Computational Swept Volume Light Painting via Robotic Non-Linear Motion

Yaozhun Huang[1] Sze-Chun Tsang[2] Miu-Ling Lam[*,2,3]
[1]Department of Mechanical and Biomedical Engineering, City University of Hong Kong
[2]School of Creative Media, City University of Hong Kong
[3]Centre for Robotics and Automation, City University of Hong Kong

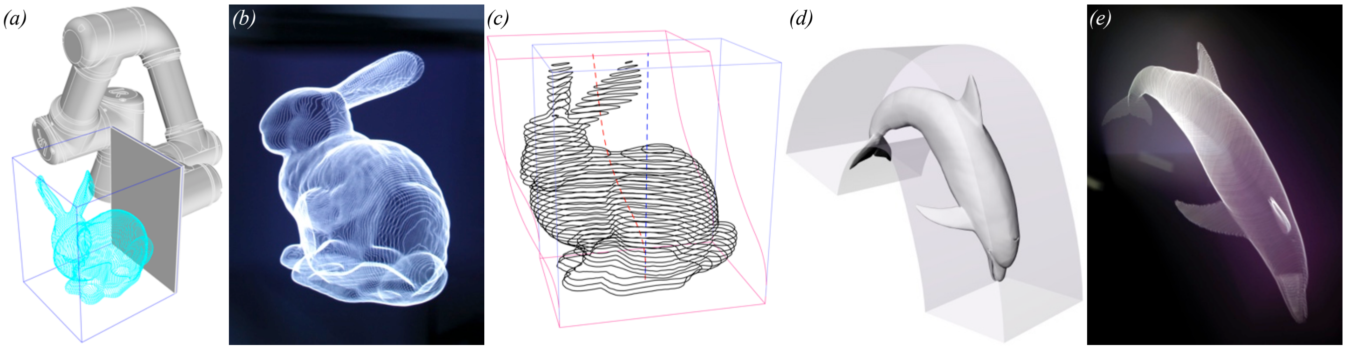

Figure 1: *(a)* Illustration of our light painting set-up: a display is mounted on a 6-axis robot arm travelling in a planned path to illuminate various 3D points in the swept volume. *(b)* A volumetric light paining of the Stanford bunny captured by long exposure. *(c)* Part of the object is not covered by the *blue* volume swept by the *blue* linear path; and the *red* swept volume with *red* curved path accommodating the object shape can fully cover the object. *(d)* Simulated swept volume by extruding the display along a curved path while keeping the normal of the display tangent to the path. *(e)* Light painting captured in real space based on the path curve in (*d*).

Keywords: computational light painting, robot, swept volume

Concepts: **• Hardware ~ Communication hardware, interfaces and storage;** *Displays and imagers;*

1 Introduction

Light painting is a photography technique in which light sources are moved in specific patterns while being captured by long exposure. The movements of lights will result in bright strokes or selectively illuminated and colored areas in the scene being captured, thus decorating the real scene with special visual effects without the need for post-production. Light painting is not only a popular activity for hobbyists to express creativities, but also a practice for professional media artists and photographers to produce aesthetic visual arts and commercial photography. In conventional light paintings, the light sources are usually flashlights or other simple handheld lights made by attaching one or multiple LEDs to a stick or a ring. The patterns created are limited to abstract shapes or freehand strokes.

Computational light painting is a more advanced technique to produce "representational" (in contrast to "abstract") visuals in which the shape and motion of the lights in every time instant during the exposure time are precisely computed and synchronized. The objective of performing light painting in a computational manner is to use digital means to create light strokes that are in controlled shapes and at accurate positions, and exhibit complex forms, which is impossible by conventional method.

The accuracy of computational light painting relies on the tight synchronization between the light pattern and its motion. Robots and computer numerical control (CNC) systems are ideal to execute light paths with high fidelity. [Kalsi 2015] has attached a RGB LED to the nozzle position of a FDM 3D printer to create 3D light painting. The color and intensity of the LED were controlled while the print head was moving in a digitally generated tool path, thus the printer could "print 3D light". However, the process was slow while using only a point of light to draw a 3D shape. Besides point light source and 1D array of lights, a flat display may also be used as the illuminating device for light painting. The display pixels can be considered as a 2D array of densely-packed point light sources. And the display would create a swept volume when in motion. [BERG 2010] has created a short film by dragging an iPad through the air while playing some pre-rendered videos to extrude some 3D typography and objects. However, the light paintings created were not accurate as the iPads were dragged by hands while the extrusion were assumed to be in linear paths and at constant speed. [Kruysman et. al. 2013] has attached a plasma TV to a robot that moved back and forth along a linear path. The motion was synchronized to the video and camera shutter to create a fluid simulation animated in space. Our approach is similar to [Kruysman et. al. 2013]. However, rather than limiting the robot end effector to move linearly, we studied general motions and allowed the robot to travel in versatile curved paths to increase the displayable area.

2 Our Approach

We propose a novel method for computational light painting using a flat display mounted to a robot arm travelling in non-linear

*e-mail: miu.lam@cityu.edu.hk

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motion and displaying synchronized image sequences that represent the cross-section profiles of a virtual object that is sliced at arbitrary positions and orientations. As shown in Fig. 1(a), we have mounted a flat screen display to a 6-axis robotic manipulator Universal Robot UR10. Suppose the 3D digital model of the virtual object to be displayed is available. The display would show a video that is rendered in real-time. Each frame represents the contour of a cross-section of the virtual object. The instantaneous robot configuration is monitored by software. The joint positions are used to compute the 6-DOF pose of the display. The display position and orientation are then used to define the cutting plane and compute the cross-section of the virtual object on the plane. It is similar to slicing for 3D printing. However, we obtain only one slice at a time. The z-direction, coordinate and boundary of the display are input to obtain the slice. When the display is moved by the robot, it creates a swept volume and a stack of contours in space that represent the 3D shape of the virtual object. Fig. 1(b) shows the result of a volumetric light paining of the Stanford bunny captured in a 5-second long exposure while the display was moved in a linear motion. The mechanism is similar to 3D printing but the layers of different slices are built up with light.

Using pure linear motions would limit the workspace. Thus, we further used non-linear swept path to increase the displayable area of the system. As illustrated in Fig. 1(c), part of the model was not covered by the blue volume swept by the blue linear path. Using the same display with a new, red curved path that accommodates the object shape, the *red* swept volume can fully cover the object. The display (or slicing) direction remains unchanged in Fig. 1(c). In fact, one can choose to adjust the display orientation when it is travelling on the path curve. The dolphin example in Fig. 1(d) and (e) demonstrates that changing the slicing orientation can further increase the swept volume. Three cases of swept volume creations are summarized in Fig. 2:

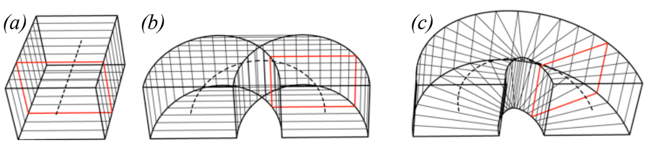

Figure 2: Three different cases of swept volumes and slicing methods.

Case (a) is created by extrusion of the flat display along a straight line. Case (b) is created by extrusion of the display along a curved path while keeping the slicing orientation constant. The display is in 3D translation motion. Case (c) is created by sweeping the display along the curved path while each slicing plane is perpendicular to the tangent line of the curve, thus the swept volume is maximized. The display is in general rigid body motion (rotation+translation). Note that the path curves in Cases (b) and (c) are identical. The swept volume of Case (b) is generally a sub-space of swept volume of Case (c). The curves do not need to be planar.

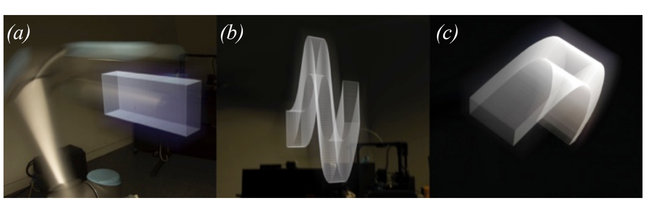

Figure 3: *(a)* Extrusion along linear path *(b)* Extrusion along curved path with constant slicing orientation. *(c)* Sweep along curved path with changing slicing orientation.

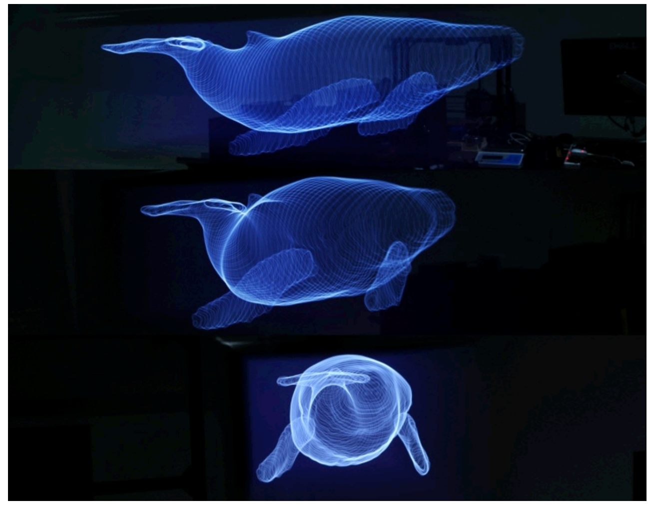
Figure 4: Volumetric light painting observed and captured from wide viewing angles.

Case (3) can create a larger swept volume than Case (2). However, rotating the display may obstruct the camera view in some positions along its path, which need to be taken into consideration during motion planning and deciding camera location. As most LCD displays have wide viewing angle, the volumetric light painting created by our method can be observed from a wide area. Fig. 4 shows different simultaneous perspectives of the same light painting can be captured by cameras located at distinct locations.

In conclusion, swept volume approach for creating computational light painting is presented. To the best of our knowledge, this is the first work that used non-linear motion of robotic manipulator to create volumetric light painting. Future works include automatic 3D path generation and maximization of observable space for camera. We will also create animations and augmented reality applications using the methods presented.

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