学位論文の要旨

題　目　A Study on High-Speed Three-Dimensional Shape Inspection Based on Self-Projection Method

（自己投影法に基づく高速三次元形状検査の研究）

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Recently, three-dimensional (3-D) shape measurement technology has begun to play an important role in machine vision in many areas of application, such as industrial inspection of products, human modeling, object recognition, and 3-D map building. There are many demands for simultaneous 3-D shape measurement to allow inline shape inspection on the production line. With the development of computer vision, many 3-D shape measurement systems based on various optical measurement methods have been developed. However, the processing speed of these systems is limited by the speed of standard video signals (e.g, NTSC 30 fps or PAL 25 fps) that are designed based on the characteristics of the human eyes. And it is also impossible for CPU to process so large size of data in real-time calculation with traditional optical 3-D measurement methods. On the other hand, the high-speed production lines are more and more applied in the factories to raise the production efficiency during these years. However, the production inspection speed was not so satisfied while the speed of production lines has been improved to a desirable level nowadays.

To resolve this problem I develop a self-projection method which can reduce the calculation data in various vision based 3-D measurement techniques in real-time processing without narrowing the measured range and affecting the accuracy in 3-D measurement. The concept of self-projection has been applied in light-section method and structured light method.

A) Self-projected light-section method

Self-projected light-section method is an improved light-section method that can reduce the pixel dimensions of an image to be processed for obtaining the difference between the 3D shape of a measurement object and that of a reference object.

Instead of a straight-line light pattern projection, the self-projected light-section method uses a curved-line light pattern for projection on an object to be inspected; we assume that a 3D shape of a reference object is given as prior information. The curved-line light pattern is initially generated as a self-projected light pattern using the 3D shape of the reference object. The angles formed by beams of light that consist of the self-projected light pattern and a level plane are spatially diversified in proportion to its concavity or convexity. In the meantime, a straight-line slit image in a camera view can be captured as a reduced image for fast triangulation computation when the 3D shape is matched with that of the reference object. This characteristic is maintained even when the shape of the object is concave and convex. The self-projected light pattern works as a template for 3D shape inspection, and the differential shape object can be easily picked up by checking if there is deviation on the captured straight-line. And because we introduce a self-projected light pattern projection with prior information, our method can directly calculate differential height information from the 3D shape of the reference object instead of calculating absolute height information from

a level plane in the conventional method. Thus, even small differences in the 3D shape between a measurement object and a reference object can be enhanced in a narrower image region when their shapes are strongly concave or convex.

Based on our self-projected light-section method we developed a projector-camera measurement system that can simultaneously obtain 3-D shapes of cylindrical objects moving in one direction. This system consists of a high-speed vision platform which can capture and process images in real time at 10000 fps, an LCD projector and an electronic linear stage to convey an object in one direction. The high-speed vision platform applied in our system has an FPGA image-processing board that can be coded for image processing function in hardware and a column-moment calculation circuit module that can calculate the centroids for 3-D shape measurement was implemented as hardware logic to improve the processing speed.

To verify the performance of our system, the 3-D shapes of objects were measured by using the self-projected light-section method in the experiments. At first, I measured a mountain-shaped cylinder with both of the conventional light-section method and the proposed self-projected light-section method. Compare the result images in the two methods, it can be seen that the proposed method can maintain the same accuracy in 3-D shape measurement as that in the conventional method, while the image region to be processed was remarkably reduced. In the other experiment measurement results for a stair-shaped object carved with marks were obtained using our 3-D shape measurement system. The stair-shaped object to be measured has three steps at different heights. The measurement results of absolute 3-D shape and differential 3-D shape show that the self-projected light-section method enables both global 3-D shape measurement and local abnormality inspection in real time at 10000 fps to the same accuracy level as the conventional light-section method, even when the measurement object has different heights that would require a large-size image region in the conventional method.

B) Self-projected structured light method

In the self-projected light section method, the pixel dimensions of the image to be processed can be reduced by projecting a curved light pattern generated by a reference 3-D shape. To expand the idea of self-portrait projection in the self-projected light section method for fast and real-time 3-D profile acquisition, we propose an improved structured light method (hereinafter referred to as the "self-projected structured light method") that can reduce the number of projections needed to obtain the 3-D shape of a measured object without affecting the 3-D measurement accuracy, assuming that a reference 3-D shape is initially known.

The self-projected structured light method projects multiple self-projected curved-stripe patterns onto the measured object, rather than straight-stripe patterns, assuming that a reference 3-D shape is provided initially and that the self-projected patterns are generated as curved-stripe patterns calculated using prior information. When the 3-D shape of the measured object matches the reference 3-D shape, the straight-stripe pattern images in the camera view are captured as curved-stripe patterns projected onto the object. This property is maintained when the 3-D shape is concave or convex with a large height difference. In our self-projected structured light method, the self-projected patterns can serve as templates for 3-D shape inspection and different 3-D shapes can be readily identified by checking for deformations in the captured straight-stripe-like patterns because the degree of deformation is expressed as differential depth information based on the reference 3-D shape, instead of absolute depth information based on a level plane, as observed in the conventional method. As a result of the self-projected patterns, our method can obtain the depth image of a measured object even in a complex 3-D background scene by projecting fewer light patterns without narrowing the measurable range or affecting the accuracy in 3-D measurement, in contrast to the conventional method. Thus, even small local differences between the 3-D shapes of a measured object and a reference object can be expressed using fewer bits of structured light code if the reference 3-D shape contains large height differences.

To apply the proposed self-projection structured light method on moving objects, we developed a structured light system that can output depth images of 512 × 512 pixels in real time at 500 fps, and accelerated it by installing a GPU board for parallel processing of a gray-code structured light method using eight pairs of positive and negative patterns with an 8-bit gray code, which we projected at 1000 fps from a high-speed projector. Compared with standard videos at dozens of frames per second, capturing eight pairs of light patterns projected at a high frame rate significantly reduces synchronization errors caused by projection with different timings. By implementing our self-projection structured light method, the synchronization error in 3-D measurement determined by the number of projections and their frame interval can be reduced and we can get more accurate depth images.

In the experiments I verified the accuracy of the depth images using a static 3-D scene with different heights observed using our system. And to compare with the measured 3-D shape using our self-projected method with the reduced projection patterns, I give the depth images computed using the conventional structured light method with patterns of the same bit number. The conventional structured light method with less projection patterns was not capable of accurate depth measurement of the 3-D scene with large height differences. The 3-D shape of the cuboid at different heights were more accurately measured using the self-structured light method than using the conventional structured light method with the same number of projection patterns. These results indicate that the self-projected structured light method with space code of reduced bit number can keep as much accuracy in 3-D shape measurement as that in the conventional structured light method with space code of normal bit number, while reducing the number of patterns to be projected. At last, I conducted experiments of a PC mouse conveyed by a linear slider, and human hands moving at different heights to show the real-time performance of the system in 3-D shape measurement for moving objects.