Image-Based Motion Compensation for Structured Light Scanning of Dynamic Surfaces

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Abstract. Structured light scanning systems based on temporal pattern codification produce dense and robust results on static scenes but behave very poorly when applied to dynamic scenes in which objects are allowed to move or to deform during the acquisition process. The main reason for this lies in the wrong combination of encoded correspondence information because the same point in the projector pattern sequence can map to different points within the camera images due to depth changes over time. We present a novel approach suitable for measuring and compensating such kind of pattern motion. The described technique can be combined with existing active range scanning systems designed for static surface reconstruction making them applicable for the dynamic case. We demonstrate the benefits of our method by integrating it into a gray code based structured light scanner, which runs at thirty 3d scans per second.

Keywords. 3d scanning; motion compensation; optical flow; structured light, dynamic surfaces.

1 Introduction

A structured light scanner typically consists of a projector-camera pair. Different light patterns are projected onto the scene such that the projector column can be reconstructed at every pixel in the acquired camera images. Different calibration methods [1], [2], [3] are used to map camera pixels to 3d rays and projector columns to 3d planes. Simple ray-plane intersection finally yields 3d surface points.

The projector column can be coded in one pattern via spatial correspondences (i.e. one-shot approaches), in several patterns multiplexed over time (i.e. gray code), in light intensity (i.e. phase shift) or in a combination of these approaches [4]. The purely spatial coding of projector columns in one-shot approaches is at first sight very attractive because of high frame rates and very simple realization in hardware. On the other hand it is extremely hard to deal with textured surfaces and depth discontinuities. Therefore time-multiplexing of several patterns is necessary for most applications. For static scenes time-multiplexing is a

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well established approach. Application to dynamic scenes is much more complicated as the temporal correspondence is destroyed by the motion of the projector patterns in the camera images, which is induced by the scene motion.

Partial compensation of the pattern motions are possible by coding the column information in intensity changes as done by the stripe boundary code approach [5]. Intensity edges are detected and matched over time. This allows the compensation of pattern motions that are in the order of the stripe widths. But faster motions cannot be compensated.

In this work we propose a motion compensation scheme that introduces an additional tracking pattern in between the structured light patterns. The special tracking pattern is optimized for maximal tracking performance. Although more patterns have to be acquired in our approach, the improved tracking allows 3d scanning of dynamic scenes with faster motions. [6] propose a real-time hybrid stereo phase-shift method with automatic motion compensation. This is done by analysis of the motion error on pixel level. Our approach on the other hand can be combined with all multi-pattern structured light approaches and we demonstrate this exemplarily on the basis of gray-code scanner.

2 Reconstruction with Motion Compensation

Let $P_1, \ldots, P_n$ be the n different light patterns and $C_1, \ldots, C_n$ the acquired camera images. Any structured light approach has a method *rec* to reconstruct the projector column j for each camera pixel (x, y)

$$j(x,y) = rec\,(C_1(x,y), \ldots, C_n(x,y))$$

The following two major sources for reconstruction errors are due to motion during the acquisition process.

2.1 Object and Pattern Motion

Figure 1 illustrates the two kinds of motion that arise in the camera images. On the left side the plane is moving in tangential direction to the right. The surface motion becomes visible through the motion of the surface texture in

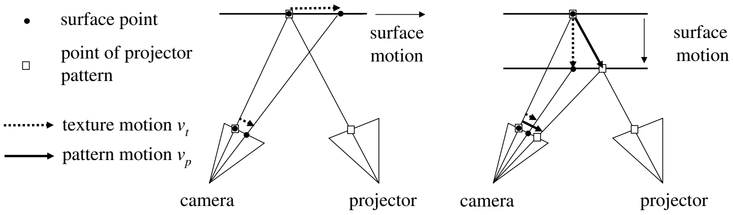

Fig. 1. Illustration of texture and pattern motion.

the camera image. The corresponding motion is denoted v_t and illustrated with dotted arrows. The illustrated point of the projector pattern stays fixed in the camera image yielding a pattern motion of $v_p = 0$. On the right side the plane is moving in normal direction. This time both the surface point and the projector point move in the camera image, but with different velocities $v_t \neq v_p$. For a correct reconstruction the motion v_p has to be compensated.

2.2 Pattern Separation

On- and off-reference patterns P_{on}/P_{off} are used to separate the patterns from the surface texture and illumination in the camera images. In dynamic acquisition on- and off-camera-images change over time due to texture motion. For good pattern separation on- and off-references have to be introduced in between the patterns, resulting in the pattern sequence $P_{on}, P_1, P_{off}, P_2, ..., P_n, P_{off}$.

2.3 Motion Compensation

To estimate the pattern motion $v_p(x, y)$ we interleave the tracking pattern P_T resulting in the pattern sequence $P_{on}, P_T, P_1, P_{off}, P_T,\ P_2,...,P_{on}, P_T, P_n, P_{off}$. For p_T we used a perlin noise pattern as it exhibits best tracking performance. Although we further increase the number of patterns, the better tracking performance on the optimized tracking pattern P_T allows to acquire faster scene motions. From each successive pair of synchronously captured tracking camera images C_T we use an optical flow algorithm to estimate the displacement fields $F_{i \to j}$ from the i-th acquired pattern C_T to the j-th pattern C_T. But for reconstruction we are interested in the displacement between two acquired structured light patterns $F_{C_i \to C_j}$, which are computed via linear interpolation from the surrounding optical flow fields. Projector columns can finally be reconstructed via

$$j(x, y) = rec\left(C_1(x, y), C_2(F_{C_1 \to C_2}(x, y)), \ldots, C_n(F_{C_1 \to C_n}(x, y))\right).$$

If the optical flow algorithm fails to estimate the motion of the tracking pattern safely due to depth discontinuities no surface point is reconstructed. To increase the frame rate we use any n successively acquired patterns in a sliding window fashion resulting in one 3d scan per structured light pattern.

3 Experimental Results

The scanner setup consists of a synchronized pair of high speed DLP projector and camera. We applied our compensation framework to a 10 bit gray code approach. We used a step motor in conjunction with a turntable to generate reproducible rotational motions. Figure 2 compares the result of scanning with and without motion compensation. Camera frames are acquired at a rate of 90 fps. This leads to a reconstruction speed of 30 scans per second in the motion

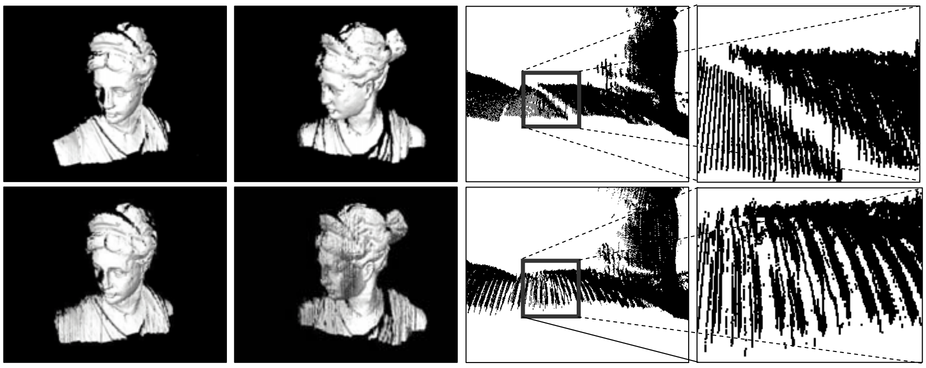

Fig. 2. Rotating bust with (top row) and without (bottom row) motion compensation. Right: Zoomed views of the second reconstruction.

compensation scheme because every third pattern is a reconstruction pattern. Without compensation no tracking pattern is necessary resulting in 60 scans per second. In the scans without motion compensation severe artifacts arise because of wrongly decoded projector column positions. Enabling motion compensation increases the quality of the reconstructed surface and density of valid samples significantly.

4 Future work

It is planed to use faster and more robust optical flow algorithms and to integrate the proposed tracking into other structured light approaches.

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