_cap, rounded_end and thread.

The machining operation is defined by abstract Type operation as general description. The more detailed operation is specified by inheritations of abstract supertypes. An example bottom and side finish milling operation is shown in Table 1 with help by EXPRESS to HTML Converter by STEP Tools [17]. Some of the attributes are worth noting. The Entity retract_plane defines a retract plane, which the start and end points of the operation are within. Attributes approach and retract are in the same type approach_retract_strategy, which specifies the way that cutter approaches/plunges or retracts to or from the workpiece. The Attribute its_machining_strategy defines the strategies for generating tool-paths for the operation including unidirectional, bidirectional, contour_parallel, bidirectional_contour, contour_bidirectional, contour_spiral, center_milling, and explicit_strategy.

Table 1. Attributes in Entity bottom_and_side_finish_milling.

Attribute	Type	Defined By
its_toolpath	toolpath_list (ENTITY)	operation
its_tool_direction	tool_direction (ENTITY)	operation
its_id	identifier (STRING)	machining_operation
retract_plane	length_measure (REAL)	machining_operation
start_point	cartesian_point (ENTITY)	machining_operation
its_tool	machining_tool (ENTITY)	machining_operation
its_technology	technology (ENTITY)	machining_operation
its_machine_functions	machine_functions (ENTITY)	machining_operation
overcut_length	length_measure (REAL)	milling_machining_operation
approach	approach_retract_strategy (ENTITY)	milling_type_operation
retract	approach_retract_strategy (ENTITY)	milling_type_operation
its_machining_strategy	two5D_milling_strategy (ENTITY)	two5D_milling_operation
axial_cutting_depth	length_measure (REAL)	bottom_and_side_milling
radial_cutting_depth	length_measure (REAL)	bottom_and_side_milling
allowance_side	length_measure (REAL)	bottom_and_side_milling
allowance_bottom	length_measure (REAL)	bottom_and_side_milling

3. REACTING TO STOPPAGE INCIDENTS

For the incident from which the monitoring system only gives warning and the interpolation of the axis can still be operate, it is the interpolator's responsibility to retract the cutter from the workpiece to guarantee the realtime response. The interpolator's state transition diagram is shown in Figure 2.

The referencing state and the continuous speed control state are for reference returning operation to establish the machine coordinate system and continuous jog mode respectively. Other operation modes that involving position control e.g. incremental jog mode and auto-machining mode operate under State interpolating, in which the interpolator retrieve tool-paths from toolpath list in a manner called look-ahead, i.e. reading in multiple tool-paths and decide the feed rate at the connecting point of adjacent toolpaths. If the toolpath list is empty, the interpolator will stop after the last toolpath and wait for the new toolpath. When a stoppage incident occurs, the interpolator enters the cutter disengaging state, in which flowing three actions operate simultaneously.

- Continues feeding the axis along the toolpath but with the maximum deceleration.
- Drives the cutter away from the workpiece to the retract plane in the maximum acceleration and speed. The distance of drive-away movement can be calculated by the current operation's attribute retract_plane. For plane milling or side milling, the disengaging movement's direction is along z axis or perpendicular to the machined surface.
- Clears the toolpath list for the current operation.

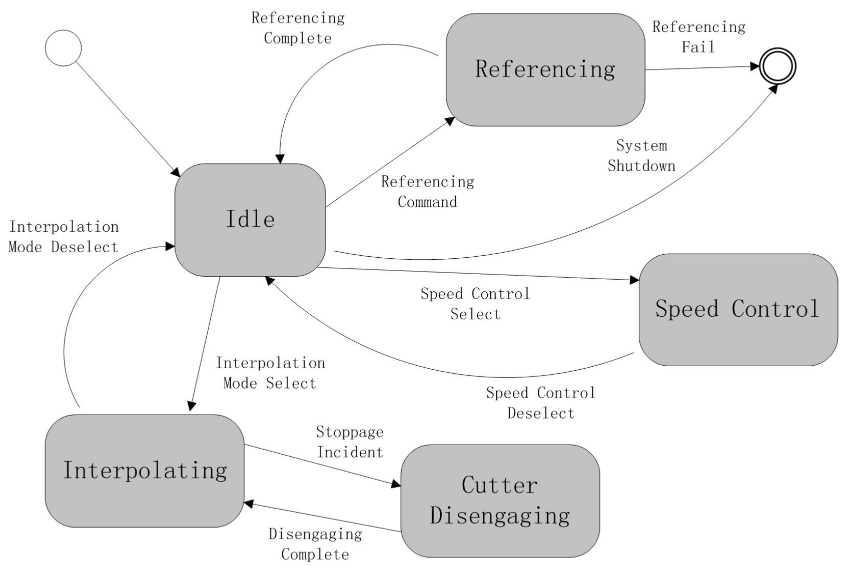

Figure 2. State diagram of interpolator.

In this way, the time need for disengage the cutter from the workpiece can keeps minimum, and in that process, the feed movement is under motion control, which will not destroy the un-machined area. The drive-away movement is always along the normal of the machining surface, so it will not exceed the capacity of the machine tool.

After completing all three actions, the interpolator enters its normal interpolating state and wait the tool-paths from retract plane to security plane of the workpiece and tool-paths from security plane to a specific position e.g. for tool inspection or tool changing.

For the incidence that causes an emergency stop, it is common that the system lose the machine coordinate system. Reference returning is necessary, and relocating of workpiece coordinate system may also be needed, which will be discussed in Section 5.

4. RECOVERY FROM STOPPAGE

In this section, the general procedure and strategy of recovering from stoppage will be described. If the resuming of machining has to be finished by another machine tool, additional information and actions are needed, which will be discussed in Section 5.

4.1. CRITICAL TOOLPATH

We define critical toolpath as the one that forms the final surfaces of a feature, which will affect the machining feature's final dimension and surface finish. If the stoppage incidence occurs when executing a critical tool-path, the feature under machining is possibly damaged and cannot be recovered any more.

It is obvious that all tool-paths in finish workingsteps are critical toolpath. For the tool-paths of roughing workingstep, the critical tool-paths are the ones closest to the defined surfaces of the feature. When tool-paths are generated and sent to toolpath list, a flag denoting if it is a critical toolpath is also generated.

4.2. RECOVERY STRATEGY

The recovery process and strategy is shown in Figure 3. After entering recovery model, if the stoppage occurs to a critical toolpath, the system will ask for a human inspection. If the inspection results indicate that the workingstep is recoverable, different strategies are applied based on whether the toolpath is in roughing or finishing workingstep. In roughing working step, the 2.5D features are machined layer by layer. If the same cutter is available, the recovery starts from the disengaging point following approach strategy defined. If an alternative cutter has to be used, new toolpath are generated from the unfinished layer. If the incident takes place in finishing workingstep, in case that the same cutter is not available and the second-best cutter has lower capacity regarding the depth of cut, the system go through the executables to find out the corresponding roughing workingstep and retrieve value stored in allowance attribute. If the allowance left in roughing workingstep exceeds the allowed depth of cut for the available cutter, an additional roughing workingstep will be added. The system will then select a proper cutter and cutting parameters considering the combined machining time and tool changing time. It is possible that the same cutter is used for the additional roughing workingstep and the finishing workingstep.

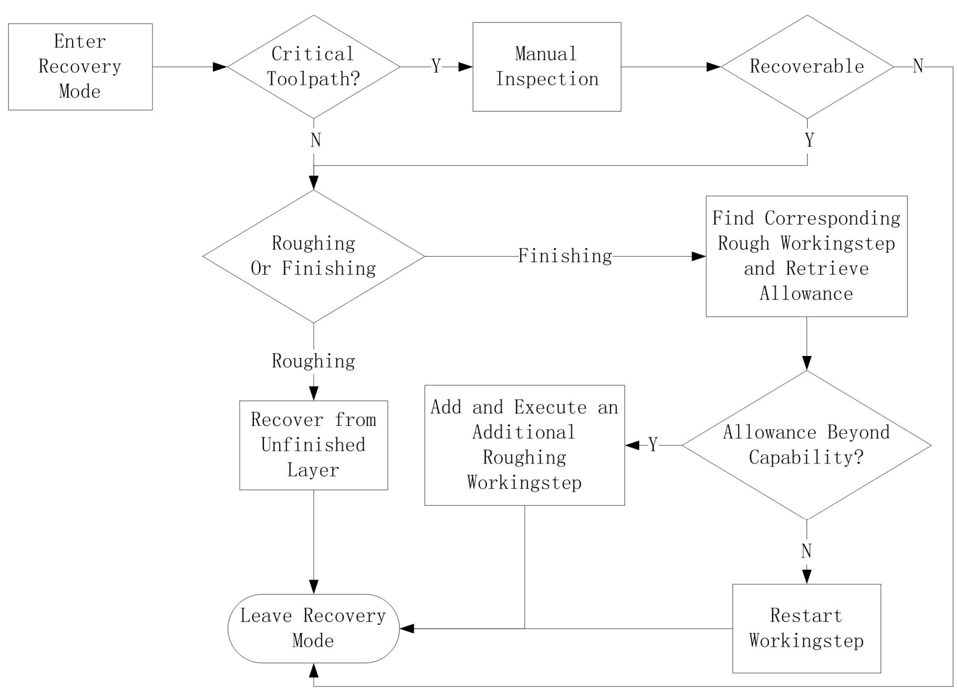

Figure 3. Recovery procedure.

5. RECOVERY MACHINING FROM ANOTHER MACHINE TOOL

After an incident occurs, it is likely that the workpiece is dismounted from the machine tool for inspection, which will result in the loss of co-relation between workpiece coordinate system and machine coordinate system. In the case when the machine tool demands maintenance or even repair, if the machining of the unfinished workpiece needs to be continued in a different machine tool, additional machining information is required.

5.1. RELOCATING WORKPIECE COORDINATE SYSTEM

For three-axis milling machine, the relationship between workpiece coordinate system and machine coordinate system can be established by three parameters, which are coordinates of workpiece origin in the machine coordinate system and angle of rotation around z axis. If the coordinates of two points in both machine coordinate system and workpiece coordinate system are known, the three parameters can be calculated. As illustrated in Figure 4, suppose Point P1 whose coordinates are (x_1,y_1) in machine coordinate system and (x_1',x_1') in machine coordinate system and Point P2 whose coordinates are (x_2,y_2) in machine coordinate system and (x_2',x_2') in machine coordinate system are known. The rotation angle of workpiece coordination system around z axis α and the workpiece origin's coordinates X and Y can be calculated by Equation (1).

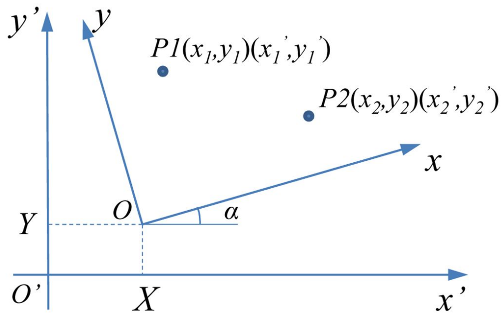

Figure 4. Relationship between machine and workpiece coordinate system.

$$\begin{aligned}
\alpha &= \tan^{-1}\frac{y_2 - y_1}{x_2 - x_1} - \tan^{-1}\frac{y_2' - y_1'}{x_2' - x_1'} \\
X &= x_1 - \sin\left(\frac{\pi}{2} - \tan^{-1}\frac{y_2 - y_1}{x_2 - x_1}\right)\sqrt{x_1'^2 + y_1'^2} \\
Y &= y_1 - \cos\left(\frac{\pi}{2} - \tan^{-1}\frac{y_2 - y_1}{x_2 - x_1}\right)\sqrt{x_1'^2 + y_1'^2}
\end{aligned} \tag{1}$$

For arbitrary point (x',y'), the corresponding coordinates (x,y) in machine coordinate system can be calculated by Equation (2).

$$\begin{aligned}
x &= x'\cos\alpha - y'\sin\alpha + X \\
y &= y'\sin\alpha + x'\cos\alpha + Y
\end{aligned} \tag{2}$$

It is common that the origin of workpiece coordinate system is placed near the top corner of the raw piece. That physical point in the raw piece is possible to be machined and no longer exist, which make it hard to measure the arbitrary point's coordinates in workpiece coordinate system. By predefined location points in workpiece coordinate system, after locating those points' coordinates in machine coordinate system either manually or by devices, the displacement of workpiece coordinate system can be calculated.

To define the points used for relocating workpiece coordination system, a new attribute its_locating_points is added into the Entity workpiece_setup, which is a list of cartesia_point, a list of three real numbers. The EXPRESS representation is shown as follows.

```
ENTITY workpiece_setup;                                          (* m0 *)
   its_workpiece:              workpiece;
   its_origin:                 axis2_placement_3d;
   its_offset:                 OPTIONAL offset_vector;
   its_restricted_area:        OPTIONAL restricted_area_select;
   its_instructions:           LIST [0:?] OF setup_instruction;
   its_locating_points:        OPTIONAL LIST [0:2] OF cartesian_point;
END_ENTITY;
```

5.2. FEATURE BASED HISTORICAL MACHINING INFORMATION

When the unfinished workpiece continues to be machined on other machines, it is important that the machining history data in feature level be transferred to the subsequent machine tool for process planning and toolpath generation. Two new attributes are added to the schema.

Attribute its_completion_status is added to Entity machining_workingstep to store the process status for a certain workingstep, which is shown as following.

```
ENTITY machining_workingstep      (* m0 *)
SUBTYPE OF (workingstep);
   its_feature:               manufacturing_feature;
   its_operation:             machining_operation;
   its_effect:                OPTIONAL in_process_geometry;
   its_completion_status:     OPTIONAL workingstep_completion_status;
END_ENTITY;
```

Where, the type workingstep_completion_status is an enumeration, defined as,

```
TYPE workingstep_completion_status = ENUMERATION OF (to_be_machined, unfinished,
   finished);
END_TYPE;
```

Before executing of a workingstep, the value of its_completion_status remains to_be_machined. During the machining of the feature, the value will be changed to unfinished, and after completion finished. It is worth noting that the entity has an attribute its_effect, which is used by the CAM system to describe the expected effect on the geometry of the workingstep. The type of it_effect is in_process_geometry, which defines three attributes as_is, to_be and removal, describing the geometry before the workingstep, the effect and removed volume respectively. However, the value of its_effect is provided by CAM system which will not be changed afterwards and cannot be used for storing the workingstep's completion status.

Another attribute unfinished_depth is added to Entity machining_feature, which is the abstract super type of 2.5D features.

```
ENTITY machining_feature          (* m1 *)
ABSTRACT SUPERTYPE OF (ONEOF(planar_face, pocket,
 slot, step, round_hole, toolpath_feature,
 profile_feature, boss, spherical_cap,
 rounded_end, thread))
SUBTYPE OF (two5D_manufacturing_feature);
   depth:                     elementary_surface;
   unfinished_depth:             OPTIONAL elementary_surface;
END_ENTITY;
```

All the added attributes are of optional attribute, which means the value is valid only when needed. For a workingstep machining a 2.5D feature, if its_completion_status has the value unfinished, it means that the specified 2.5D feature has stopped during machining, and the remaining depth of the feature is specified by unfinished_depth, which is used for re-generating tool-paths for machining the rest of the feature.

6. SUMMARY

This paper focuses on the STEP-NC based machining stoppage auto-recovery. The action to be taken for retracting the cutter from workpiece after stoppage incidents happen and the procedure and strategy of recovering are discussed. Higher level information stored in STEP-NC part program is used for disengaging the cutter and regenerating toolpath, in case when the same cutter is unavailable. Also presented is the method to relocate the workpiece coordination system when the workpiece is dismounted from the machine or when information of machine coordinate system is lost. Finally, information needed for resuming the machining by another machine is discussed. New entities are developed and added to ISO14649 schema to facilitate the relocating process and storing history machining information in the feature level.

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