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Development of simulation system for machining process using enhanced Z map model

Sang-Kyu Lee, Sung-Lim Ko*

*Department of Mechanical Design and Production Engineering, Konkuk University,
1 Hwayang-dong, Kwangjin-gu, Seoul 143-701, South Korea*

Abstract

To verify NC programs as well as to optimize the cutting conditions, the importance of machining process simulation system is increasing. The paper discusses new approach for milling operation simulation using enhanced Z map algorithm. To extract the required geometric information from NC code, suggested algorithm uses supersampling method to enhance the efficiency of a simulation. By executing redundant Boolean operations in a grid cell and averaging down calculated data, presented algorithm can accurately represent material removal volume though tool swept volume is negligibly small. Supersampling method is the most common form of antialiasing and usually used with polygon mesh rendering in computer graphics. The key advantage of extended Z map is that the data structure is same with conventional Z map, though it can acquire higher accuracy and reliability with same or lower computation time. By simulating machining operation efficiently, this system can be used to improve the reliability and efficiency of NC machining process as well as the quality of the final product.

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Keywords: Computer-aided manufacturing; Z map model; Machining process simulation; NC code verification

1. Introduction

Productivity and quality of machined parts highly depend on the NC program used in machining. Because of the need for unattended machining and higher productivity, it is becoming more critical to simulate machining process more precisely for the optimization of cutting condition including chip load and material removal volume. By simulating machining process in three axes milling of sculptured surfaces prior to actual cutting operation, errors and inefficiency of tool path can be corrected at the programming stage.

Geometric simulation of milling process using Z map method is based on Z buffer algorithm which is developed for making shaded images of solid models in computer graphics. Anderson [1] introduced Z map method to display final shape of sculptured surfaces. Subsequent investigations were conducted by Hook [2] and Hsu and Yang [3] to enhance capability and simulation efficiency of Z map method. To verify NC program as well as to optimize the cutting condition using Z map model, estimation of cutting force and establishment of machining data base has been

suggested by several researches [4,5]. Because of its simple data structure and fast computation time of conventional Z map model, it is considered that Z map can be used to predict cutting force in ball end milling and generate tool path planning [6,7].

Due to the aliasing errors caused by discrete sampling of Boolean operation in conventional Z map model, it is hard to acquire high accuracy using Z map method. To develop more precise simulation model, solid modeling method including CSG, B-rep and decomposition method, is suggested by several researchers. Each solid modeling algorithm has its advantages and disadvantages relative to the others in terms of accuracy, robustness, data structure and computation time. Kondo [8] suggested DIMOS system which is composed of a decomposition method and a B-rep method. Roy and Xu [9] proposed extended octree-based algorithm to represent Boolean operation of complex object more accurately. The decomposition model can acquire relatively high accuracy, but there is several disadvantages like large memory consumption and complicate data structure.

Construction solid geometry (CSG) method is most popular because this method can complete Boolean operation of any 3D part model relatively easily and accurately [10]. Using CSG method, cutter-part immersion geometry can be

* Corresponding author. Tel.: +82-2-450-3465; fax: +82-2-447-5886.
E-mail address: slko@kkucc.konkuk.ac.kr (S.-L. Ko).

70 accurately retrieved by Boolean operation between the part
 71 model and the tool swept volume and it can be used to
 72 optimize cutting condition by applying constant material
 73 removal volume rate [11]. The problem in the CSG approach
 74 is that it is computationally expensive to represent the parts
 75 with irregular surfaces as in sculptured surface milling
 76 [12,13]. Large data volume with complicate geometry is
 77 another problem that makes the model not to be used for
 78 general cutting simulation except for relatively simple Boolean
 79 operation [14,15].

80 The simplicity in the data structure of conventional Z map
 81 model makes it possible to generate and update a part model
 82 very fast. This advantage of Z map made most commercial
 83 CAM program use Z map algorithm for NC code verification
 84 and optimization. However, to increase the accuracy of Z
 85 map model, computation time and memory consumption
 86 increased quadratically.

87 In this paper, new algorithm named enhanced Z map
 88 algorithm is proposed to extract the required geometric
 89 information with complicated sculptured surfaces from
 90 NC program. The basic idea of enhanced Z map algorithm
 91 is based on antialiasing theory which is generally used with
 92 polygon mesh rendering in computer graphics [16,17].
 93 Using modern VLSI technology, rendering hardware makes
 94 it possible to increase computation efficiency dramatically
 95 [18].

96 By executing redundant Boolean operations in a grid cell
 97 and averaging down acquired data, presented algorithm can
 98 accurately represent material removal volume though tool
 99 swept volume is negligibly small. The key advantage of
 100 suggested algorithm is that the data structure is same with
 101 conventional Z map, though it can acquire high accuracy and
 102 reliability with same or lower computation time. By imple-
 103 menting geometrical Boolean operation more accurately,
 104 this system can be used to improve the reliability and
 105 efficiency of NC machining process as well as the quality
 106 of the final product.

107 **2. Conventional Z map algorithm**

108 The conventional Z map is a special form of decomposition
 109 model in which the heights at the grid center are stored
 110 in 2D arrays. The process of obtaining Z map data can be
 111 regarded as a ‘virtual’ digitizing process. The Z map sam-
 112 pling process is carried out as follows. Let (x_0, y_0) be the
 113 corner point (bottom-left corner) of a rectangular non-para-
 114 metric domain on which the regular grid is to be defined in xy
 115 plane as Fig. 1. When r is the grid size, the grid point (x_i, y_i)
 116 is determined by

117
$$x_i = x_0 + ri \tag{1}$$

118
$$y_i = y_0 + rj \tag{2}$$

123 The update of workpiece geometry, i.e. the simulation of
 124 cutting process, merely consists of checking calculated

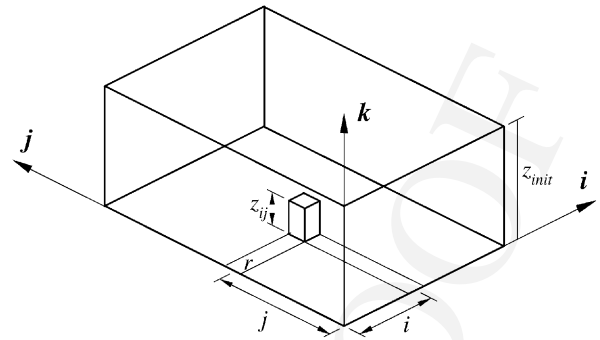


Fig. 1. Data structure of conventional Z map.

125 height value at a grid (x_i, y_i) . If stored value is higher than
 126 the surface of the tool movement swept volume, then Z map
 127 model is updated to the surface generated by the cutter. The
 128 distance between the initial (before cutting) and the final
 129 (after cutting) Z value can be used for describing the actual
 130 chip removal volume.

131 Due to the discrete nature of the data structure in con-
 132 ventional Z map model, Boolean subtraction is executed
 133 only at the center of each pixel. In conventional Z map, part
 134 model or cutter immersion geometry is detected at regular
 135 grid point as Fig. 2. As a tool envelope moves downward
 136 continuously, removed volume is acquired by Boolean
 137 subtraction operation.

138 The accuracy of point sampling process in conventional Z
 139 map model is determined only by the grid size as Fig. 2. As
 140 a tool envelope moves downward continuously, removal
 141 volume in conventional Z map is detected only at each grid
 142 center as solid line though exact removal volume is
 143 increased linearly as dotted line in Fig. 2(a). Smaller grid
 144 size can increase the accuracy of simulation, but cannot
 145 eliminate them. When the grid size of Z map is decreased by
 146 half as shown in Fig. 2(b) and (c), the resolution of Boolean
 147 operation is increased twice. And, consequently, computa-
 148 tion time and memory usage is quadrupled. By this excessive
 149 cost in improving accuracy, it is hard to eliminate simulation
 150 error in conventional Z map. In represents of final surface

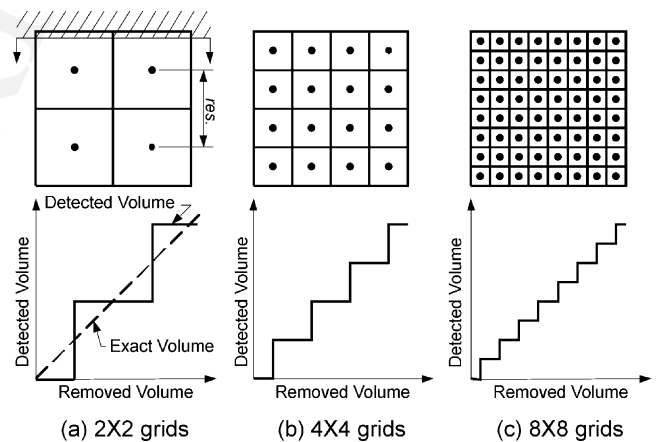


Fig. 2. Relations between resolution of Boolean operation and grid size in conventional Z map model.

151 with relatively flat geometry, the accuracy of conventional Z
 152 map is sufficient. But, it is insufficient to detect material
 153 removal volume with relatively small tool diameter or
 154 narrowly aligned tool path where fine Boolean subtraction
 155 is required.

156 3. Enhanced Z map algorithm using supersampling 157 method

158 Due to the similarity of data structure between Z map
 159 model and raster graphic system, it is easy to adapt super-
 160 sampling method as an antialiasing technique of conventional
 161 Z map model. Many supersampling methods have been
 162 developed to raise the sampling rate and increase the
 163 resolution of sampling operation [17]. In this paper, sug-
 164 gested model uses inclined sampling method to increase the
 165 resolution of Z map model, because it is simple and easy to
 166 use with relatively high accuracy. In NC code generated
 167 from commercial CAM module, almost every tool path is
 168 constituted with orthogonal movement in xy plane. Due to
 169 this property, better sampling accuracy can be acquired with
 170 inclined sampling method.

171 The approximation accuracy of point sampling is deter-
 172 mined only by the grid size as Fig. 3(a) and (b). To represent
 173 all the polygons that contribute to each pixel, sampling
 174 process must take into account the areas of all the polygons.
 175 In Fig. 3(c) and (d), more than one point samples are taken in
 176 the region of each pixel and these samples are integrated to
 177 obtain the final pixel shading value. By increasing sampling
 178 points per pixel, the resolution of sampling process can be
 179 increased without any more memory usage. The resolution
 180 of supersampling method is proportional to the number of
 181 sampling points per each pixel. If more sampling points
 182 detect polygon, the intensity of pixel is increased as Fig. 3(d).

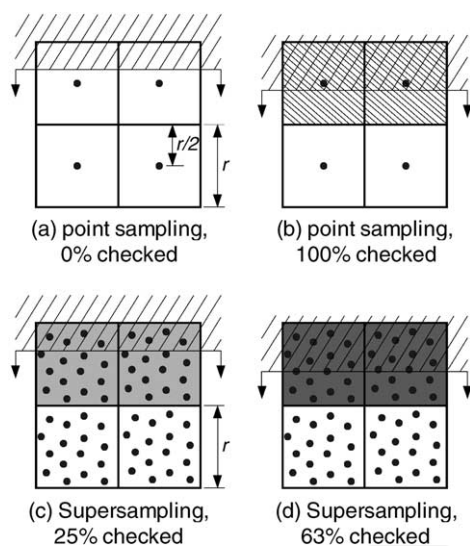


Fig. 3. Increase of resolution at each pixel by supersampling algorithm. Note that the square area represents one pixel ($r =$ grid size).

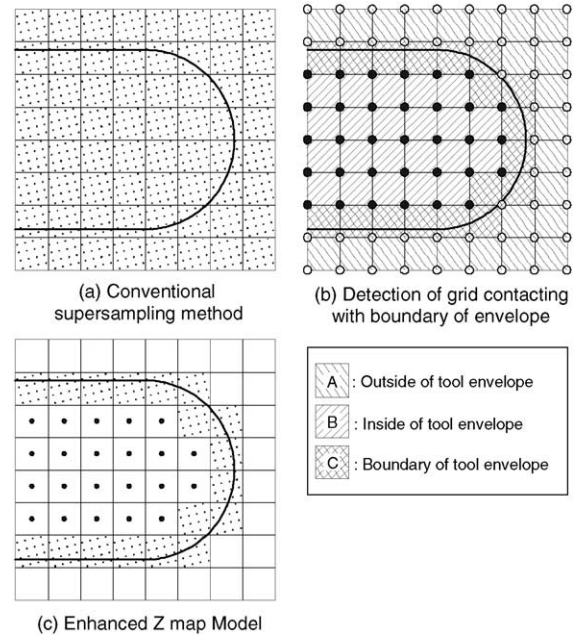


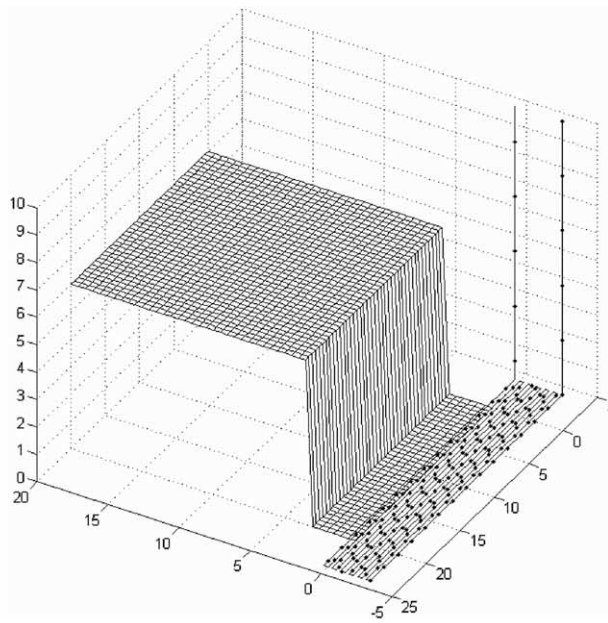
Fig. 4. Enhanced Z map model by adopting supersampling algorithm into tool envelope boundary.

The disadvantage of this approach is relatively high computation time in oversampling process. Basically there is no difference in computation cost between 16 points supersampling process as Fig. 4(a) and 4 by 4 pixels point sampling method.

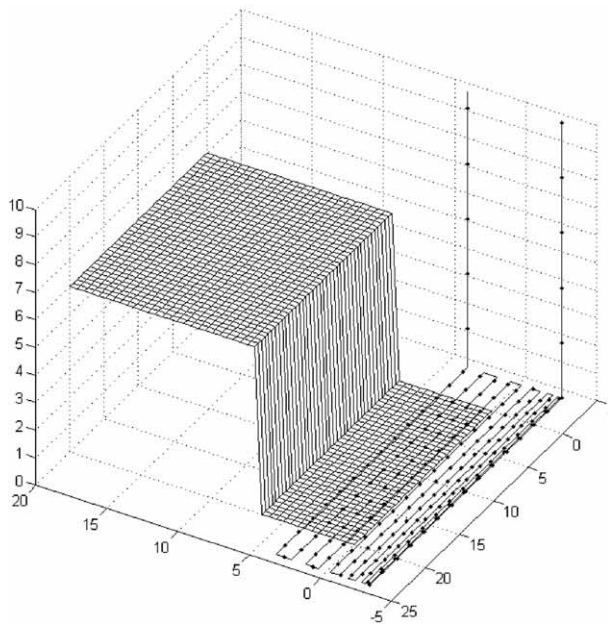
To reduce unwanted overhead in oversampling process in each pixel, suggested algorithm detects the boundary grid where the edge of tool envelope is crossing as shown in Fig. 4(b). The supersampling algorithm is applied into the cross hatched boundary area of tool envelope. And conventional point sampling is used inside of tool envelope as Fig. 4(c). By reducing required oversampling process as Fig. 4, computation time is 3–4 times faster than conventional supersampling method.

4. Simulation of machining process

To verify the effectiveness of newly suggested algorithm, computation time and accuracy of Boolean operation are compared in parallel cut by flat end mill. Tool path of cutting operation is shown in Fig. 5. To acquire the data for analysis of efficiency between conventional Z map and enhanced Z map model, pick feed of each tool path is arranged as shown in Fig. 5(a) that regular pick feed is applied and Fig. 5(b) that incremental pick feed is applied. By simulating milling process in parallel cut, aliasing error can be easily analyzed and the robustness of system can be also verified. The geometrical parameter for simulation is as follows: pick feed of regular tool path is 0.3 mm and 0.1–1.1 mm. Axial depth of cut is 6 mm for both simulations. Tool diameter is 6 mm and grid size is increased from 0.05 to 1 mm. Though



(a) Parallel cut with regular pick feed using end mill (Pick feed = 0.3mm)



(b) Parallel cut with incremental pick feed using end mill (Pick feed = 0.1~1.1mm)

Fig. 5. Simulation of milling process using end mill (tool diameter = 6 mm, axial depth of cut = 6 mm).

233 it is too small compared to commercial system, computation
 234 time is still very fast using Pentium II 450 MHz personal
 235 computer. Because the length of tool path is not equal
 236 produced by general CAM module, represented system
 237 automatically splits each tool path into unit length as dots
 238 regularly attached in tool path in Fig. 5. In this paper, unit
 239 length of each tool path is assigned as 2 mm.

240 Fig. 6 shows simulated material removal volume rate in
 241 equally spaced parallel cut using conventional Z map and
 242 enhanced Z map model. Exact solution acquired by analy-
 243 tical method is plotted as dotted line in each graph. Though

244 pick feed is constant, simulated results show large deviation
 245 between each tool path when grid size is 0.1 or conventional
 246 Z map is used. Due to aliasing effect of regular sampling
 247 process in conventional Z map, it is hard to acquire steady
 248 results except the case when grid size is 0.05 mm. As grid
 249 size is decreased, simulation accuracy has a tendency to
 250 increase in each algorithm. But, it is hard to eliminate
 251 aliasing error using conventional Z map. When grid size
 252 is equal, simulated results using enhanced Z map is highly
 253 robust and accurate compared to the results acquired using
 254 conventional algorithm. Using conventional Z map, it is

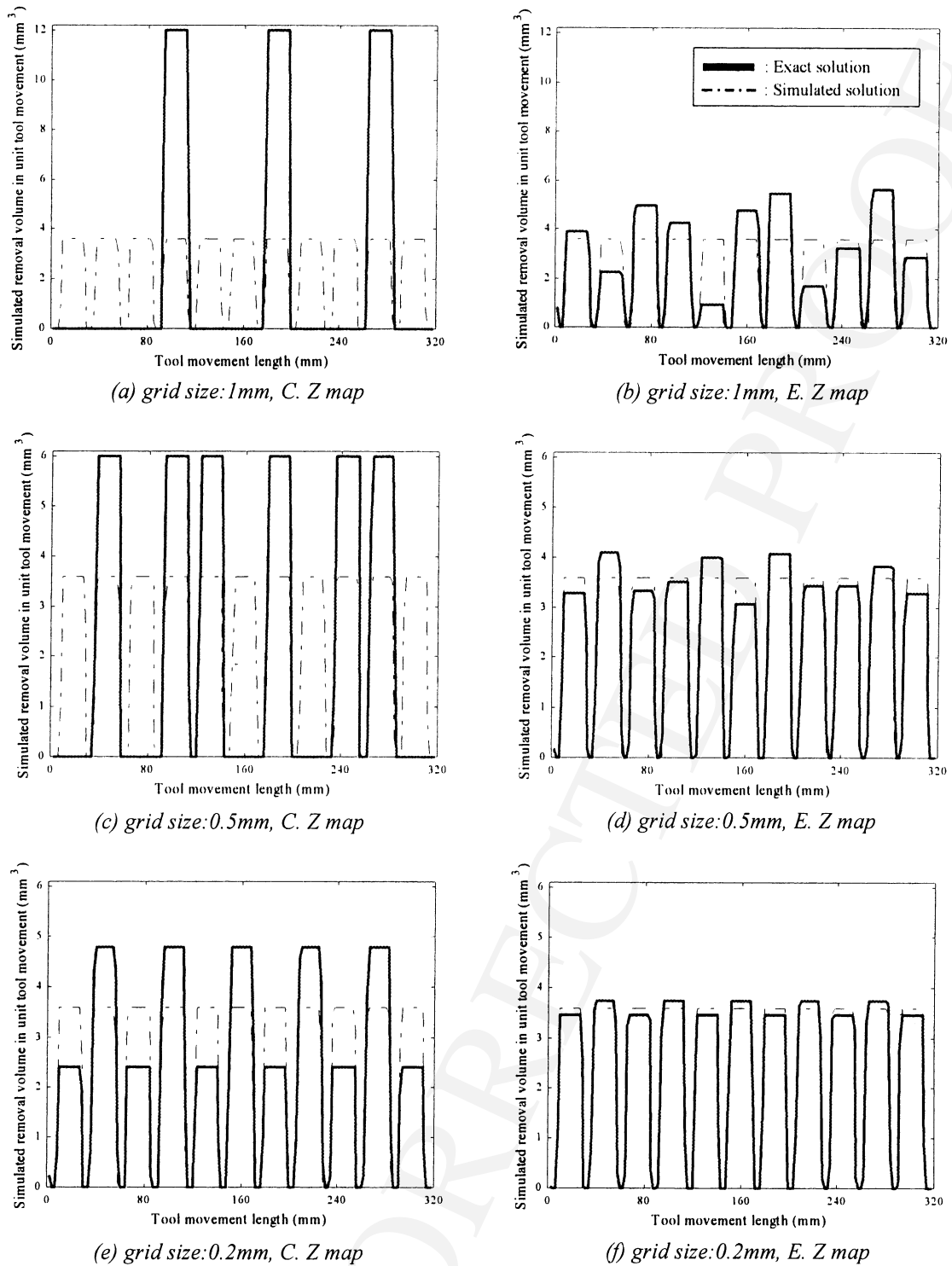


Fig. 6. Simulated material removal volume in according to unit length of tool movement with conventional Z map model and enhanced Z map model.

255 impossible to utilize in simulation of physical process
 256 including chip load and cutting force. When grid size is
 257 decreased to 0.05 mm, both systems produced very exact
 258 solutions.

259 Though simulation accuracy is highly improved in
 260 enhanced Z map model with same grid size, computation

cost and accuracy of simulation must be properly analyzed. 261
 To verify simulation accuracy, maximum error and standard 262
 deviation of error can be used as Fig. 7. By increasing grid 263
 size from 0.05 to 1.0 mm with both Z map algorithms, 264
 simulation efficiency has been analyzed. Because cutting 265
 tool can be damaged or broken instantly when simulation 266

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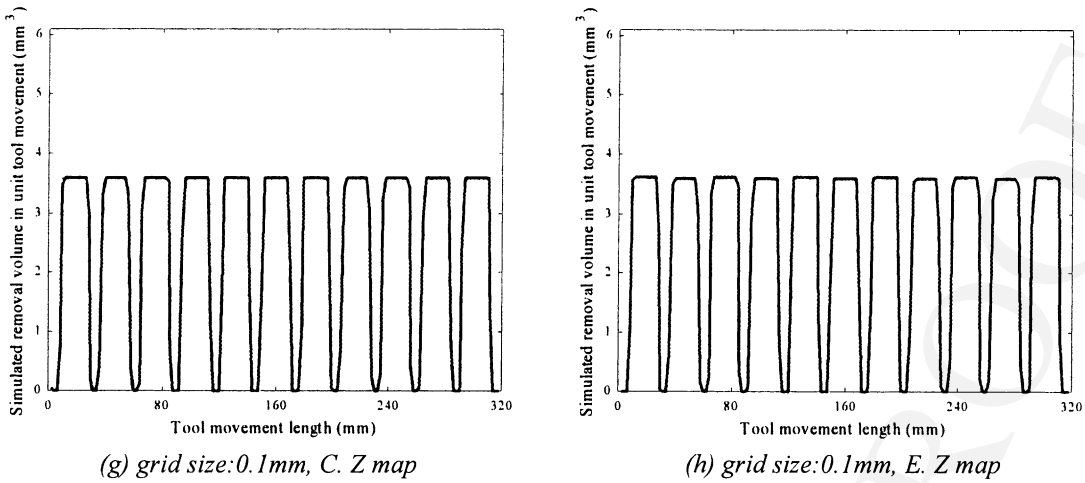
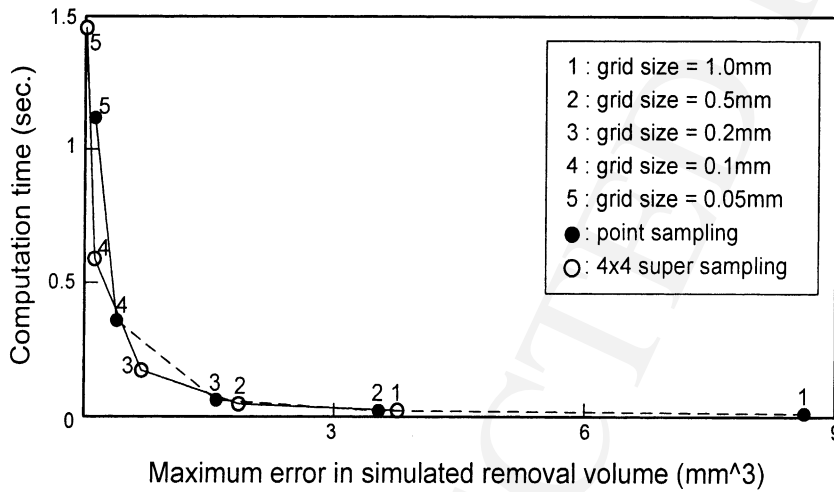
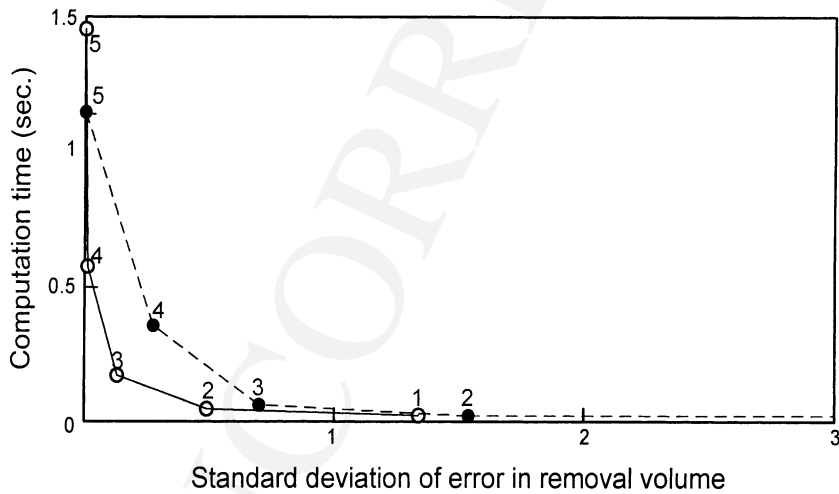


Fig. 6. (Continued).

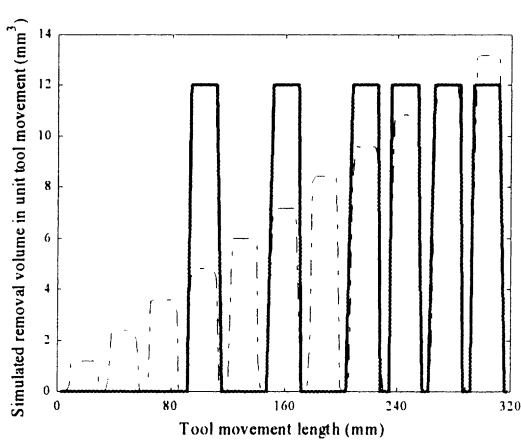


(a) Comparison of simulation time and accuracy in regular parallel cut with various grid size

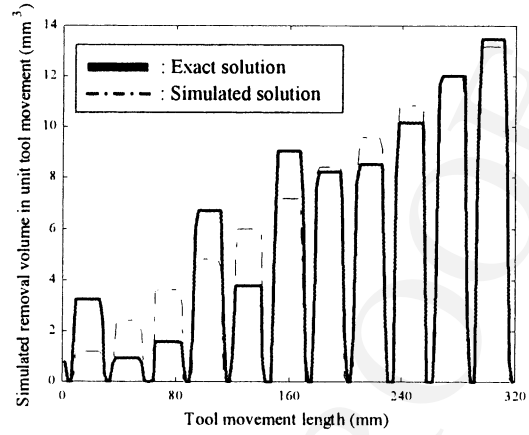


(b) Comparison of simulation time and standard deviation of error in regular parallel cut with various grid size

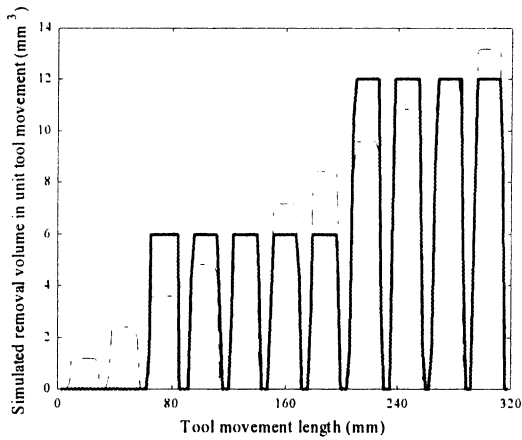
Fig. 7. The relationship between computation cost and accuracy between conventional Z map model and enhanced Z map model.



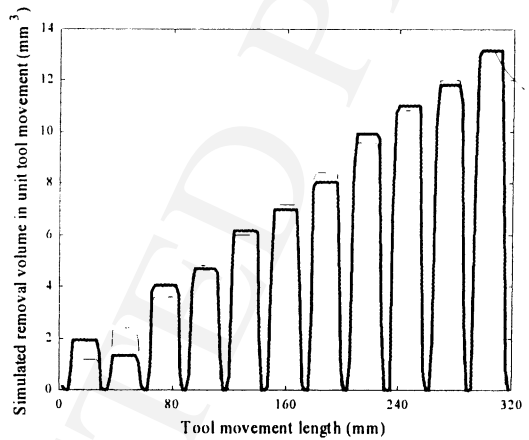
(a) grid size: 1mm, C. Z map



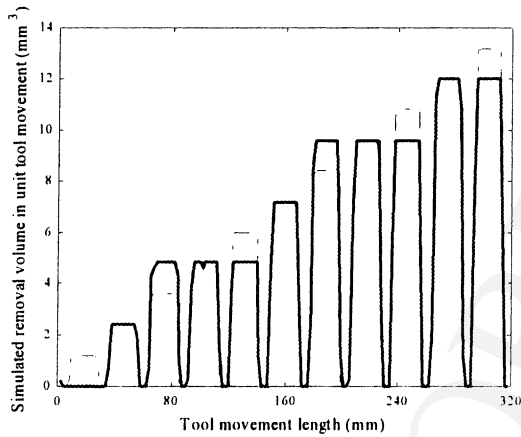
(b) grid size: 1mm, E. Z map



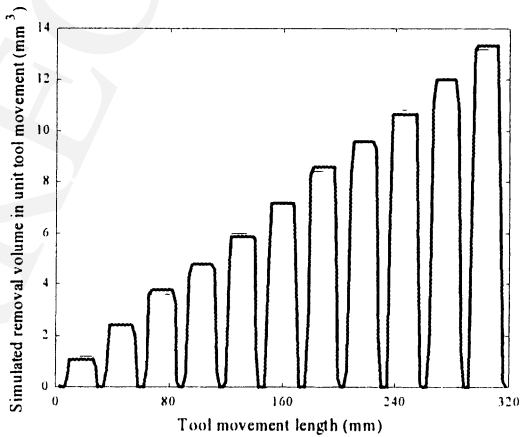
(c) grid size: 0.5mm, C. Z map



(d) grid size: 0.5mm, E. Z map



(e) grid size: 0.2mm, C. Z map



(f) grid size: 0.2mm, E. Z map

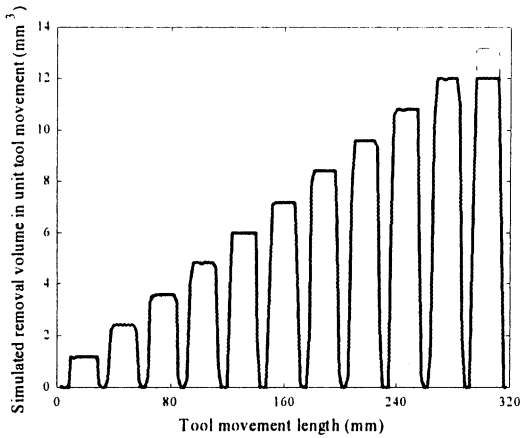
Fig. 8. Simulated material removal volume in according to unit length of tool movement with conventional Z map model and enhanced Z map model.

267 error is too large, maximum error is considered to verify
 268 simulation efficiency in according to computation time.
 269 Standard deviation of error shows overall accuracy of simu-
 270 lation, too. As shown in Fig. 7(a), there is no significant
 271 difference in maximum error between each algorithm. But,

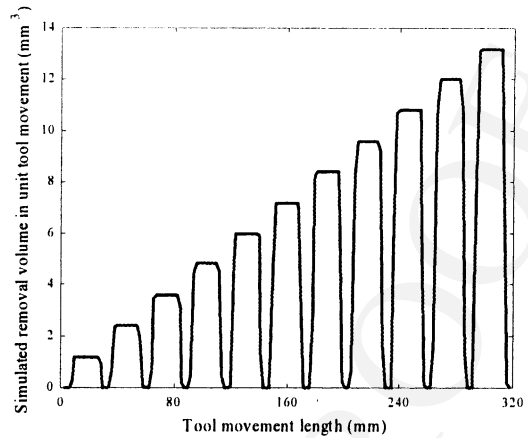
in Fig. 7(b), standard deviation of error using enhanced Z
 map algorithm is 2–4 times smaller than the results using
 conventional algorithm.

Due to the overhead in supersampling process, computa-
 tion time of simulation using enhanced Z map is about two

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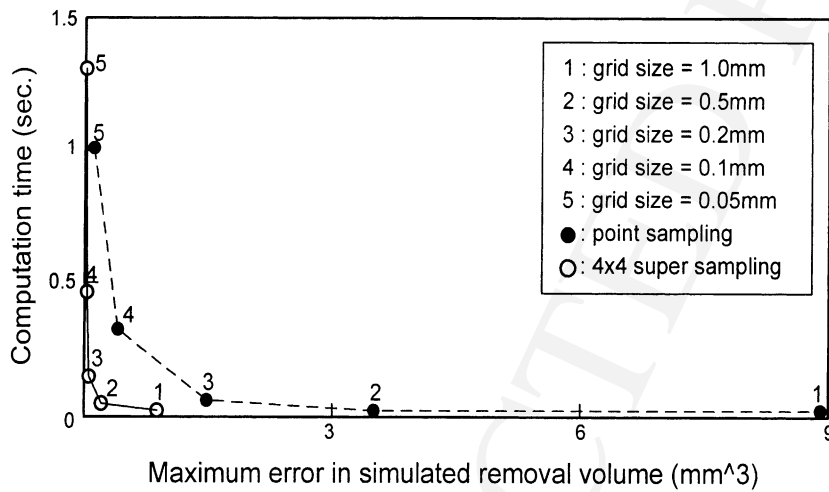


(g) grid size:0.1mm, C. Z map

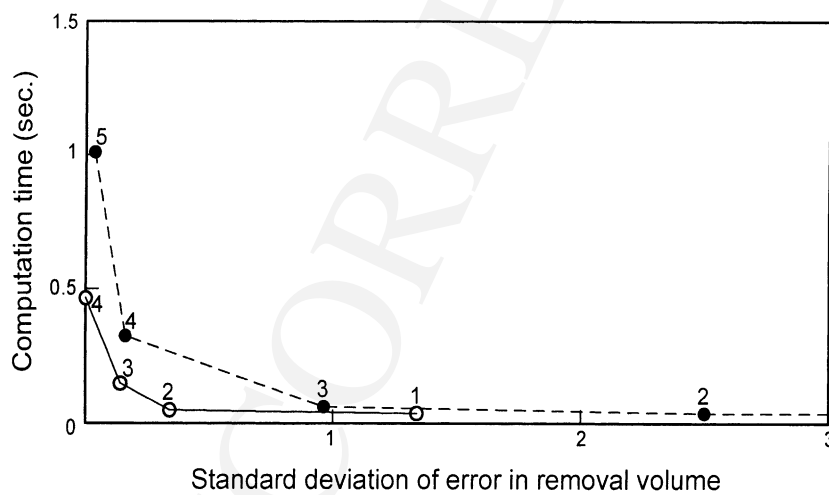


(h) grid size:0.1mm, E. Z map

Fig. 8. (Continued).



(a) Comparison of simulation time and accuracy in incremental parallel cut with various grid size



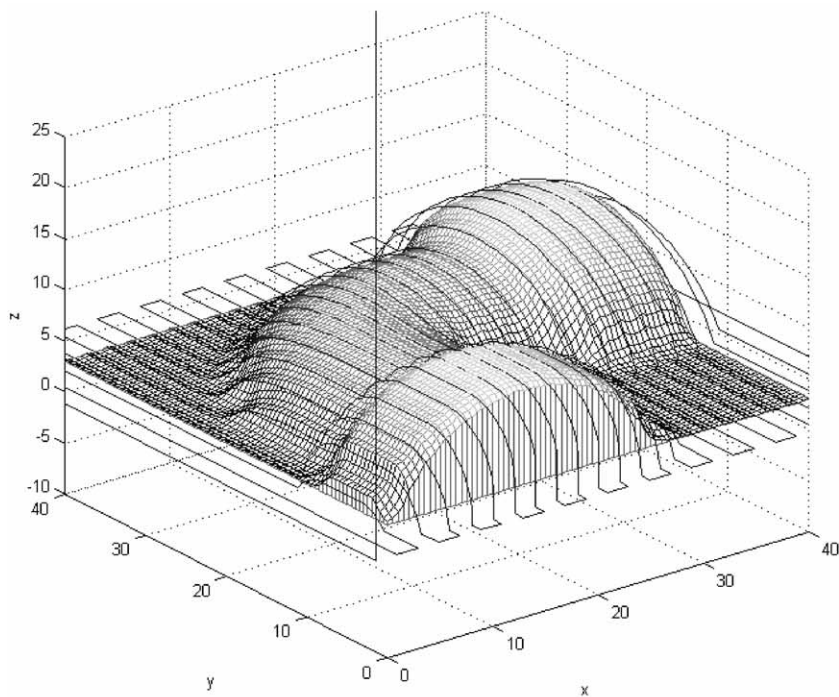
(b) Comparison of simulation time and standard deviation of error in incremental parallel cut with various grid sizes

Fig. 9. Relationships between computation cost and accuracy between conventional Z map model and enhanced Z map model.

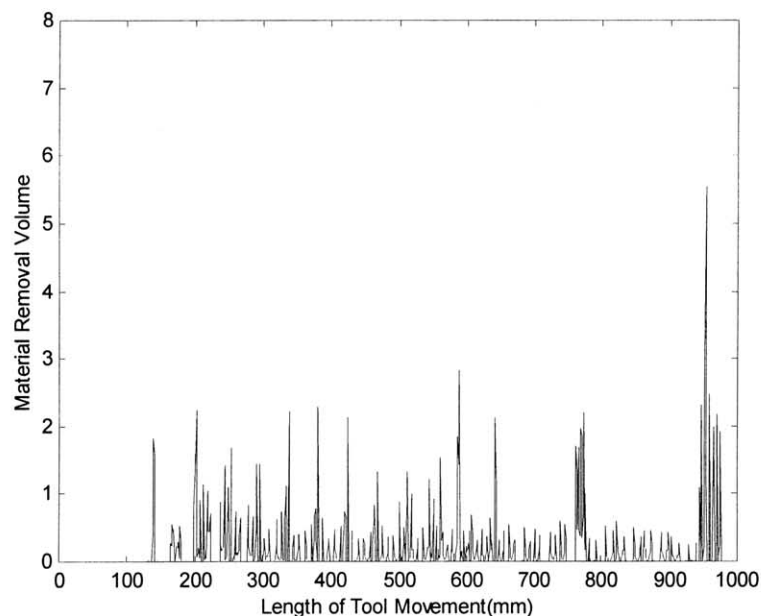
277 times longer when grid size is equal. But, dramatic increase
 278 of accuracy compromises its cons as shown in Fig. 7. This
 279 analysis is well coincident to the results of Fig. 6.

280 Fig. 8 shows simulated removal volume in linearly incre-
 281 mental pick feed is applied. Using both simulation algo-
 282 rithms, grid size is varied from 1 to 0.05 mm. The results
 283 acquired with 0.05 mm grid size is omitted because the

284 results were almost exact solution as Fig. 8(h). When grid
 285 size is 1.0 mm in conventional Z map algorithm, there is
 286 only one step as shown in Fig. 8(a). It can be said that the
 287 aliasing effect of discrete sampling in regular point sampling
 288 process produces such results. If grid size is reduced to
 289 0.5 mm, there are two steps as Fig. 8(c). In conventional Z
 290 map, there is always aliasing error when the grid size is



(a) Simulation of tool path and sculptured surface



(b) Simulated removal volume of general rough machining process

Fig. 10. General rough machining process with ball end mill.

larger than pick feed of tool path. On contrast, there is no regular step in the results acquired using enhanced Z map model. It is due to the antialiasing mechanism of super-sampling method.

Because pick feed of incremental tool path is relatively large compared to equally spaced tool path, the simulated accuracy using enhanced Z map is highly increased as shown in Fig. 9. There is significant difference between the results of each algorithm. Large maximum error and high standard deviation means that it produces highly overestimated or underestimated simulation results. When simulating machining process regarding physical interaction between tool and workpiece, large error in simulation can produce fatal damage to product or tool. In Fig. 9, it can be said that enhanced Z map produces 2–5 times more robust simulation than conventional Z map algorithm.

A good simulation system is faster and more accurate. Because enhanced Z map model produces more accurate simulation with same or lower computation time and memory usage compared to conventional Z map model, new general simulation system based on enhanced Z map algorithm is developed. Using general NC program, developed system can simulate cutting operation with exact material removal volume estimation. Fig. 10 shows simulated results using ball end mill of 6 mm diameter. Not only geometrical interference between tool and workpiece, this system estimates material removal volume with unit tool movement as shown in Fig. 10(b).

5. Conclusions

In this paper, the development of simulation system in milling operation using enhanced Z map algorithm is presented to be used for verification and analysis of NC program. The most significant benefits of suggested algorithm are its improved accuracy and reliability without any change in data structure of conventional Z map model.

By analyzing simulated results, it is shown that suggested simulation system with inclined supersampling method produces 2–5 times more accurate results with same computation time. When considering simulation efficiency of computation cost and simulation accuracy by comparing maximum error and standard deviation of error, suggested model can simulate NC program 2–3 times faster than conventional Z map model with better accuracy and better robustness in material removal volume rate.

It may be possible to develop cutting process optimization algorithm for machining dies and molds with sculptured surfaces using developed simulation system. Further

research is continuing to enhance suggested algorithm to implement into industrial environments.

Acknowledgements

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