Computer Integrated Adaptive Slicing and Vision Technologies for High Performance Rapid Prototyping System

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Abstract

This paper discusses the application of adaptive slicing algorithm and computer vision technology on Rapid Prototyping (RP) system to enhance fabrication performance of Model Maker (MM) RP system. Usually, the layer number determines the RP system performance in terms of fabrication time and accuracy. In this research, a new practically adaptive slicing algorithm is developed and easily implemented for RP system, because it only recalculates the scanning path according to the criterion of adjacent profile variation. The experimental results of the proposed adaptive slicing algorithm show that the saving of 54% fabrication time is achieved and the model accuracy is still remained in the same level. MM presents a problem of stability because of tiny nozzle. Computer vision technology is employed in this paper to on line inspect the layer accuracy and defect of a model fabricated by RP system. The results of vision inspection is used to close-loop monitor the process to increase the processing stability and accuracy. These new practically adaptive slicing algorithm and machine vision technology are implemented in the commercial Model Maker (MM) RP system to increase its fabrication speed, accuracy and stability, but not accuracy sacrifice. Hence, the performance of the MM RP system can be significantly enhanced using vision and practically adaptive slicing technologies.

Keywords: Rapid Prototyping, Machine Vision, Adaptive Slicing, Texture Analysis.

Introduction

Rapid Prototyping (RP) technology has been widely applied in all industries to accelerate products into the market, since the first stereolithography machine is commercialized in 1988. However, the RP fabrication speed is still limited by the requirement of model accuracy, although the prototype fabrication has been accelerated using the layer manufacturing and automation technologies. The reason is that the higher the requirement for model accuracy, the smaller the layer thickness, and hence, the more layers required and therefore the slower the fabrication speed. This conclusion is only valid for constant layer thickness, which is employed by most commercial RP systems. Actually, the model accuracy not only depends upon the layer thickness but also the geometrical complexity. If the layer thickness varies with the geometrical complexity, the fabrication speed can be accelerated without accuracy sacrifice. Also, the model accuracy can be improved without sacrifice of fabrication speed, because the total layer number does not increase. In order to accelerate the fabrication speed but not accuracy sacrifice, several researches concentrate on the development of the adaptive slicing algorithm (Hope 1997, Tada 1998, and Sabourin 1996). All of these currently proposed adaptive slicing algorithms need a new slicing engine, which is not practical for or compatible with most of the commercial RP systems.

Although the on-line monitoring of RP is an interesting research topic, there is few documentation concerned with this topic. Reeves and Cobb at the University of Nottingham established a mathematical representation of the surface roughness of stereolithography parts to reduce the surface deviation of stereolithography using in-process techniques (Reeves, 1997). Some Japan researchers used eddy currents to real time measure the stress and strain in the cured photoresin for Stereolithography. In comparison with other RP research topics, the research into on-line monitoring and defect inspection of RP processes is still very limited. In order to monitor the fabrication process and inspect the defect of MM on-line, vision technology is employed in this research. Also, the captured image was processed to identify the defect and feedback to control the process to fix the defect.

The fabrication speed of MM RP system, using the proposed adaptive slicing algorithm, can be significantly accelerated but not accuracy sacrifice. Also, the system is on-line monitored layer by layer using the vision technology to solve the problem of processing stability caused by the adaptive slicing method and the potential blockage of nozzle. Hence, the fabrication performance of the MM RP system is dramatically enhanced and demonstrated by the integrated application of the adaptive slicing algorithm and computer vision technology.

Model Maker RP system

In this research, a practically adaptive slicing algorithm is implemented in the MM RP system, and the layer fabrication process of MM is monitored on-line using a CCD camera. A MM RP system uses two ink-jet type print-heads, one depositing the thermoplastic green building material and the other depositing red supporting wax. The liquefied material cools as it is ejected from the print-head and solidifies upon impact on the model. Wax is deposited to provide a flat, stable surface for the deposition of material in the subsequent layers. After each layer is complete, a cutter planes off the layer's top surface to provide a smooth, even surface for the next layer. The MM RP system is one of the most accurate RP systems, producing layers from 0.0005in to 0.005in. It can produce a model with very small features and fine surface finish.

The .STL file of the fabricated model is loaded into the ModelWorks program, which is a preprocessor of MM, to be sliced and viewed. Then, the .BIN and .BLD files for further model fabrication are generated. The .BLD file is a build process parameter file, which contains the data that describe how the model will be built. The .BIN file contains data describing the physical geometry of the model. It defines the model as a series of cross-section layers. Each layer is defined as a series of individual lines (vectors).

A new practical adaptive slicing method using finest layers stacking

Sabourin et al (1996) proposed an adaptive slicing algorithm to first slice the CAD STL model uniformly into slabs of thickness equal to the maximum available fabrication thickness. Each slab is then re-sliced uniformly as needed to maintain the desired surface accuracy. This adaptive slicing algorithm using stepwise uniform refinement is not practical, because some of the geometrical features may be already lost at the first slicing procedure using the maximum available fabrication thickness. The contradictory concept of Sabourin's adaptive algorithm is used in this study to slice the model uniformly into slabs of thickness equal to the minimum available fabrication thickness. Hence, the best accuracy available in the RP system can be met. Although model fabrication using the minimum available fabrication thickness, i.e. the best accuracy, is demanded for all RP systems, it sacrifices fabrication speed because of too many layers. In order to compromise between the fabrication speed and accuracy, the number of layers must be reduced to an acceptable range and the model accuracy must not be sacrificed. The profiles of the adjacent finest layers are examined to evaluate whether these adjacent layers can be stacked as a single layer. If the profile variations of these adjacent layers are within the tolerance required, these adjacent layers are stacked as a single layer. Hence, the number of layers can be reduced and the fabrication speed can be accelerated without accuracy sacrifice.

The level of the profile variation is the criterion of the adaptive slicing method using the adjacent finest layers stacking. The level of the profile variation is represented as an angle, which is tangent to the adjacent finest layers. If the profile tangent angle θ is equal to 90°, it means that there is no profile variation between the adjacent layers. Or if the profile tangent angle is greater than an acceptable angle, the profile variations between the adjacent layers are within the acceptable tolerance. Hence, these two adjacent layers can be stacked as a single layer without accuracy sacrifice. This stacking procedure repeats until the layer thickness reaches the maximum layer thickness allowed in the RP system. On the other hand, if the tangent angle is less than a critical angle, that means the layer must be fabricated using the finest layer thickness, because the profile variation is too much. These two adjacent layers cannot be stacked together. It is also possible to only stack two, or three, or four, or several layers before reaching the maximum allowed layer thickness, because the profile variation is still within the acceptable tolerance. Therefore, the new fabrication layer thickness depends upon the criterion of the tangent angle. Of course, the fabrication parameters must be adjusted according to the new layer thickness. This adaptive slicing method using the finest layer stacking is implemented in the MM system.

Results and evaluation of the adaptive slicing method using finest layers stacking on the Model Maker system

Table 1 shows the detailed layer information of bench models using both constant layer thickness slicing and the adaptive slicing method on the MM system for three different criteria. As shown in Table 1, the original first 40 layers of bench models, using minimum slicing layer thickness, were stacked as 10 layers, because there is no profile variation at the bottom of the models. The original total layer number of models using the finest layer thickness is 140, but the total layer number of models using the adaptive slicing method is only 66 for the criterion at the tangent angle 30 degrees. For the criterion at tangent angle 60 degrees, the total layer number is only 86, because not only the bottom of the model was stacked as 10 layers from 40 layers, but also the middle of the model was sliced using normal slicing thickness.

As the result the detailed fabrication information of bench models using constant layer thickness and adaptive slicing thickness. It took 6881 seconds to fabricate bench model (a) using the finest layer thickness, 0.1mm, and to fabricate the same model using the maximum layer thickness only took 34% of the fabrication time, in comparison with the finest layer thickness. Of course, the model accuracy using the finest layer thickness is much better than that using the maximum layer thickness. For the criterion of tangent angle at 30 degrees, the fabrication time of bench model (a) using adaptive slicing method is only 62% of that using the finest layer thickness. There are serious steps at the round curves of the original model using constant slicing thickness, but these steps did not exist in the model fabricated using adaptive slicing algorithm. The reason for the better accuracy of the bench model (b) using adaptive slicing method, is that the high level of the profile variation area of bench model B was fabricated using the finest layer thickness

0.1mm. However, the bench model B was all fabricated using the same layer thickness 0.2mm no matter what the profile variation.

In order to quantitatively evaluate the accuracy of the bench models, the roundness error of the model (A) and (B) is measured and tabulated in Table 1. As shown in Table 1, the roundness error of the models, fabricated using adaptive slicing method, is slightly less than that of models fabricated using layer thickness 0.2mm and much smaller than that of models fabricated using layer thickness 0.4mm. Though the roundness error of the models, fabricated using adaptive slicing method, is slightly larger than of models fabricated using finest layer thickness 0.1mm, the fabrication time of the models, fabricated using adaptive slicing method, is much smaller than that of models fabricated using finest layer thickness 0.1mm. Hence, the adaptive slicing method is approved to accelerate fabrication speed of Model Maker RP system and without too much accuracy sacrifice.

Table 1. The result of the bench models test in terms of the fabrication time.

Bench model (A)

Slicing Method		**Number of Layers**			**Total Layer No.**	**Fabrication Time (s)**	**Relative Fabrication Time (%)**	**Roundness Error (mm)**
		Tmax = 0.4mm	**T=0.2mm**	**Tmin = 0.1mm**				
Constant Layer Thickness	**Tmin**	-	-	140	140	6881	100	0.205
	T	-	70	-	70	3566	51.82	0.294
	Tmax	35	-	-	35	2358	34.27	0.437
Adaptive Slicing Thickness	**Tangent Angle=30**	10	44	12	66	4284	62.58	0.276
	Tangent Angle=45	10	34	32	76	5003	72.71	0.248
	Tangent Angle=60	10	24	52	86	5353	77.79	0.229

Bench model (B)

Slicing Method		**Number of Layers**			**Total Layer No.**	**Fabrication Time (s)**	**Relative Fabrication Time (%)**	**Roundness Error (mm)**
		Tmax = 0.4mm	**T=0.2mm**	**Tmin = 0.1mm**				
Constant Layer Thickness	**Tmin**	-	-	140	140	5801	100	0.156
	T	-	70	-	70	2958	50.99	0.282
	Tmax	35	-	-	35	1934	33.34	0.435
Adaptive Slicing Thickness	**Tangent Angle=30**	10	43	14	67	4144	71.74	0.257
	Tangent Angle=45	10	35	30	75	4344	74.88	0.215
	Tangent Angle=60	10	24	52	86	4550	78.43	0.167

Vision monitoring of MM fabrication process

The experimental layout of the on-line layer monitoring and defect inspection is schematically illustrated in Figure 1. The MM machine is controlled by the fabrication commands (.BIN and .BLD files) generated from the process control computer. Another computer is employed to process the captured image from the CCD camera to identify the defect, calculate the defect coordinate, and generate the compensated program. Also, the sliced profile data obtained from the slicing software, ModelWork, is used to compare with the image profile for further on-line monitoring of the MM system. The coordinates of the layer defect can be calculated and fed back to the process control computer to move the nozzle and deposit new material at the position of the defect. If the profile is oversize rather than defective, the compensated program will raise the platform and move the cutter to plane off the current layer. Only the problem of defect is presented in this paper, because the oversize problem is similar to that of the profile accuracy analysis.

In order to evaluate the feasibility of the on-line monitoring of the MM process, a simple square part of $20X20mm^2$ is designed with a rectangular defect in the central area. The image of the defect area is found in the previous layer rather than in the current layer. Hence, the image of the previous layer is an important reference to identify the morphology of the defect. An image difference algorithm is then employed to remove the effect of the previous layer image on the identification of the defect. Also, in order to immediately inspect the layer defect, the image is captured as soon as the build material is deposited rather than after the cutter operation. Since, the surface condition of the material deposition before cutting is very different from that after cutting, the surface texture of the material deposition and the defect can be discriminated. As a result, the defect can be inspected and the process can be further on-line monitored.

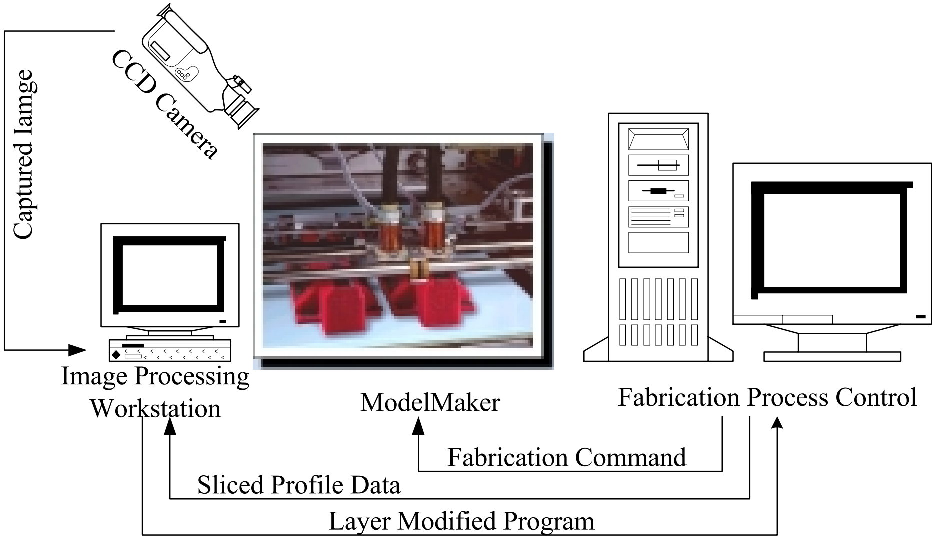


Figure 1. Experimental layout of on line layer monitoring and defect inspection of MM using vision technology.

ON-LINE DEFECT INSPECTION USING AN ADAPTIVE TEXTURE ANALYSIS

The printing path characterizes the build material deposition image, and the defect is characterized by the smooth surface after the cutting operation in the previous layer. The characteristic difference of the deposition and the defect is modeled as adaptive texture analysis to discriminate the defect from the direct image of the current layer, rather than two images captured in the image difference algorithm. The algorithm used in this adaptive texture analysis is the ‘adjusted *Texture-Energy-Ratio* approach.’ as shown in Figure 2. (Wang, 1998).

Only one image is captured after the deposition of the build material at the current layer, which is different from the two images captured before and after material deposition, respectively.

The captured image of the adaptive filter texture analysis is the target image to identify the defect. The captured image is then processed to identify the defect using an adaptive filter texture analysis. As shown in Figure 3.(b), there are two pattern textures in the image after the build material deposition at the current layer. The first pattern is the texture of the printing path, which is the deposition area of the new build material. The other pattern is the texture of the defect, which is the smooth surface of the previous layer after the cutting operation.

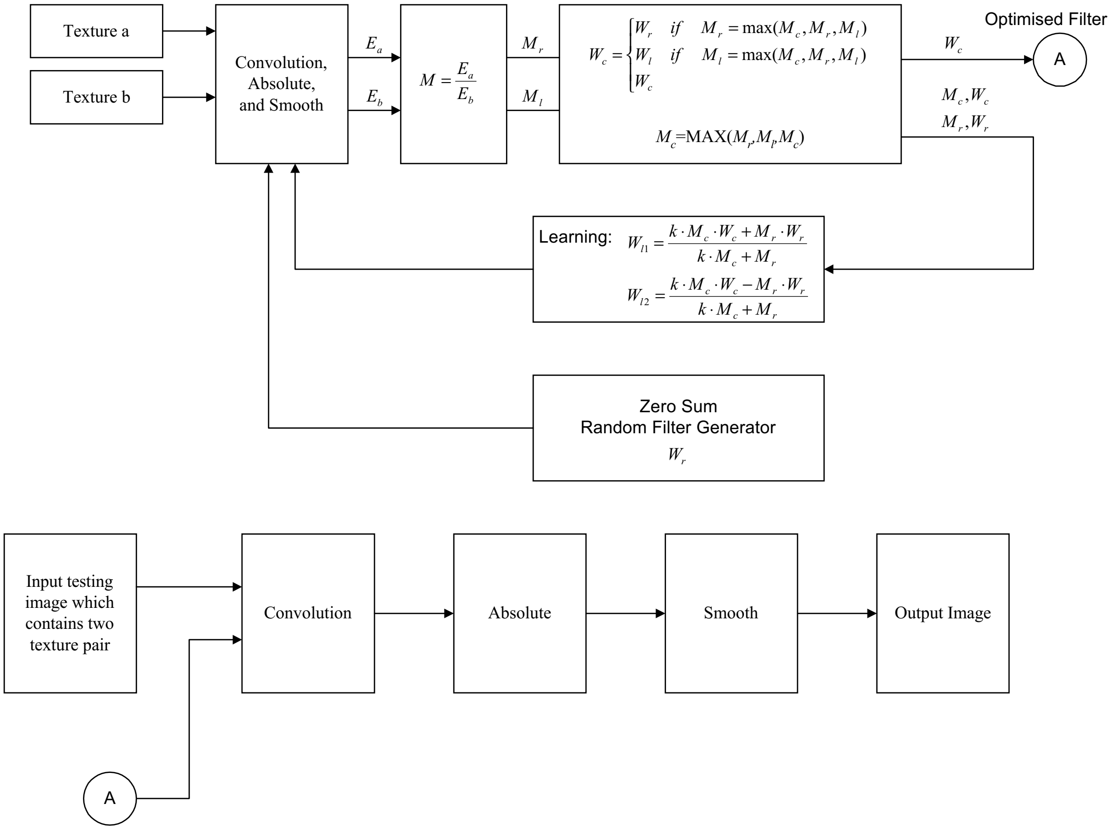
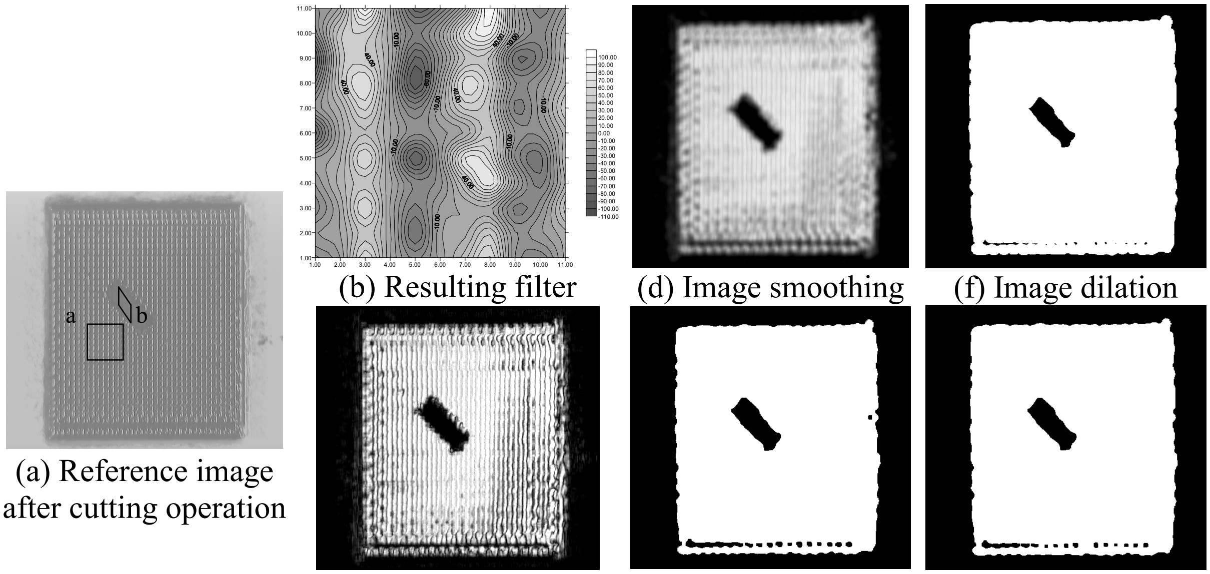


Figure 2. Adaptive texture analysis and inspection using the adjusted *Texture-Energy-Ratio* approach. (Wang, 1998)

In order to analyze the texture of the new printing path and the defect, two masks are employed to extract the characteristics of these two textures as shown in Figure 3.(a). The texture of the printing path for the new build material is extracted using mask “a”, and the texture of the defect is extracted using mask “b”. The textures from mask “a” and “b” are processed using an adaptive texture algorithm, presented in the next section, to iteratively calculate the resulting filter as shown in Figure 3.(b). This resulting filter is an 11×11 array, and the value of the array distributed from -100 to 100. The equal height of the resulting filter is identified and labeled. The distribution of the resulting filter is regularly repeated like a sine function, and its characteristic is similar to the line by line characteristic of the printing path. It is used to filter out the line characteristic texture of the printing path into one single feature and isolate the defect texture as another single feature. The resulting filter is applied to the image of the current layer to adaptively discriminate the defect feature from the whole image of the current layer. Then, the discriminated image is adjusted for higher brightness and contrast ratio as shown in Figure 3.(c). The smoothing, thresholding, dilating, and eroding operations are then applied to the image to identify the defect as shown in Figure 3.(d), 3.(e), 3.(f), and 3.(g) respectively, which is the same as that of last four steps in image difference processing. In comparison of defect image processing using image difference and adaptive texture as shown in Figure 3.(f) to Figure 3.(h) and Figure 3.(e) to Figure 3.(g) respectively, the result of the adaptive texture analysis is a little bit better than that of image difference. The reason is that the noisy area of texture analysis is smaller than that of image difference.



(a) Reference image after cutting operation

(b) Resulting filter

(c)Adjustment of image brightness and contrast

(d) Image smoothing

(e) Image thresholding

(f) Image dilation

(g) Image erosion

Figure 3. The results of the defect image processing using an adaptive texture filter, smoothing, thresholding, dilation, and erosion algorithms.

Finally, the defect coordinates are calculated from the defect image. If the defect size is within the range of tolerance, the fabrication process continued. However, if the defect size is unacceptable, a compensation program is generated and transferred back to the control program to redeposit build material on the defect area. Hence, the on-line monitoring of MM is achieved.

GENERATION OF DEFECT COMPENSATION PROGRAM FOR ON-LINE MONITORING OF MM RP

Once the defect is identified, a compensated program is generated in the image processing workstation and transferred back to the fabrication process control computer to reprint the defect area for on-line monitoring of MM RP. In order to calculate the defect coordinates, a translated matrix is calculated using simple linear translation and rotation algorithms to transform the image coordinates to the MM coordinate system. Then, the coordinates of the defect are extracted and determined from the image using scanning lines. Once the defect coordinate is determined and transformed into the MM coordinate system using the transformation matrix, a compensated program is generated in .BIN file format and is transferred back to the control computer. Hence, the defect area is redeposit with new build material controlled by the compensation program. Therefore, the fabrication process of MM RP is on-line layer monitored using vision technology.

CONCLUSION

A new practical adaptive slicing method using finest layers stacking for the RP system is presented in this paper. This new proposed adaptive slicing method is easy to implement in the RP system, because it just modifies the profile information after slicing operation and does not involve a new slicing engine. The proposed adaptive slicing method was implemented on the Model Maker RP system to accelerate fabrication speed without accuracy sacrifice. The experimental results show that it only takes 62% of the fabrication time at the similar accuracy to use the new practical adaptive slicing method in comparison with the constant layer thickness.

The detailed image process of defect inspection using the adaptive texture analysis is presented. The defect is on-line inspected and fixed by the reprinting of new build material, layer by layer. Hence, the computer integrated adaptive slicing algorithm and vision technologies enhance the performance of RP system, because it not only increase fabrication speed but not sacrifice with accuracy, but also on-line monitor and stabilize the fabrication process.

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