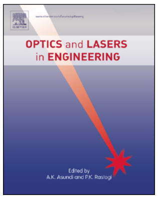
Optics and Lasers in Engineering 68 (2015) 180–187

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Laser cutting of irregular shape object based on stereo vision laser galvanometric scanning system

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ARTICLE INFO

Article history:
Received 5 July 2014
Received in revised form
19 November 2014
Accepted 15 December 2014
Available online 22 January 2015

Keywords:
Laser materials processing
Three-dimensional image processing
Industrial optical metrology

ABSTRACT

Irregular shape objects with different 3-dimensional (3D) appearances are difficult to be shaped into customized uniform pattern by current laser machining approaches. A laser galvanometric scanning system (LGS) could be a potential candidate since it can easily achieve path-adjustable laser shaping. However, without knowing the actual 3D topography of the object, the processing result may still suffer from 3D shape distortion. It is desirable to have a versatile auxiliary tool that is capable of generating 3D-adjusted laser processing path by measuring the 3D geometry of those irregular shape objects. This paper proposed the stereo vision laser galvanometric scanning system (SLGS), which takes the advantages of both the stereo vision solution and conventional LGS system. The 3D geometry of the object obtained by the stereo cameras is used to guide the scanning galvanometers for 3D-shape-adjusted laser processing. In order to achieve precise visual-servoed laser fabrication, these two independent components are integrated through a system calibration method using plastic thin film target. The flexibility of SLGS has been experimentally demonstrated by cutting duck feathers for badminton shuttle manufacture.

1. Introduction

Current laser machining systems are mostly designed for the processing of regular shape objects such as sheet metal and other flat materials. However, it is not flexible to perform laser process on objects with diverse 3D surface appearances. Such objects include metallic/plastic scraps with tilted or curved surfaces, and animal products such as duck feathers with similar but not identical 3D structures. Since these objects are either non-flat, or not uniformly produced, the laser processing path for each work piece needs to be changed according to their surface topography every time.

Due to its precision, efficiency and flexibility, laser galvanometric scanning system (LGS) has been proven to be a prominent laser machining device with applications on metals [1,2], ceramic [3], papers [4], nanostructured dielectrics [5], polymers [6,7] and so on. Adjustable laser processing path of the LGS is realized through deflecting the incident laser by rotating two orthogonally distributed mirrors. Nonetheless, the LGS alone is still incapable of performing laser process on irregular shape objects for its lack of feedback mechanism that allows on-line processing path adjustment. As shown in Fig. 1, if one wants to cut out a square patch from a flat material by LGS, then the material should be placed strictly parallel to the LGS focal plane (Fig. 1(1)). However, severe deformation will be induced when a curved surface is processed with the same LGS image path since the surface is no longer parallel to the LGS focal plane (Fig. 1(2)). The key issue lying behind this problem is whether we can generate a laser processing path that fits the 3D geometry of the object. If the 3D spatial coordinates of the curved surface are known, then the 3D laser trajectory of the square patch can be generated and be used to readjust the LGS image path (Fig. 1(3)). Little deformation of the cut out surface should be observed when viewed from its normal direction.

Vision sensors are outstanding tools for object characterizing and have been employed in various LGS based laser processing applications, including laser marking assistance [8], accuracy enhancement for LED wafer cutting [9] and field distortion analysis in laser drilling machines [10]. However, these approaches are all limited to 2D analysis that cannot fully reveal the 3D information of the processing object. This issue has hardly been investigated in literatures yet except for the laser marking system proposed by Diaci et al. [11], in which they utilize a structured-light 3D sensor to determine the 3D surface of the marking object. Their system is based on an active 3D measuring principle, which has the inherited drawbacks of low

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http://dx.doi.org/10.1016/j.optlaseng.2014.12.007
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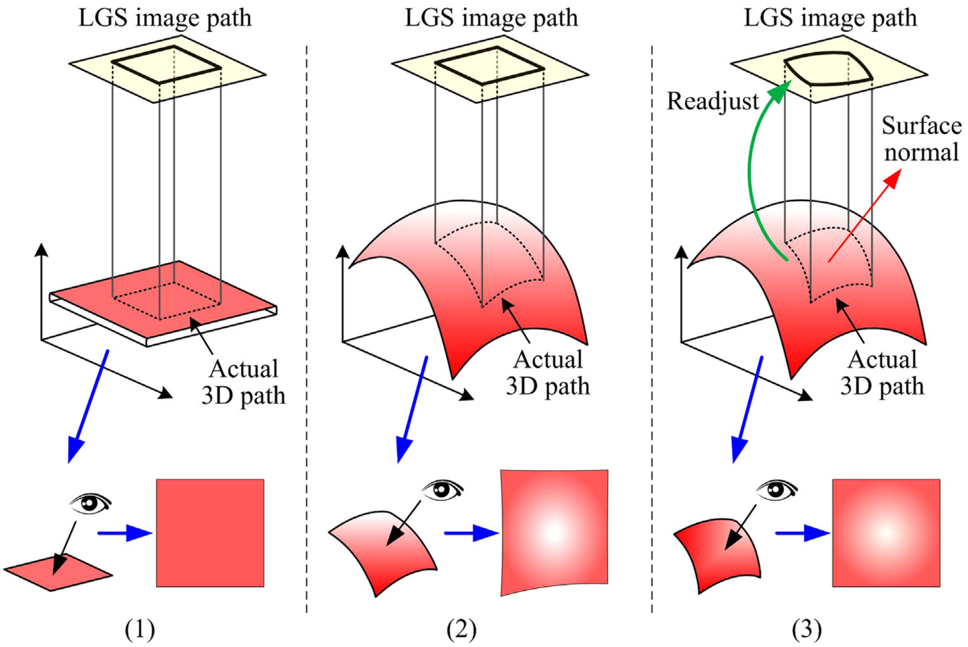

Fig. 1. (1) Flat surface must be placed parallel to the LGS focal plane for cutting out non-deformed square patch; (2) deformation occurred when processing curved surface; (3) knowing the 3D orientation of the surface can help readjust the LGS processing path and produce square patch with minimum deformation.

speed (more than 3 images should be taken for analysis) and requires an additional light modulation device (e.g. fringe pattern projector or line-structured laser [12]).

Alternatively, stereo vision, as a passive 3D sensing approach, could be a strong candidate to provide laser process guidance for the LGS since it offers advantageous features: it has the ability to measure both 2D and 3D geometric information; it is also of non-contact type and easily configurable. With the stereo vision technique, the 3D spatial coordinates of the object surface is acquired by stereo cameras and the 3D laser processing path can be generated accordingly. In other words, one can actually draw the processing path onto the 3D object surface rather than on a virtual flat drawing plane.

In this paper, a stereo vision laser galvanometric scanning system (SLGS) is proposed. The SLGS is a combination of stereo vision mechanisms and the LGS. By processing the stereo camera images, the 3D geometry of the processing object can be determined and then be used to guide the scanning galvanometers for laser machining applications. In order to effectively integrate these two independent components, we investigated the 2D–3D mapping strategy among the stereo cameras and the galvanometric scanning system. Based on this analysis we introduced a system calibration method using plastic thin film target to achieve high precision collaboration between stereo vision and laser shaping.

2. System setup and measuring mechanism

2.1. System structure

Fig. 2 shows the configuration of the proposed SLGS. The output CO_2 laser first goes through a beam expander and is then guided by the galvanometric scanning head and focused through a pre-objective lens onto the target object. Both the CO_2 laser and the galvanometric scanning head are controlled through the LGS control board connected to a personal computer. Stereo cameras are set up on both sides of the galvanometric scanning head. LED illuminations are employed to enhance the object features in stereo images. Object features such as edges or corners in the stereo images are detected and their 3D coordinates are reconstructed through epipolar constrained stereo triangulation [13]. The reconstructed feature can be treated as a precise measurement of the original object.

2.2. 2D–3D mapping of the SLGS

Substantially, the laser guided by the galvanometric scanning system can be considered as a point light source with its direction constrained within a square frame, as demonstrated in Fig. 3(1). Considering an ideal situation ignoring the distortions of LGS [20], if we denote the path planning plane of the LGS as the LGS image plane, then this image plane can be regarded as a mirror image of the spatial focal plane of the pre-objective lens. Extending this relation into 3-dimensional space by constructing a Cartesian world coordinate system *Oxyz* originated at the light source point $\boldsymbol{O}$, we can see that the relationship between an actual spatial marking point $P(x,y,z)$ in *Oxyz* and its corresponding LGS image coordinates (u,v) is merely a scaling only affine transformation [14] with the form

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} z/f_x & 0 & 0 \\ 0 & z/f_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \quad (1)$$

in which f_x and f_y are the vertical distances from origin $\boldsymbol{O}$ to a point $\boldsymbol{X}'$ focused exactly on the focal plane of the pre-objective lens. As specified in [16], the LGS can also be modeled as a camera pin-hole object; therefore f_x and f_y are also known as the focal lengths of the LGS. Notice that in practical situations, the structure shown in Fig. 3(1) is established only when there is a comparatively large depth-of-field (DOF) of the LGS to make sure the laser process will not be out of focus.

Furthermore, as illustrated in Fig. 3(2), if we let $\boldsymbol{X}_l\,(x_l, y_l, z_l)^T$ be a stereo reconstructed 3D point under the left camera coordinate system, then this spatial point $\boldsymbol{X}_l$ could be transformed to the LGS world coordinate system *Oxyz* when additional rigid transformations, including rotation $\boldsymbol{R}_{L2G}$ and translation $\boldsymbol{T}_{L2G}$, are taken into account [14]. Hence, letting s be the scale factor, we have

$$s\boldsymbol{U} = s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \boldsymbol{A}_{LGS}\boldsymbol{X} = \begin{bmatrix} f_x & 0 & 0 \\ 0 & f_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \boldsymbol{A}_{LGS}[\boldsymbol{R}_{L2G}|\boldsymbol{T}_{L2G}] \begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} \quad (2)$$