FUNCTION BLOCK DESIGN FOR ADAPTIVE MACHINING OF THIN-WALLED PARTS

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Abstract: The thin-walled structures are widely existed in complex machined parts, such as aircraft structural parts. The thicknesses of the thin-walled structures are hard to achieve because their machining is subject to deformation. Therefore, the machining features of complex parts are usually manufactured by several machining operations. In order to adjust the tool path according to the feedback of in-process inspection, a function block-based approach is proposed for real-time operation planning. After process planning, the sequenced ideal machining status of a dynamic feature is embedded in a function block. The deviation between the actual intermediate status and the ideal intermediate status of the dynamic features are computed as the event to trigger the function blocks to adjust the unexecuted operations. How the function blocks are designed and how they can achieve the operation adjustments are described in this paper.

Keywords: Adaptive machining, function block, dynamic feature, thin-walled part

1. INTRODUCTION

The thin-walled structures such as ribs and webs are widely existed in complex machined parts, such as aircraft structural parts. The thicknesses of the thin-walled structures are hard to achieve because their machining is subject to deformation. Therefore, the machining features of complex parts are usually manufactured by a series of machining operations. Each machining operation is assigned with the appropriated process parameters such as feed-rate, the width of cut, the depth of cut and machining allowance, to remove materials under good rigidity conditions gradually. However, the deformation of a thin-walled structure still appears due to the random factors, for instance, the discontinuity of materials and the residual stress in the materials. For the purpose of obtaining the actual status of the thin-walled structure, in-process inspection is introduced. At present, the information collected by in-process inspection is compared with the ideal status information in an off-line and inefficient manner. Therefore, a real-time operation adjustment mechanism is required to guarantee the crucial dimensions, effectively and efficiently.

In order to adjust the tool path according to the feedback of in-process inspection, a function block-based approach is proposed for real-time operation planning in this paper. The dynamic feature model that includes all the statuses of a machining feature is employed to represent the machining features. After process planning, the sequenced ideal machining statuses and their associated machining operations of a dynamic feature are embedded in the function block. The deviation between the actual intermediate status and the ideal intermediate status of the dynamic feature is computed as the event to trigger the function block to adjust the unexecuted operations. Because the adjusting algorithm is embedded into the function block, the feedback is no longer processed by engineers. Instead, the real-time operation adjustment mechanism is established to realise adaptive machining of thin-walled parts.

The contents of this paper are organised as follows. In Section 1, the research background is introduced. In Section 2, related researches are reviewed. In Section 3, the concept of dynamic machining feature and the manufacturing process of a dynamic feature are introduced. In Section 4, the detailed designs of different types of function blocks are described. Finally, the contributions and future work are summarised in Section 5.

2. LITERATURE REVIEW

The related research works are reviewed below in the context of process planning and tool path generation.

2.1. Process Planning

A good process plan can lead to an efficient and high quality manufacturing result. Most research on process planning focused on setup planning, machine tools and cutters selection, process parameters optimisation, operation selection and sequencing, nonlinear process planning and so forth (Xu *et al*., 2011). There were a few researches on drive geometry. Heo *et al*. (2011) presented a methodology to partition the machining region of pockets. They used a series of slice planes to partition a pocket feature into multiple layers. The intersections between the slice planes and the side faces of the pocket feature are the drive geometries for pocket milling. The partition rules are the emphasis in their research. The drive geometries construction is relatively simple. Harik *et al*. (2008) proposed a feature-based process planning method for aircraft components manufacturing. Their method is mainly divided into three steps: geometrical enrichment, elementary manufacturing features (EMF) extraction and manufacturing feature identification. In the second step, machining modes, machining tools and machining directions are associated with every elementary manufacturing feature that is composed of one machining face. In the third step, the elementary manufacturing features that have the same information issued in the second step are combined into the manufacturing features that are then labelled with different colours. Because only the machining faces are extracted, the drive geometries consisting of faces are constructed. Jin *et al*. (2013) developed an adaptive process planning method for rapid prototyping and manufacturing. This research uses the similar slice method described in (Heo *et al*., 2011) to generate multiple sliced layers. The contours of sliced layers of biomedical CAD models are the drive geometries for tool path generations.

According to the analysis above, using a series of slice planes to intersect the feature model to generate the drive geometries is the core method. On one hand, the intersection operations cause the increase of computer memory consumption and the part model size. On the other hand, the intersection operations do not always work well. The constituent faces of the drive geometries are extracted and re-grouped based on the machining process. However, the relations between the constituent faces have not been established.

2.2. Tool Path Generation

As the knowledge carrier of machining process, machining features are used to achieve machining knowledge reuse and the automation of tool path generation (Baxter *et al*., 2008; Dimov *et al*., 2007). Most tool path generation approaches focused on tool path strategy (Zhang *et al*., 2004), machining time reduction (Msaddek *et al*., 2012), tool path optimisation for achieving better machining quality (Yang *et al*., 2006; Nojedeh *et al*., 2011) and others such as (Hatna *et al*., 1998). In contrast with process planning, there have been more works on drive geometries.

Zhang *et al*. (2000) developed a next generation NC machining system based on NC feature unit (NCFU) and real-time tool path generation. As a subclass of the traditional high-level feature class, the NCFU is composed of geometric form and control parameters. The machining area represented by each NCFU is non-gouging which facilitates the tool path generation in real time. The geometry information in each NCFU should be drive geometries. However, the details of the drive geometries construction are not described in this article. Miao and Shah (2002) developed a feature-based integrated CAD/CAPP/CAM system which could automate the tasks in machining process planning and tool path generation for 3-axis machining. The drive geometries for machining operations are encapsulated into machining operation objects. Similarly, they did not describe the drive geometries construction of machining operations. Hou and Faddis (2006) developed an integration layer between Unigraphics software and FBMach which has the function of packaging the geometrical information and process parameters of machining features into some CAM objects defined in Unigraphics software. However, the details of how to generate the geometrical information used in CAM objects are not described. Contour-parallel offset (CPO) machining is the most popular machining strategy for pocketing. The islands resided in the pockets lead to more tool retractions and lower material removing efficiency. Hence, Park and Chung (2002) provided an offset tool-path linking method for pocket machining to improve the productivity of the tool path. After offsetting the original contour, the linking method partitioned the machining area into several isolated sub-machining areas which have their own new contours that is the drive geometries. For the same purpose, Hinduja *et al*. (2010) proposed a Voronoi-diagram-based linking of contour-parallel tool paths generation method for two-and-a-half-dimensional closed-pocket machining. Tapie *et al*. (2012) established a topological model for machining of parts with complex shape which appeared widely in the aeronautics, automotive and other applications. The topological relationships between different machining features are extracted and represented by topological graph in order to reduce the preparation time for process planning.

3. DRIVE GEOMETRY OF MACHINING FEATURES

Drive geometry is a technical term that is referenced for tool path generation in NC CAM software. The drive geometries of a machining feature determine the machining area in the space across which the cutter cannot move. It is used to compute the tool path for each machining operation. According to the machining mode, the drive geometries are categorised into guide lines and guide faces.

3.1. Guide Lines

In 2.5- and 3-axis machining, the spindle of a machine tool is constantly in Z direction. As a result, the boundary lines are employed to define the machining area and act as the drive geometries. The drive geometries are applied for tool path generation for closed tool-path strategies and open tool-path strategies. The details of different machining features for 3-axis machining are shown in (Wang *et al*., 2014). It should be pointed out that the drive geometries of rib side milling are different on account of the thickness of the rib. When the rib is thick with good rigidity, the drive geometries is in closed loop. Nevertheless, if the rib is thin with poor rigidity, some special tool-path strategies are adopted, such as the “jump to jump” tool path described in (Bravo *et al*., 2005). Then the closed loop should be separated into several single guide lines.

3.2. Guide Faces

In multi-axis machining, the spindle and the worktable are swing. Only the boundary lines are not enough to define a machining area. Therefore, the guide faces are introduced to do the duty as drive geometries. The details of different machining features for multi-axis machining are shown in (Wang *et al*., 2014).

4. DYNAMIC MACHINING FEATURE

4.1. Dynamic Machining Feature

Traditionally, a machining feature is defined as a repeated similar shape or a single removal volume that is associated with a machining operation based on the final shape of a part. However, a machining feature included in a thin-walled structure often requires more than one machining operation. For example, a pocket feature is machined by volume machining operation, bottom milling operation, side milling operation and corner milling operation. Especially in side milling, the thin-wall of the pocket is easy to deform, and an in-process inspection operation is added to obtain the information of deformation for the rest machining operations. The intermediate status after each machining operation is defined as an in-process machining feature, and a series of in-process machining features is defined as a dynamic machining feature. Therefore, a dynamic machining feature is defined based on each machining statuses of a traditional machining feature. A dynamic machining feature can be expressed in equation (1):

$$DMF = \sum_{i=1}^{n} IPMF_i \tag{1}$$

where DMF is a dynamic machining feature, $IPMF_i$ the ith in-process machining feature, and n the total number of in-process machining feature of DMF.

4.2. Dynamic Machining Feature-based Representation of a Set of Machining Process

Generally, the machining process of a part is represented by a hierarchical structure composed of setups, steps and machining operations. A setup with the machine tool as its label is made of a number of steps. A step with the cutter as its label is made of a number of machining operations. A machining operation such as volume machining and pocketing is the lowest level component of a machining process. As described in Section 4.1, an intermediate status of a dynamic machining feature after an executed machining operation is defined as an in-process machining feature. Therefore, a machining operation is labelled by an in-process machining feature. A set of machining processes of a part represented by dynamic machining feature is showed in Figure 1.

In Figure 1, $Process_1$ is the 1st set of machining process. $Setup_{1,1}$ is the 1st setup of the 1st set of machining process. Machine and Setup share the same subscript due to their association. $Step_{1,1,1}$ is the 1st machining step of the 1st setup of the 1st set of machining process. Similarly, *Step* and *Cutter* share the same subscript due to their association. $Operation_{1,1,1}^{1}$ is the 1st machining operation of the 1st machining step of the 1st setup of the 1st set of machining process. *Operation* and *IPMF* have the same subscript due to their association, too. In order to represent the machining operations of a dynamic feature, the second superior characters of *IPMF* is the ID of the dynamic feature, and the third superior character of *IPMF* is the order of the machining operation in the dynamic feature.

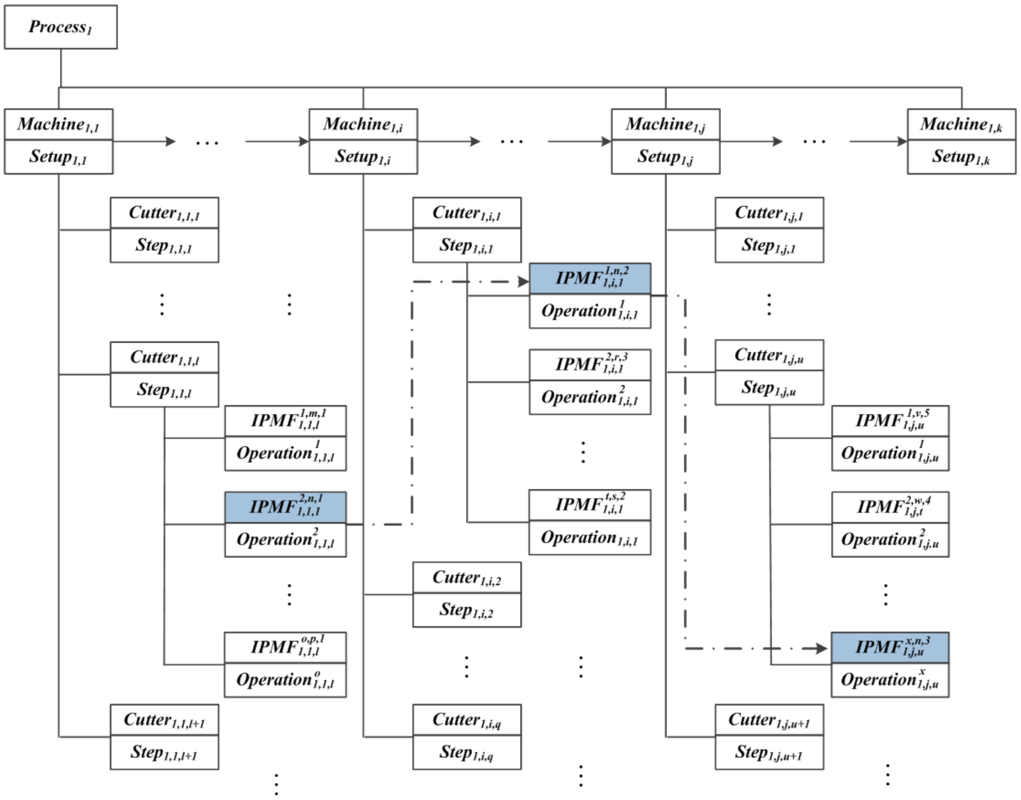

Fig. 1. Dynamic machining feature-based representation of a set of machining processes.

4.3. Inspection Process

After several machining operations are executed, the in-process inspection operations are inserted to obtain the actual machining status of the dynamic machining feature due to possible deformations. Take the part shown in Figure 2 as an example, its machining process can be specified as listed in Table 1.

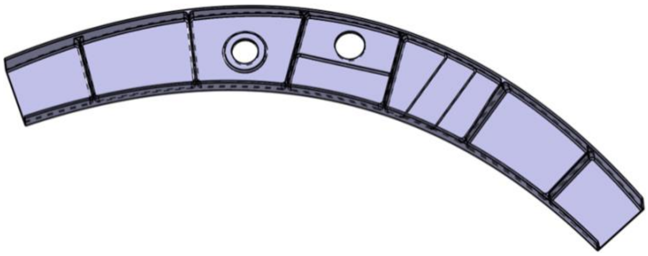

Fig. 2. An aircraft structural part.

Table 1. A set of machining processes.

Setup	Step	Cutter	Machining Mode	Machining Feature
1	1	32mm	3 axis milling	Datum plane A
2	1	32mm	3 axis milling	Datum plane B
	2	30mm	3 axis milling	Holes
	3	18mm	3 axis drilling	Holes
	4	32mm	3 axis milling	Profiles
	5	32mm	3 axis milling	Pockets and Ribs
	6	24mm	5 axis milling	Ribs
	7	24mm	5 axis milling	Holes
	8	24mm	5 axis milling	Pockets
	9	20mm	5 axis milling	Pockets
	10	20mm	5 axis milling	Profiles
	11	20mm	5 axis milling	Profiles

There are two opened pockets located at each end of the part. The widths of the rib features are hard to be assured. Therefore, the finishing milling of the profile is divided into Step 10 and Step 11 in Setup 2. When Step 10 is executed, an in-process inspection is performed to get the status of the rib features. The cutter is changed to a probe for the inspection. The actual status of the rib features are used to update the drive geometries of the machining operations in Step 11 to re-compute the tool path to achieve the online adjustment of the machining operation. At present, which in-process machining feature is required for inspection is determined by the process planner and defined in the corresponding in-process machining feature. In the future, the research result on integration of machining, inspection and monitoring will be used to determine the required inspection operation dynamically. Cutting force, spindle torque and other information will be collected to determine whether an in-process machining feature is required.

Following the representation of machining process, the inspection process can be represented by the similar hierarchical structure. The cutter is replaced by a probe and the machining operation is replaced by an inspection operation.

5. FUNCTION BLOCK DESIGN

The Function Block (FB) concept is described in the IEC 61499 specification (Wang *et al.*, 2009), as an IEC standard for distributed industrial processes and control systems. Therefore, it is suitable for realising inline machining operation adjustment. In this paper, the dynamic machining feature and the related inspection process are modelled using function blocks. By using the event-driven model of the function blocks, the inspection operation of in-process machining feature can be executed to get the machining status information to update the drive geometry for the next machining operation automatically and timely.

5.1. Operation Function Block (O-FB)

Operation function block is a basic function block to complete the related tasks of a single operation such as machining operation or inspection operation. The definition of a basic function block type can be expressed in a graphical presentation. Figure 3 shows the graphical definition of a machining O-FB. The internal algorithms are triggered by appropriate events as defined in the finite state machine shown in Figure 4.

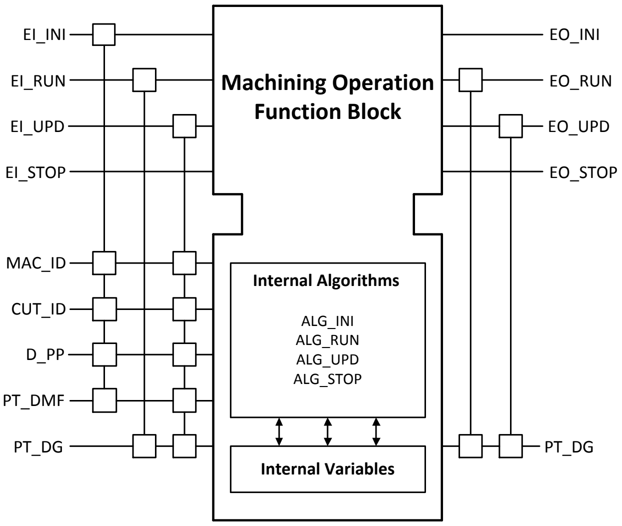

Fig. 3. Graphic definition of a machining operation function block.

In Figure 3, MAC_ID, CUT_ID and D_PP are used to pass the selected machine tool, cutter and default process parameters to the machining operation. PT_DMF is a list of persistent tags of the topological objects which make up the final shape of a dynamic machining feature. Limited by the data type supported by the function block, the persistent tags of the topological objects are used to transport geometrical information. PT_DG is a list of persistent tags of drive geometries of the machining operations. As shown in Figure 4, an event EI_STOP can trigger a state transition from START to STOP. Once STOP is active, the algorithm ALG_STOP is executed to stop machining, and ALG_ STOP will fire an event EO_STOP indicating the success of the machining. Similarly, for state transitions to RUN/INI/UPD, different algorithms ALG_RUN (for machining execution), ALG_INI (for creating drive geometry and generating tool paths), and ALG_UPD (updating the information of the machining operation and generating the tool paths) are triggered accordingly.

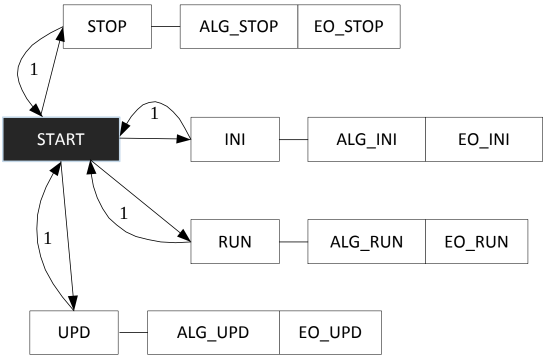

Fig. 4. Event-driven control of embedded algorithms.

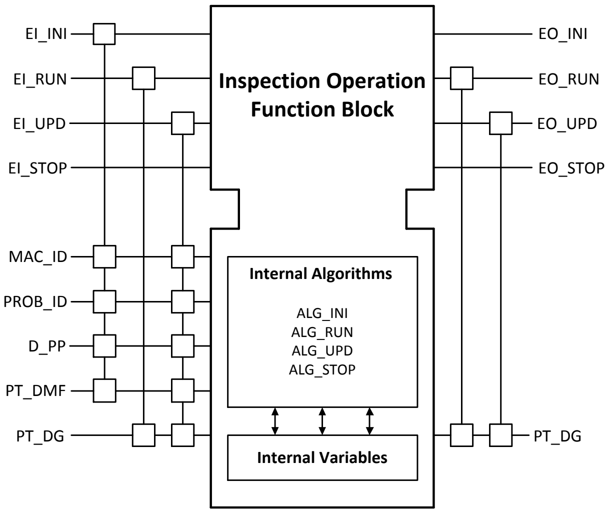

Fig. 5. Graphic definition of an inspection operation function block.

Similarly, the graphical definition of an inspection O-FB is depicted in Figure 5, where PROB_ID is used to pass the selected probe.

5.2. Supervisor Function Block (S-FB)

Supervisor Function Block is defined to dynamically manage the executing sequence of O-FBs when needed. In other words, an S-FB can alter the executing sequence of the O-FBs by changing the event flows to each O-FBs without affecting the contents of the O-FBs. A machining operation S-FB is given in Figure 6.

5.3. Step Function Block (Step-FB)

Benefiting from the hierarchical structure of a composite function block, a step function block can be defined as a composite function block. A machining Step-FB is defined in Figure 6. Hence, the whole machining process can be represented by a function block network.

5.4. Update Machining Operation by Function Block Network

In each machining step, a sequence of cutting motions is defined. Therefore, the in-process inspection is inserted only between machining steps. In other words, the communication between machining and inspection occurs between a machining Step-FB and an inspection Step-FB as shown in Figure 7.

When an inspection Step-FB is executed, an EO_RUN event is fired and passes the event to EI_UPD of a machining Step-FB. Consequently, the machine tool, cutter, default process parameters, the list of persistent tags of dynamic machining features and the list of persistent tags of drive geometries are made ready to the following machining Step-FB for updating. The machining operations will invoke the ALG_UPD algorithm to re-compute the tool path. In summary, the function block network represents a dynamic process plan that may be adjusted during machining operations to assure machining quality.

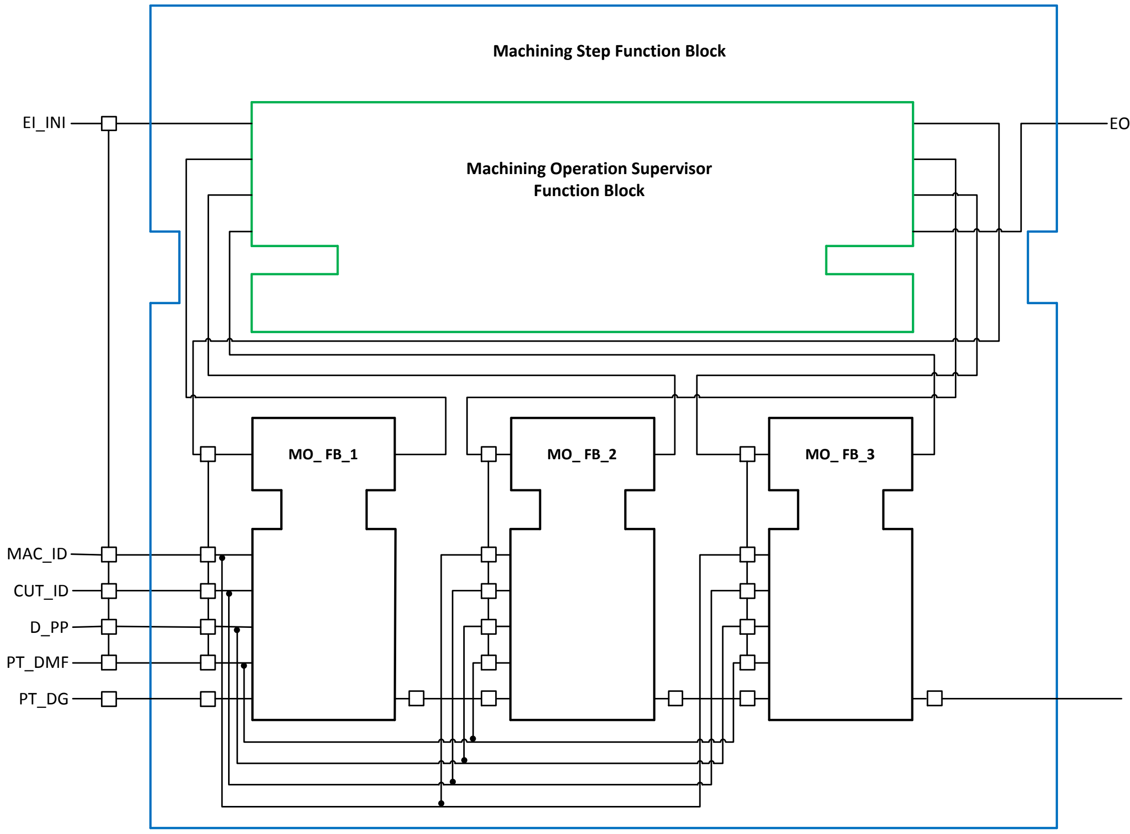

Fig. 6. Graphical definition of a machining step function block.

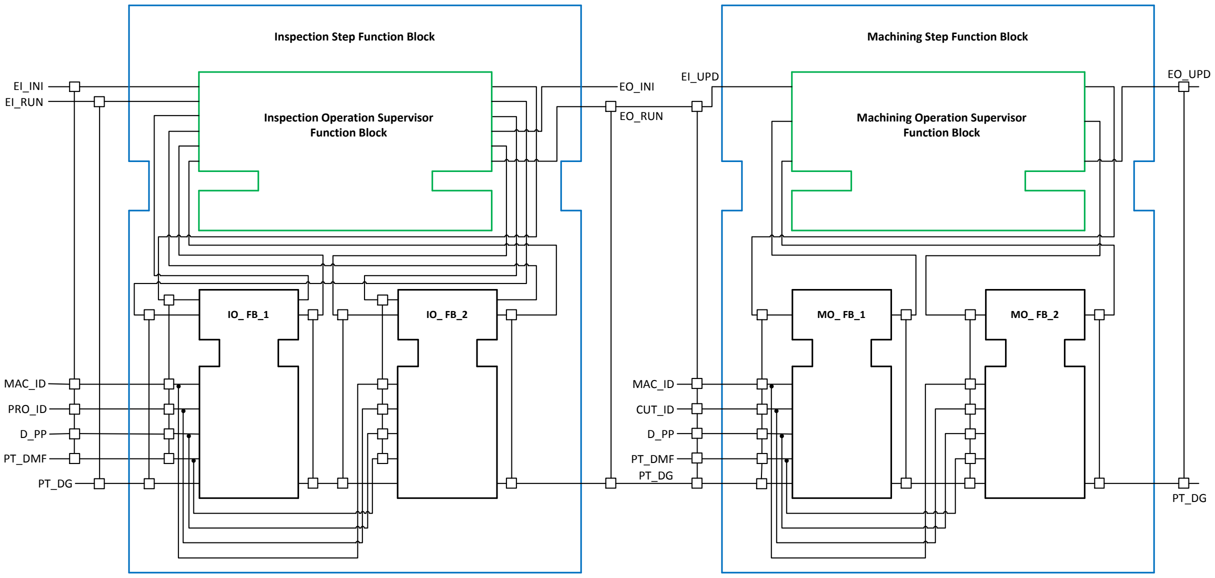

Fig. 7. Communication between a machining Step-FB and an inspection Step-FB.

6. CONCLUSIONS

The thin-walled structures are widely existed in complex machined parts, such as aircraft structural parts. The thicknesses of the thin-walled structures are hard to achieve because their machining is subject to deformation. Therefore, the machining features of complex parts are usually manufactured by several machining operations. In order to adjust the tool paths according to the feedback of in-process inspection, a function block-based approach is proposed for real-time operation planning. After process planning, the sequenced ideal machining statuses of a dynamic feature are embedded in a function block. The deviation between the actual intermediate status and the ideal intermediate status of the dynamic features are computed as the event to trigger the function block to adjust the unexecuted operations. The function block is used to model the dynamic machining feature and inspection process for operation adjustments.

This paper presents the concept and initial design of the function block-based approach. Its implementation and testing will be our future work, the results of which will be reported separately.

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