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DESIGN FOR MICRO-STEREOLITHOGRAPHY USING AXIOMATIC APPROACH

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ABSTRACT

Micro-stereolithography technology has made it possible to fabricate any form of three-dimensional microstructures. Until now, however, the micro-stereolithography device was not designed systematically because the key factors governing the device were not considered. In this paper, we designed micro-stereolithography device using axiomatic approach. This paper contains an overview and an analysis of a new proposed system for development of micro-stereolithography device, and detailed descriptions of the activities in this system. The new system offers reduced machine size by minimizing of optical components, and shows that the design matrix is decoupled.

Keywords: Micro-stereolithography, Axiomatic approach

1 INTRODUCTION

Micro-stereolithography, which made it possible to fabricate a 3D microstructure, was first introduced by Ikuta [1, 2]. This technology is based on conventional stereolithography, in which a UV laser beam irradiates the open surface of a UV-curable liquid photopolymer, causing it to solidify. Figure 1 shows the principle of micro-stereolithography technology schematically.

In micro-stereolithography, similar to conventional stereo-lithography, many UV laser scan lines are overlapped to fabricate a given cross-sectional area. And these cross-sectional areas are stacked together to form the desired 3D shape. However, in micro-stereolithography, a laser beam that is of a few ㎛ in diameter is used to solidify a very small area of the photopolymer. This is one of the key technological elements and can be achieved by using a focusing lens. Besides, to fabricate a very small 3D microstructure, a precision control system and optic system are needed. The micro-stereolitography system has to be designed systematically to fabricate desired 3D structures because the system and fabrication process are affected strongly by some key factors.

In this paper, we designed micro-stereolithography system using axiomatic approach. As a result of this analysis, the key factors affecting fabrication of microstructure were obtained and improved micro-stereolithography system was reconstructed.

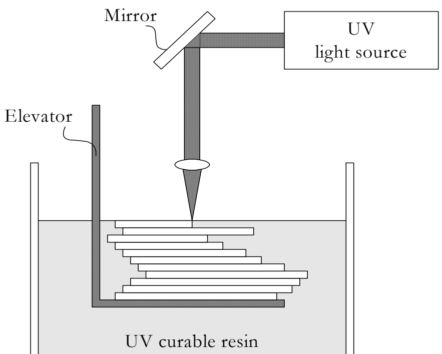

Figure 1. The principle of micro-stereolithography.

2 MICRO-STEREOLITHOGRAPHY

The micro-stereolithography technology has its origin to the conventional stereolithography technology. When a UV light was irradiates on the photopolymer, the photo-initiator polymerize monomers in the photopolymer and the photopolymer become solidified. The photopolymerization is a process that is initiated by the photons, generated by the UV light with the monomer double bond broken or ring opening leading to the chain propagation, and the cross-linked polymer chains are finally formed when the chain propagation is terminated. In order to create a 3D structure, two-dimensional slicing shapes (slice data) of the desired 3D data are required. Generally, these slice data can be obtained from the CAD data. Stacking up layers of these slice data layer-by-layer, a 3D shape can be obtained as shown in Figure 2.

However, in comparison with the conventional stereo-lithography technology, there are many serious difficulties due to miniaturization to micro scale, i.e., so called 'scale effect' of physical phenomena appears in the micro scale. Many problems are caused by this effect in micro scale in the micro-stereolithography technology. For example, the viscosity of the liquid photopolymer increases in micro scale and this can cause deformation or destruction of the fabricating microstructure. Also, a high precision control of the x-y-z stage is required for photopolymer solidification.

In this regards, technologies for the micro-stereolityhography have to be developed. Development of a process considering the viscosity of the photopolymer is necessary. Furthermore, precise x-y-z stage control and focus control of the UV laser beam within a few ㎛ of focal diameter are necessary.

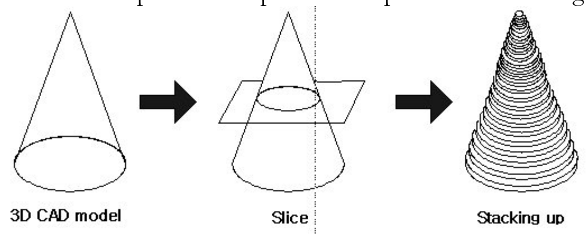

Figure 2. Fabrication process of stereolithography by stacking up the sliced cross-sections.

2.1 OPTICS AND CONTROL SYSTEMS

Figure 3 shows the schematic drawing of the previously developed micro-stereolithography apparatus[3, 4].

A CW (continuous wave) Ar ion laser was used as the light source, which had a wavelength λ of 351.1 ㎚ (single line). The maximum power of the laser is about 460 ㎽ at 351.1 ㎚ and the power can be controlled continuously by attached controller. The UV laser beam from this laser advanced through a series of optical system (including mirrors and beam splitters) for changing the beam path. This beam was focused on the photopolymer through a focusing lens. The power of the laser beam had to be adjusted according to the characteristics of the photopolymer and shape of the fabricated structures. Moreover, fabricated structures using the micro-stereolithography apparatus were range from few micrometers to few millimeters. Therefore, very high laser power from the laser had to be reduced. Consequently, some ND (neutral density) filters are used to decrease the laser power. Beam splitters were used for changing the beam path and decreasing the laser power.

In the optical system, precise beam path arrangement is very important. However, arrangement of the beam path is relatively hard because of the UV beam's invisibility. Some linear stages equipped with micrometers were used for the arrangement of the UV laser beam for some devices such as for the beam expander and the focusing lens. Especially, at the final stage of the laser beam path, the beam axis had to coincide with the axis of the focusing lens. Some misalignment induces unsatisfactory beam quality at the focal plane. Therefore, three linear stages with micrometers are used to align the beam axis between the laser beam and the focusing lens.

The solidified photopolymer has to be fixed to the moving x-y-z stage during solidification process and it has to be removed easily after the process. The elevator was fixed to the x-y-z stage and moves in x-y-z directions in the photopolymer. On this elevator, a substrate whereon the microstructure was fabricated could be attached. The x-y-z stage system and the shutter should be controlled adequately to form a desired cross-section, i.e., movement of x-y stages had to be controlled under given cross-sectional shapes and hatching conditions in a layer. Furthermore, when a layer was completed, the z-axis stage had to be moved for the layer genera tion and the shutter also had to be operated to intercept the laser beam path simultaneously.

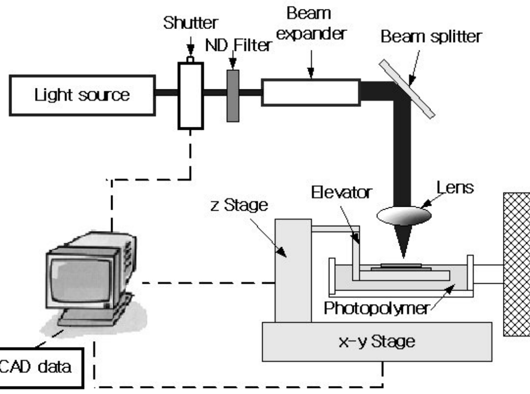

Figure 3. Schematic drawing of the previous micro-stereolithography apparatus.

3 AXIOMATIC DESIGN

In order to optimal design of micro-stereolithography system, the axiomatic design theory [4] was used. The functional requirements (FRs) are as follows.

FR_1 = Control the laser beam path.
FR_2 = Stack the photopolymer layers.

FR_1 was selected due to the photopolymer was solidified along the laser beam path when a microstructure was fabricated. FR_2 was selected due to the layer of solidified photopolymer was stacked to construct a 3D microstructure.

To satisfy these two FRs, a micro-stereolithography system with two compartments is designed. Two DPs for this system may be stated as

DP_1 = The optic control system
DP_2 = The stacking system

To satisfy FR_1 and FR_2, the optic control system should affect only the laser beam path to be controlled and the stacking system should affect only the photopolymer layer to be stacked without the optic control system. For these high-level DPs, the design equation may be written as

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \quad (1)$$

This is an uncoupled design. This is the best design at this level of decision making. All subsequent lower level design equations must be consistent with this higher level design equation. Because DP_1 and DP_2 cannot be implemented without further design details at a lower level of the hierarchy, they must be decomposed FR_1 may be decomposed to generate the next-level FRs as

FR_{11} = Control the laser scan path.
FR_{12} = Reflect the laser beam.

FR_{13} = Focus the laser beam.

To satisfy the second-level FRs, we have to conceive a design and identify DPs that can satisfy the FRs at this level of decomposition. Just as FR_1 and FR_2 were independent of each other through the choice of proper DP_1 and DP_2, we must now ensure that FRs at this second-level are independent of each other. Furthermore, the choice of the lower level DPs must be consistent with the higher level design matrix, i.e., they must not compromise the independence of FR_1 and FR_2.

The requirements of the optic system can be satisfied by (1) moving the laser scan path, (2) positioning the laser beam on the elevator for solidification of photopolymer , (3) reducing the laser beam diameter for fabrication of microstructure. Then, the second-level DPs may be chosen as

DP_{11} = x-y stage system that moves along the x-y plane when the laser beam solidify the photopolymer
DP_{12} = Optical mirrors that reflect the laser beam to optic components
DP_{13} = Optical lens that focus the laser beam on the solidified point

Then the design equation may be written as

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix} \qquad (2)$$

Equation (2) indicates that the design is an uncoupled design.
Similarly, based on the choice of DP_2 made, FR_2 may be decomposed as

FR_{21} = Flat the photopolymer surface.
FR_{22} = Control the layer thickness.

We can now design the stage system that has to flat the photopolymer surface and control the layer thickness for stacking the layers. To satisfy the FR_{21} and $FR_{22,}$ we must look for a design with two DPs. The design parameters are

DP_{21} = The viscosity of photopolymer
DP_{22} = The layer generation process

The DP_{21} is essential to solidify the next layer after the previous layer solidification, because the flat surface can be reduced the dimensional error of vertical direction when layers are piled up in turn. However, the viscosity of photopolymer affects generation of the layer thickness also. In other word, it is more difficult to make a thin layer thickness as the viscosity of photopolymer is higher. Thus, the design matrix for the $\{FR_{21,} FR_{22}\}$-$\{DP_{21,} DP_{22}\}$ relationship is triangular as shown below

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ x & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix} \qquad (3)$$

Equation (3) indicates that the design is a decoupled design and satisfies the Independence Axiom.

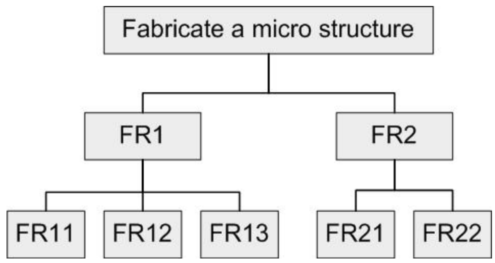

Figure 4. Tree diagram representing the functional requirements (FRs).

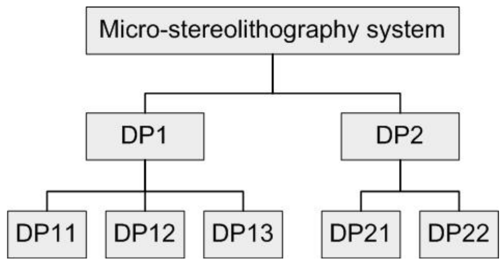

Figure 5. Tree diagram representing of the design parameters (DPs)

Table 1. Master design matrix for new system.

		DP_1			**DP_2**	
		DP_{11}	DP_{12}	DP_{13}	DP_{21}	DP_{22}
FR_1	FR_{11}	X	0	0	0	0
	FR_{12}	0	X	0	0	0
	FR_{13}	0	0	X	0	0
FR_2	FR_{21}	0	0	0	X	0
	FR_{22}	0	0	0	x	X

Figure 4 and Figure 5 show the hierarchy of decomposed FRs and DPs. The master design matrix that shows these two levels of decomposition is shown in Table 1.

3.1 SYSTEM CONSTRUCTION

Using axiomatic design theory, new micro-stereolithography system was constructed. Figure 6 shows the schematic drawing of the newly designed micro-stereolithography apparatus. Figure 7 shows photograph of constructed micro-stereolithography system.

The great difference between previously developed system and newly designed system is that the design matrix of previous system is coupled while the newly designed system is decoupled. This result can be obtained separation of x-y stage and z stage from x-y-z stage.

In previous system, the elevator fixed to x-y-z stage moved in the photopolymer. In such a case, there was a disadvantage that the layer thickness was changed depend on the scan speed of elevator located in photopolymer reservoir. However, in newly designed system using axiomatic approach, the laser beam path was controlled by driving the separated x-y stage. And the layer thickness was controlled by driving the separated z stage.

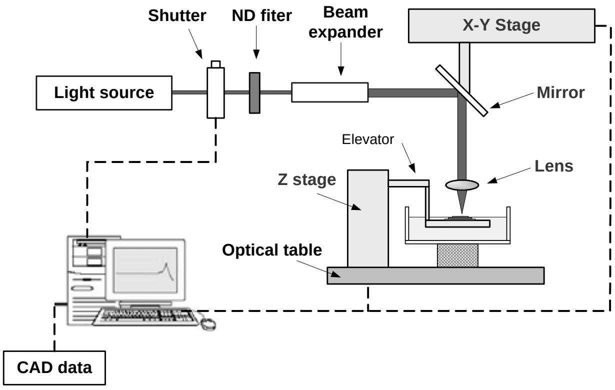

Figure 6. Schematic drawing of the newly designed micro- stereolithography apparatus.

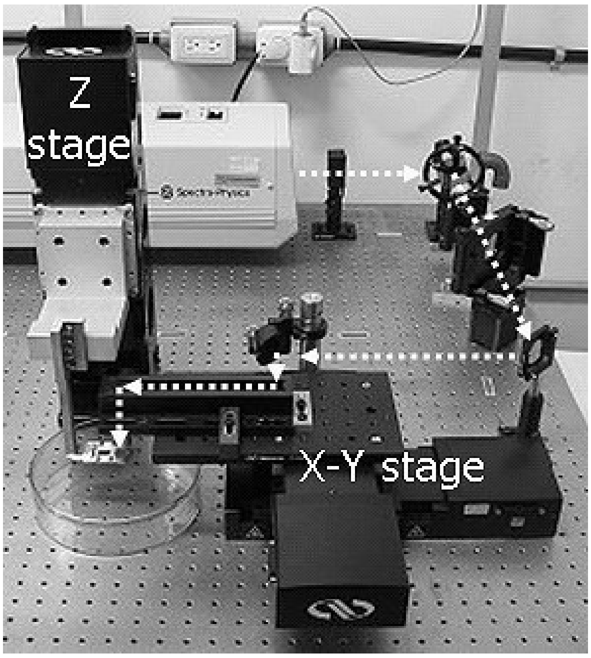

Figure 7. Photograph of the newly developed micro-stereolithography using axiomatic approach.

In this regards, it was eliminated that the effect of photopolymer's viscosity occurred by x-y stage movement.

Figure 8. shows the photograph of previous developed micro-stereolithography system and Table 2 represents master design matrix for this system. From this design matrix, it can be known that the system was coupled design. To change the coupled design to decoupled design in the newly designed system, the two prisms were substituted for optical mirrors on the x-y stage. In addition, an objective lens and prisms were integrated into one body. It enables that the error caused by vibration and inertial force was decreased when the x-y stage was moved because of reducing the weight and volume of optical components. Moreover, the laser beam was reflected precisely by using the prism and precisely machining components used for fixing optics. Therefore, it is easy to optic alignment using this integrated optic component and it enables that optic error was decreased.

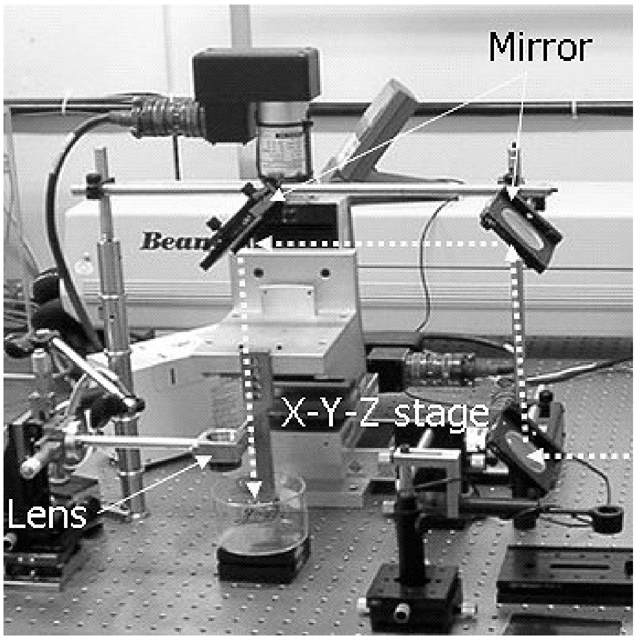

Figure 8. Photograph of previous micro-stereolithography.

Table 2. Master design matrix for previous system.

		DP_1			DP_2	
		DP_{11}	DP_{12}	DP_{13}	DP_{21}	DP_{22}
FR_1	FR_{11}	X	0	0	x	0
	FR_{12}	0	X	0	0	0
	FR_{13}	0	0	X	0	0
FR_2	FR_{21}	X	0	0	X	0
	FR_{22}	0	0	0	x	X

4 CONCLUSION

In this paper, a previously developed micro-stereolithography system was analyzed and redesigned using axiomatic design theory. The analysis results on the previous system shows that the previous design was coupled. Thus, we redesigned a new micro-stereolithography system and proposal design was a decoupled design. In addition, considering key factors in fabrication process of micro-stereolithography, the problems existed in the previous system could be eliminated. Furthermore, developing integrated optic component provides accurate optic alignment and compact system.

5 ACKNOWLEDGMENTS

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