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# TOOL PATH PLANNING FOR RECONFIGURABLE MACHINES

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## ABSTRACT

All process elements of a reconfigurable manufacturing system should accommodate future changes. This paper looks at one such process element, tool paths, with focus on face milling and pocket milling. Tool paths for the first part are designed to optimize the process outcomes for the initial constraints. Change in market conditions or part design leading to change in cycle time requirements, geometry or complexity of the part, are met using incremental tool paths. Changes in cycle time are achieved by changing the feedrate and tool diameter. Changes in part design are tackled by modifying tool path segments. This system would provide a quick turn around time, less testing and quicker ramp up.

**Keywords:** planning, tool path, milling.

## INTRODUCTION

Reconfigurable manufacturing systems force a change in thinking at every level of production from design to process to systems. Modularly architected machine tools, controller, and software have been identified as the principal aspects of RMS. The conditions that necessitate reconfigurations and the solution have also been clearly identified in several research publications (Koren et al., 1999). This puts forward an implicit requirement for designing all elements of the process to have the ability to accommodate future reconfigurations. This paper looks at one such process element, tool paths, under the filter of reconfigurable manufacturing systems. The objective is to formulate the tool path planning problem in a form that lends itself to redesign

in keeping with the changes encountered by a firm utilizing the alternative reconfiguration choices. This is in tune with the stated advantages of reconfigurable systems, specifically quick ramp up with design changes.

Reconfigurable systems can potentially include and be applied to any manufacturing process; this paper will focus only on its application to pocket milling and face milling processes. Concepts used in this paper can be extended for other processes with complex, controllable tool paths. Tool paths for the first part are designed to optimize the process outcomes for the initial constraints. Changes in market conditions or improved part design can lead to changes in cycle time requirements, geometry, and complexity of the part. Current tool paths may not optimally satisfy the requirements, either by exceeding the capabilities of newly instituted drives or column height, not machining the whole part surface, exceeding the cycle time, or having considerable under utilized machine time. With an FMS and availability of suitable software tools, a new tool path will be designed for the above set of requirements leading to several design iterations and process verifications. For RMS this would be reformulated as an incremental tool path problem rather than a completely new problem. Changes in cycle time can be formulated as a constraint on incremental length change required. Uncovered part surface will be formulated as a difference (in the Boolean sense) between tool-swept region from current tool path and tool and new part surface.

A particular milling example is presented to introduce some of the ideas on effective planning for reconfigurable machine tools in

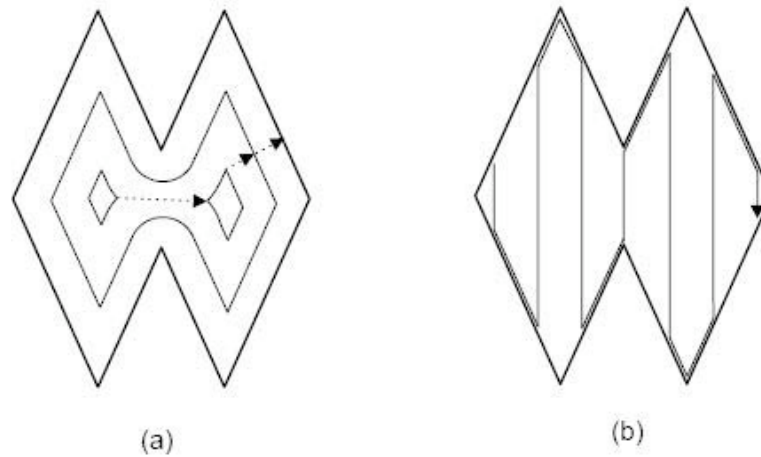


FIGURE 1. (A) CONTOUR PARALLEL TOOL PATH (B) DIRECTION PARALLEL TOOL PATH (PARK AND CHOI, 2000).

general. Manufacturing problems can be solved under a framework comprised of four different stages or levels: design, planning, process tuning, and post processing. Tool path planning for reconfiguration is an attempt to move problem solving from process tuning to planning for reconfiguration. This system would provide a quick turn around time for reconfiguration, less testing, and quicker ramp up to the new part. Also, over time, a set of tool path design strategies would evolve for reconfigurable manufacturing systems that can be quickly applied for part families.

The paper is organized as follows. First, a review of research on tool path strategies for face and pocket milling is presented. Second, we suggest methods to change the tool path when there is a requirement for shorter cycle times. Third, we look at how tool paths are incrementally modified to deal with changes in part geometry and topology. Fourth, we look at a method for defining a configuration space for different machine modules and fixtures within which the tool paths must be contained. Finally, conclusions and recommendations for further work are given.

### TOOL PATH PLANNING FOR POCKET AND FACE MILLING

NC path planning for pocket and face milling has been studied by various research groups. Usually there are two common strategies for area milling: contour-parallel milling and direction parallel milling. Contour-parallel milling uses successive offsets of the pocket

contour as tool-path elements. This means the pocket area is milled in a spiral-like fashion cutting along curves equidistant to the contour and stepping inwards for the next pass. Each successive offset can be computed using the Voronoi diagram approach (Held, 1991) or the pair-wise offset approach (Park and Choi, 2000), which are computationally expensive.

In direction parallel strategy (also known as zigzag or stair-case milling) milling takes place along line segments parallel to a specified inclination. These two tool-path strategies are commonly used in the roughing stage as well as in the finishing stage (Yao et al., 2001).

Held (1991) developed the ZigPocket algorithm for generating direction parallel tool paths for pocket milling. The algorithm creates a data structure providing information on the global shape and connectivity of the pocket. The tool path is then a tour such that each horizontal edge of the data structure has been traversed. Tripathi and Dornfeld (2004) have worked on designing tool paths to minimize burrs formed during face milling of surfaces. Choi et al. (2000) have worked on direction parallel milling as well as contour parallel milling.

There has been very little work on generating tool paths for part families. Yao (2001) developed an algorithm to select tool diameter that can be used for more than one type of part, thus eliminating several unnecessary machine-tool reconfiguration operations, thereby increasing the throughput.

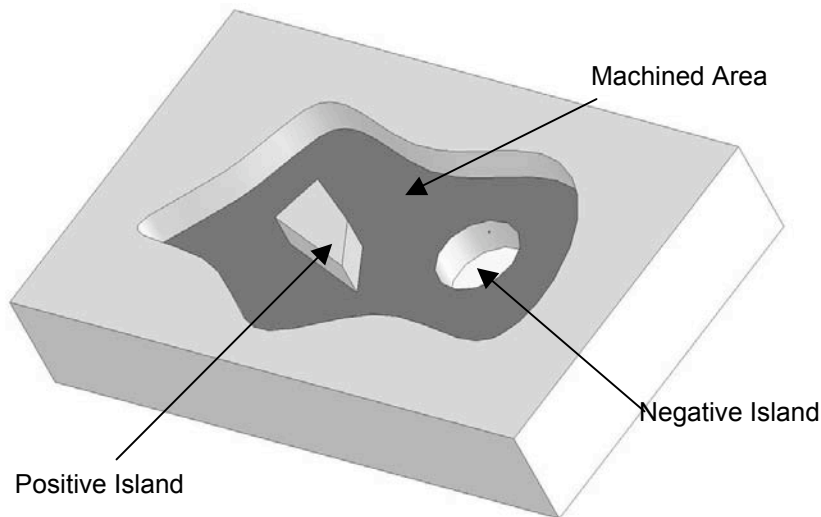


FIGURE 2. POCKET MILLING: MACHINED AREA, POSITIVE & NEGATIVE ISLANDS.

### Pocket Milling Surface

A typical milling part consists of three different types of regions:

- 1) The machined surface
- 2) The positive islands: A feature such as boss or shoulder in the part that must be avoided.
- 3) The negative islands: A feature such as holes or cavities lying below the actual machining level.

### CHANGES IN CYCLE TIME

The change in product demand can force a change in cycle time. Reduction of cycle time can be a very critical requirement on the manufacturing system. The time available for each process element would, as a result, decrease. The pocket and face milling process can have shorter cycle time by either increasing the feed rate or by decreasing the total distance traveled by the tool, which is same as increasing the amount of area machined per unit feed, i.e. by increasing the diameter of the tool used to machine. There are certain issues with both of these methods. The feedrate strongly determines the surface finish of the part; thus, the surface finish requirement, in addition to the inherent machine capability, can limit the extent to which we can increase the feed, in order to meet the cycle time requirement. Increase in tool diameter, on the other hand, does not benefit a milling operation which is done in a single pass, i.e. when the tool is wider than the part width being machined at any section of

the tool path. Also, a larger diameter can leave some unmachined areas. Modification of tool path is not considered here because it is assumed that the tool path for the initial pass is already optimized for cycle time and certain other requirements. Tool paths are usually optimized to minimize burrs, cycle time, meet surface finish requirements, reduce tool forces and impulses, and reduce tool wear.

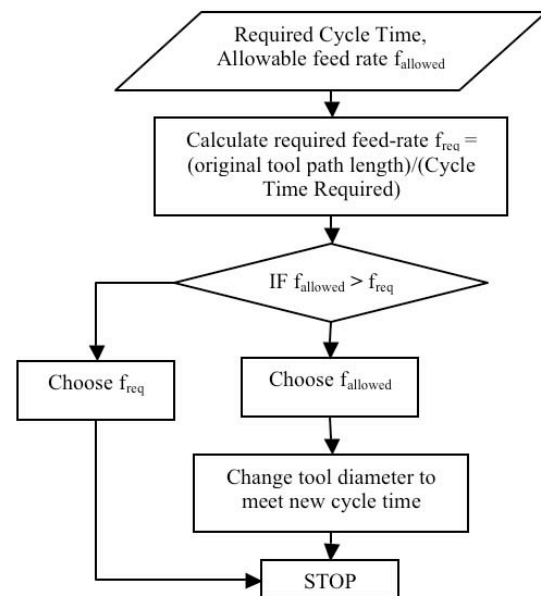


FIGURE 3. CYCLE TIME CHANGE.

The Solution algorithm proceeds as follows:

- 1) Determine
  - i) feed-rate required for meeting the new cycle time: this can be approximated as the original tool path length divided by the cycle time required; neglecting

the feed losses due to discontinuities in the tool path.

- ii) maximum feed-rate allowable determined by machine capability or surface finish requirements: this can be obtained using the feed-rate vs. surface-finish relations.
- 2) If (i) < (ii) then increase the feed-rate to (i), stop; else next step.
  - 3) Increase the feed rate to (ii)
  - 4) Change tool-diameter such that number of passes reduced & new cycle time achieved (cannot be done for all parts).

It is important to note that a change in tool diameter cannot be done for all the parts. Neither can all parts and tool paths benefit in terms of cycle time due to increase in tool diameter. This is especially true when the tool diameter is comparable to the part features being machined. In such cases the larger tool diameter may leave a lot of area inaccessible to machining, as well as the number of passes may not necessarily decrease. The area that is left unmachined may need to be cleaned-up using a smaller diameter tool. In such cases the time for clean-up and tool change also needs to be accounted for.

Depending on the shape of the surface machined and the presence of positive and negative islands, the original tool-path may have none to many tool retractions (Figure 4). The strategy behind incremental tool paths is to maintain the overall structure of tool paths. This is necessary because the original tool path is optimized for a lot of different factors that are dependent of the structure of the tool path. This process can be time consuming

because some of it is done manually.

### Finding New Tool Diameter

If the original tool path has no retractions, then the method of finding the new tool path mainly reduces to finding the new tool diameter. We have to proceed with the assumption that the choice of feed-rate and tool-diameter are independent. This may not be true for cases where tool forces are critical, as increase in both feed-rate and tool diameter result in increase in tool forces. A first step calculation of the tool diameter can be done using the area machined.

Diameter = (area machined) / (required cycle time \* feed-rate).

An available diameter value greater than or equal to the above value is chosen. Next, the width of the workpiece along a direction perpendicular to the inclination of the tool path is found. The number of passes is found using the above diameter, the overlap between passes and the workpiece width.

$$\text{Passes} = \text{width} / (\text{diameter} - \text{overlap})$$

The number obtained above will be a real number, whereas the actual number of passes will be an integer.

If  $1 > (\text{Passes} - \lceil \text{Passes} \rceil) > 0.5$  then choose the original diameter and the number of passes will be  $\lceil \text{Passes} + 1 \rceil$ .

If  $0.5 > (\text{Passes} - \lceil \text{Passes} \rceil) > 0$ ; then check for the next larger diameter

Where  $\lceil \ ]$  represents the greatest integer function.

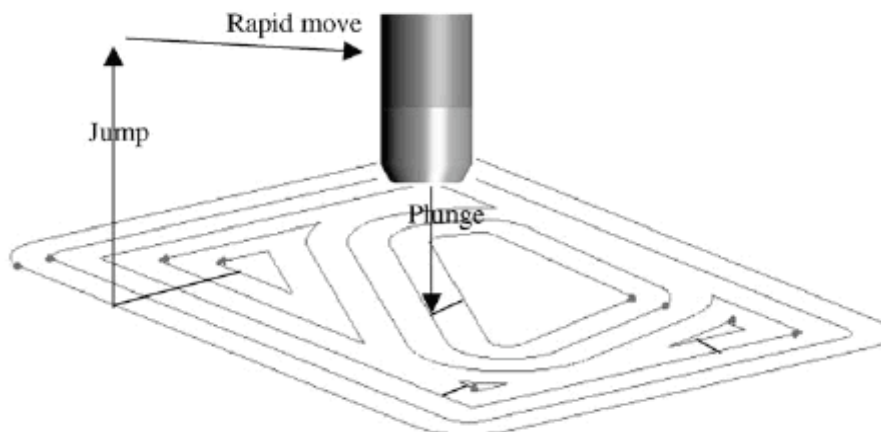


FIGURE 4. TOOL RETRACTION.

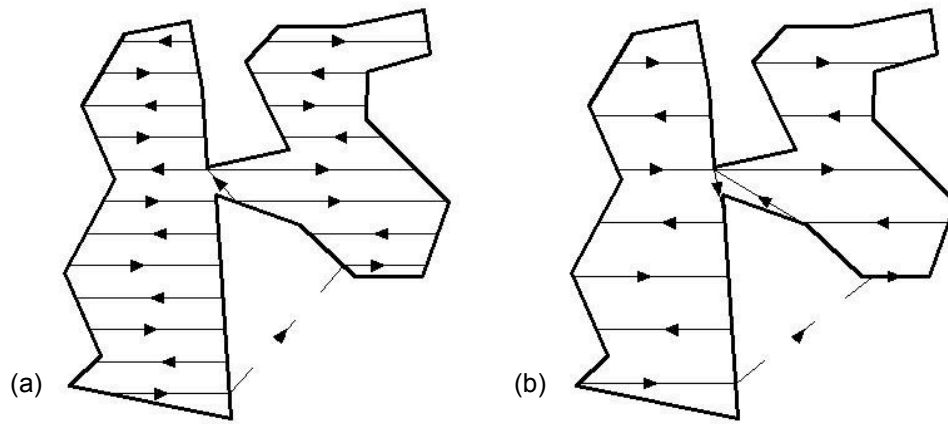


FIGURE 5. (a) ORIGINAL TOOL PATH (b) NEW TOOL PATH USING LARGER TOOL.

After the new diameter has been found the incremental tool path is generated. The tool path segments within each monotonic region become further apart, thus reducing the number of passes. The connectivity of tool paths over different monotonic regions is maintained as exemplified in Figure 5.

### CHANGE IN PART DESIGN

The volatile market forces the designers to introduce new products frequently. The new part belonging to the same product family can differ from the original in size and/or features. The tool path needs to be modified for the new part. The change in the surface machined can either be a change in area without a requirement of changing the number of tool retractions or the change can be one in features, such as addition or removal of a positive or a negative island.

#### Change In Area Machined

The change in area machined can be tackled by modifying the length of the existing tool

path segments and/or by addition or removal of tool path segments. The area change is found by taking a Boolean difference between tool-swept region from current tool path and tool and new part surface. For face milling problems it is possible that the original tool path could cover the new area. In such cases the above Boolean difference is null. For pocket milling the tool swept region is essentially the same as the machined area. Therefore, any change in area would be reflected in the above Boolean difference. This difference can further be divided into region which requires extension or shortening of certain tool path segments; and region which require additional or lesser tool path segments. The tool path modification is done accordingly. When additional tool path segments are added the original segments are not shifted to preserve the original tool-workpiece interaction.

#### Introduction of a Positive Island

If the part design change introduces a new positive island or a reflex region, then this would require additional tool retractions. The

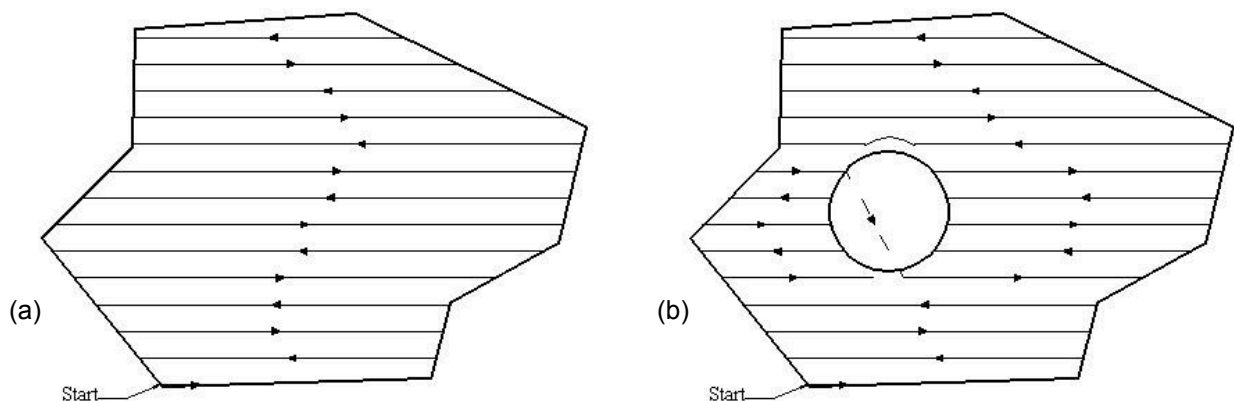


FIGURE 6. (a) ORIGINAL TOOL PATH (b) TOOL PATH AFTER INTRODUCTION OF A POSITIVE ISLAND.

incremental modification in the tool path should not introduce additional predrills, as this would increase the cycle time, as well as preserve the original tool path structure.

The incremental tool path generation involves the following steps:

1. Follow the original tool path until the first tool path segment intersects with the positive island.
2. Continue the tool path on the same side of the positive island until the maxima/minima of the positive island is encountered.
3. Retract the tool or follow the contour of the positive island back to the first point where the tool path intersects with the positive island. Generate tool path segments till the end of the positive island.
4. Continue with the original tool path.

An example of incremental tool path generation for a part with a new positive island is shown in Figure 6.

### **Removal of a Positive Island**

The removed positive island is an additional area that has to be machined. The original tool path segments on one side of the positive island that were generated first are extended till the part boundary. Tool path generation continues along the original tool path. When the original tool path is about to start machining the other side of the positive island, the corresponding tool path segments are dropped, and the tool path continues from the end point of this region. This is shown in the figure.

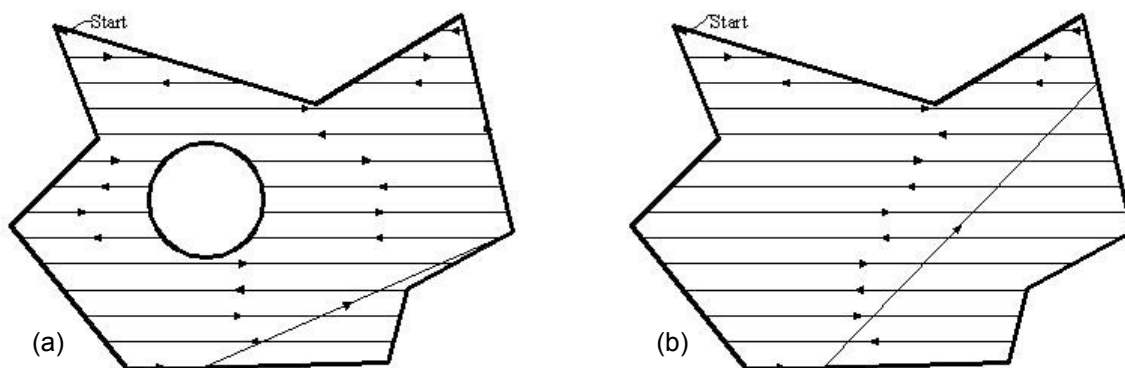


FIGURE 7. (a) ORIGINAL TOOL PATH (b) TOOL PATH AFTER REMOVAL OF A POSITIVE ISLAND.

### **Introduction of a Negative Island**

Negative islands can either be treated as machined area and original tool path may be used. If the size of the negative island is much larger than the tool diameter, then rapid feed can be used over some portion of the negative island. To identify which segments can have rapid feed, the boundary of the negative island is offset inside by a distance larger than the tool radius. The portions of the tool segments that lie within this offset region are rapid fed to reduce the cycle time.

### **Configuration Space for Tool Paths**

In addition to accommodating changes in market demand and part design, one also needs to consider the changes in configuration of the system. The tool path designed must be within the space in which the cutting spindle can move. One also needs to ensure there is no interference or collision with newly instituted modules or fixtures. This can be achieved by finding the interference configuration space for each module and fixture, and combining them together. This will also tell the designer the parts that can be machined within a given configuration. A set  $Q$  is called a configuration space (C-space) for a system if every element of  $Q$  corresponds to a valid configuration of the system and each configuration of the system can be identified with a unique element of  $Q$  (Choi et al., 1997). The following method is to calculate the C-Space within which the tool paths must be designed:

1. Determine the machining directions  $d$  (spindle), the machining surface, and tool lift.
2. Calculate the convex silhouette of the module: projection of the module on a

plane perpendicular to d.

- a. Find all the vertical faces of module: project them on the plane.
  - b. Find all the silhouette edges: draw vertical planes through all edges: if the two faces containing that edge lie on the same side of the vertical plane than that edge is a silhouette edge.
  - c. Find the convex silhouette edges: the silhouette edges where the faces have a dihedral angle greater than  $\pi$ .
3. Offset the silhouette by radius  $R'$  ( $R' = R(1+\delta)$ ;  $\delta \approx 5\%$ ).
  4. This gives the interference C-Space for the module.
  5. Calculate above for all the modules and calculate the union of all interference C-Space.
  6. Remove above from the tool-range to find allowed machinable surfaces.

## CONCLUSIONS & FUTURE DIRECTIONS

In this research some of the strategies for generating tool paths for part families encountered in a reconfigurable manufacturing system are addressed. Two of the major changes encountered by a firm: demand change and product design change, can be accommodated into the milling process which forms one of the process elements of an existing manufacturing system.

There are other promising ways in which the tool path planning problem for reconfigurable manufacturing can be addressed. One of them is use of modular tool paths. In this proposed method, tool path elements are designed for individual features that are likely to be encountered within a part family. These elements, which are optimized for each feature, are stored in a library. Depending on the current part features these are joined together. One of the major challenges for such modular tool paths would be generation of integration rules for such tool path elements. Another way to tackle the listed problems is parameterization of a part family, i.e. all the properties of a part within a part family can be defined using a set of parameters. The problem now reduces to designing generic tool paths based on these parameters. Once the actual part is encountered one would just need to plug in the values of parameters to get the

required tool path. to plug in the values of parameters to get the required tool path.

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