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An analytical model for scanning-projection based stereolithography

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ABSTRACT

There is a growing need for effective small scale production methods. Projection stereolithography (PSL) is a technological response to such a demand. In PSL, Experience shows a decrease in resolution as area of exposure increases. A relatively novel hybrid method, scanning-projection stereolithography (SPSL) is presented in this work. This method is based on previous work by a number of authors, utilizing a combination of scanning and projection to manufacture large parts with relatively high-resolution.

A modelling method to investigate the total energy received by individual pixels on resin surface is considered for both PSL and SPSL. The modelling shows near identical energy distribution for both methods. The modelling results were attempted to verify experimentally. Four patterns with circular and rectangular features were exposed with both methods. The resulting cured layers were compared via microscopic observation and measurements. Sample measurements show SPSL has a slightly better resolution using an inherently non-uniform exposure system. In large area exposure, SPSL provided less stitching and overlap issue.

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1. Introduction

Now a day's additive manufacturing like rapid prototyping (RP) for small scale production and modelling studies are becoming a part of production. These methods are capable of fabricating complex shapes. Scanning-based SL (SSL) and projection-based SL (PSL) are two different methods distinguished by their patterning process. A good review of SL systems is presented in several books including those published by Gibson et al. (2010). There are distinct advantages and disadvantages associated with each one in terms of resolution, layer thickness, accuracy, cost efficiency, and throughput. In SSL a focused laser beam with small diameter (typically 100 μm) is scanned to fabricate the desired pattern. For large areas, the laser spot is moved by fluctuations of a Galvanometer-mirrors (Jacobs, 1992). PSL uses a spatial light modulator (SLM) as a dynamic mask for generating a 2D pattern with micro-scale resolution.

Digital micromirror device (DMD) is a common SLM used as dynamic mask generators. DMD is a device consists of $M \times N$ array of individually addressable μ-mirrors. Each with a size selected from 17, 13.7 and 10.8 μm^2 (Hornbeck, 1997). Each individual μ-mirror can rapidly rotate to provide ON/OFF light switching.

PSL enables creation of features smaller than 10 μm and is converging to projection micro stereolithography. There are a number of researchers focused on improving the vertical and horizontal resolution.

Sun et al. (2005) introduced a solidification model to predict the fabrication results of line patterns and investigated cross-talk as well. Limaye and Rosen (2006) used the compensation zone approach to avoid print-through errors. Also, Limaye and Rosen (2007) and Jariwala et al. (2009) reported a model to predict solidified layer thicknesses based on experimental observation in order to optimize the vertical resolution. Zhou et al. (2009) introduced pixel blending strategy to intelligently control pixels' grayscale level to achieve much higher horizontal resolution. Quality of fabricated parts by Zhou showed an improvement especially for small features. Recently, Kang et al. (2012) has developed a pixel-based solidification model for PSL to optimize the horizontal resolution by predicting the intensity distribution.

Compared to SSL, PSL offers various advantages in the fabrication of 3D freeform structures with high resolution at high-speed. A key challenge using PSL is the limited resolution and small array size of DMDs. Projecting a pattern with a DMD array over a larger surface will result in a larger pixel size and as a result a lower resolution. For typical XGA DMDs (1024 × 760), the platform size for micro (10 μm × 10 μm) and macro (200 μm × 200 μm) resolution are 10.24 mm × 7.28 mm and 204.8 mm × 152 mm respectively. In other words, PSL is impractical when the whole pattern does not fit into the projection area for a specific resolution.

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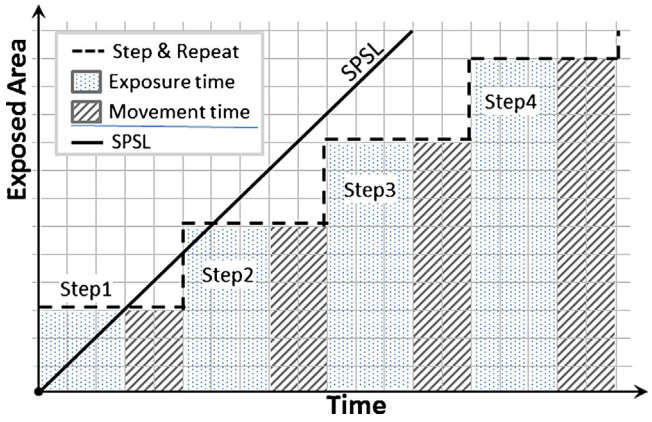

Fig. 1. Comparison of elapsed time for step-and-repeat vs. SPSL.

To overcome the limited projection area, Ha et al. (2008) demonstrated a step-and-repeat technique. In this technique, the total fabrication area is divided into multiple subareas. After exposing one sub-area, the projector moves to the next sub-area. This process is repeated until all the sub-areas are exposed. In this way, the projection area is expanded while the resolution is maintained constant.

In PSL, the issue of intensity distribution and its non-uniformity is recently addressed by a number of researchers. Zhou and Chen (2009) presented a method to calibrate such a non-uniformity by modifying the grayscale level of images. They showed quality improvement of fabricated part. Guangshen et al. (2009) modelled uniformity by establishing a light distribution model using a grayscale function. Zheng et al. (2012) also have developed a step-and-repeat technique to enhance pattern non-uniformity by iterative image correction and the grayscale capability of SLM.

Zhou and Chen (2012) introduced a strategy to achieve sub-pixel resolution for boundaries by splitting the energy of single mask with n grayscale shifted masks arranged in the offset range of $1/n$ pixel size. This is similar to step-and-repeat method but with optimized grayscale masks with a small shift. The total shift is approximately equal to one pixel.

Previously, Emami et al. (2014) provided a somewhat new synchronous scanning and projection method, as an alternative to step-and-repeat process, to create large parts with improved resolution. The method was implemented and named "Scanning-Projection Stereolithography" or SPSL. It potentially has the benefits of both SSL and PSL. In SPSL, DMD is moved continuously over the area of the medium while the projected image is updated accordingly. For large area exposure, SPSL is considerably faster than step-and-repeat. In SPSL, the projection and movement are paralleled. A better performance is obtained in larger area of exposure. This fact is illustrated in Fig. 1.

In this work, a model of curing process in SPSL is developed based on pixel-based model reported by Kang et al. (2012) and approximation method called "Effective Area" described in Section 3.1. The movment of μ-mirrors in SPSL appears to have no significant effect on the shape of the profile when compared to PSL. To compare the differences, a numerical pixel-based modelling is utilized. And four tests were performed to compare the uniformity, resolution, dimensional ratio (circularity) and stitching capability of the methods.

2. Process description

In PSL a 2D pattern is generated by light reflection from μ-mirrors. In enhanced PSL, also called step-and-repeat, the total

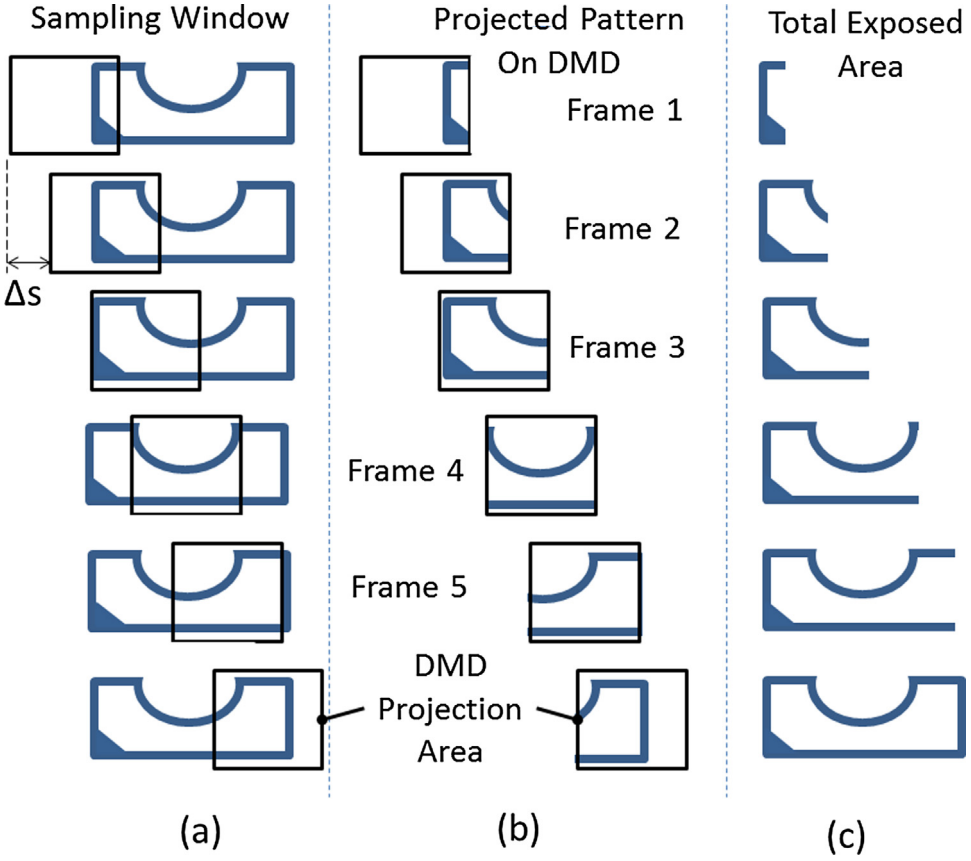

Fig. 2. Window sampling used in SPSL.

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