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答辩委员会对论文的评语

何海涛同学的博士学位论文《复杂面形的光学三维测量相关技术研究》，依托国家自然科学基金项目(50205016)和上海市光科技行动计划项目(011461059)，针对多视角、多自由度三维测量技术、理论与方法进行研究，其结果可用于先进制造中的逆向工程等目的，选题具有重要的理论意义和实用价值。论文主要贡献包括：

提出了“基于调制度—背景共生矩阵二维熵的图像自动分割技术”，解决了复杂物体轮廓有效区域的自动识别与分割问题。实践证明，该法快速、可靠，利于提高测量精度，有很好的技术意义和实用价值。

在对光栅投射系统进行严格几何分析的基础上，提出了新的“三维空间坐标标定法”，该方法借助专门设计的标定板，可同时实现测量系统的深度/位相标定和横向坐标标定，提高了标定精度。由于测量时可消除摄像机的畸变误差影响，更可提高单视角测量的精度，该方法具有重要的技术意义和实用价值。

提出的“基于虚拟圆柱的曲面拼接方法”，发展了圆柱坐标下的多孔径重叠扫描拼接技术，使诸如凹面，非 G^1 连续曲面等不宜在圆柱坐标下单值显式表达的一类曲面，仍可以实现高精度的测量与拼接，该方法还为利用多视角拼接技术，补偿单视角测量时无效区中缺损的数据成为可能。因此具有理论意义和重要的实用价值。

为“先进制造技术中的光学三维传感与重建系统”项目编写整套测量软件，成功实现了对帕萨特轿车前车灯反射体、“罗马少年”头像、人体模特和散热盖等物体的测量与拼接，使该项目以“优秀”的成绩通过上海市科委组织的专家验收。

综上所述，该论文提出多项创新技术，显示了何海涛同学的扎实的理论基础和广泛的专业知识，以及较强的独立从事科学研究的能力。论文内容翔实，撰写条理清晰，结构严谨，公式推导准确，数据可靠，文献引用合理。论文答辩条理清楚，重点突出；回答问题准确。

答辩委员会表决结果

经答辩委员会表决，全票同意通过何海涛同学的博士学位论文答辩，建议授予工学博士学位。

答辩委员会主席：**庄松林**

2005年3月25日

摘　要

逆向工程技术是随着计算机技术的发展和成熟以及数据测量技术的进步而迅速发展起来的一门新兴学科与技术。它的出现，改变了原来CAD系统中从图纸到实物的设计模式，为产品的迅速开发以及快速原型化设计提供了一条新的途径。样件的三维数据获取是逆向工程第一步，从已知的采样数据点出发，才能实现复杂曲面的建模、改进、制造。

本文依托上海市光科技专项课题“先进制造中的光学三维传感与重建系统研制”，以条纹投射测量系统在逆向工程中的应用为着眼点，主要研究复杂面形的光学测量及其相关技术，为逆向工程提供一个高效、高精度的物体面形数据采集方法。

本文选择DLP投影机作为条纹投射设备，CCD摄像机作为条纹图像记录设备，构建了以条纹投射技术为原理的多视角测量系统，并研制出具有自主知识产权的仪器装置和配套测量软件，利用该测量系统实现了复杂面形的三维测量。为实现以上目的，本文对相关技术进行了研究。

1. 单视角测量的相位分割技术

本文综合分析了包裹相位的解包裹技术，表明变频条纹投射结合时域相位解包裹技术是解决相位不连续，含有噪声点的相位解包裹最有效的方法。由于零件的几何结构，如不连续台阶、含有孔、洞的曲面等复杂面形，以及条纹投射时局部镜面反射，遮挡造成的阴影、暗背景等情况，单视角测量时部分区域不

可测，即该区域测得的数据是不可靠的。为剔除这类无效数据，本文提出了采用基于调制度阈值自动分割技术，和改进的基于调制度—背景共生矩阵模型的最大熵处理方法，通过计算调制度—背景共生矩阵的二维阈值，指导相位分割，自动识别物体轮廓有效测量区域。单视角缺损的一些数据可以通过改变测量视角和曲面拼接技术来恢复。

2. 条纹投射系统标定技术

传统的条纹投射测量系统必须满足一定的约束条件，因此存在系统标定可操作性不强，耗时且精度不易保证的问题。本文对测量系统的一般几何设置情况作了详细的推导与分析，提出了一种标定新方法：引入摄像机横向标定技术，采用基于神经网络的修正方法对参考平面的横向坐标进行误差补偿，获得标定参考面图像对应像素的精确横向坐标分布；为此，选用专门设计的标定面板——黑白相间的方形格，亚像素级提取方格顶点为特征控制点，用于摄像机标定；取板上白色方格区域的相位数据对标定板平面的相位分布作最小二乘拟合，获得整个像面的连续理论相位分布，进而得到三维坐标与图像像素的映射关系。该技术使得标定过程大大简化，可同时进行相位—深度标定和横向坐标标定，提高了标定的可操作性和检测精度。

3. 基于虚拟圆柱的多视角拼接技术

多视角拼接技术的基本思想是：使相邻子视角部分重叠，利用重叠区域面形信息建立其相对空间位置关系，据此利用坐标变换将多视角面形统一于同一坐标系下。圆柱坐标下多孔径扫描拼接技术的迭代算法，解决了三维物体特别是回转物体面形的拼接测量，其关键在于坐标变换方程的线性简化，以及误差求解与坐标变换的迭代操作，保证了误差求解的精确性。

然而，圆柱坐标下的多孔径扫描拼接方法针对复杂面形，例如凹面形状，由多个曲面片构成的非G^1连续曲面等面形的拼接测量遇到了困难。为了突破以上限制，本文提出了基于虚拟圆柱的拼接方法。根据被测面形不同视角的重叠区的几何特征，构造虚拟圆柱，使得其局部面形的近似回转轴与虚拟圆柱的轴线重合，将原圆柱坐标系平移到一个新的位置——移动后的z轴与虚拟圆柱的轴线重合，于是圆柱坐标下的多视角拼接算法在这个“虚拟的圆柱坐标系”下就适用了。该方法成功地将圆柱坐标下多孔径拼接技术适用的范围扩展到不局限于只具有单一回转轴特征的表面的拼接测量，有效地扩大了重叠扫描拼接方法的适用范围，为测量三维复杂物体表面特别是多视角测量获得的含有无效测量区域的曲面测量问题打下了理论基础。

4. 实用化

利用以上技术，本实验室研制出了基于条纹投射技术的光学三维传感与重建系统，包括用于获取三维物体面形数据的测量样机一台，具有用户友好界面的光学三维测量软件系统一套，以及三维建模和快速成型加工平台几个部分。通过实际工件的测量及重建结果实例，证实了本文中研制的用于逆向工程的数据采集的仪器系统达到设计任务书所要求的各项技术指标及要求，完成了对零件的三维测量工作，初步实现数据获取、处理，与成熟的CAD/CAE/CAM系统相集成。它的成果推动了光学三维测量技术走向实用化。

关键词 逆向工程，条纹投射技术，相位分割，系统标定，多视角拼接，虚拟圆柱

Abstract

Reverse engineering (RE) is a new subject and technology coming up with the development of computer science and data digitization method. It helps to change the design mode from drafts to models in the conventional CAD systems. It is a novel approach for rapid prototype manufacture, and the first step in reverse engineering to acquire physical data of the measured object. With the data acquired from the complex shape of one existent object, the geometrical models can be reconstructed, and then be studied, such as analyzing, modifying, and be manufactured.

Our work is a part of the project Optical Three-dimensional (3 - D) Sensing and Reconstruction System for Advanced Manufacturing, which is supported by the special-item fund for optical techniques of Shanghai Municipal Commission of Science and Technology. The main purpose of this dissertation is to study the optical measurement technique and its relevant techniques for the complex surface measurement based on fringe projection technique, aiming at developing an efficient and precision method for acquisition of geometric information on shape for RE.

A novel multi-view measurement system has been constructed based on fringe projection and a self-made instrument and

attached software with intellectual property right have also been developed. A DLP projector is used to project digitally created fringe patterns onto the object; a CCD camera is selected to capture the deformed fringe patterns. In order to realize the 3-D measurement of complex objects, we have paid more attention to the research of relative fields.

1. Phase segmentation technique for reliable phase data in single-view measurement

We first provide a review of fringe phase unwrapping algorithms, and then we focus on the temporal phase unwrapping via multi-frequency fringe projection, which is the most efficient solution in the measurement of discontinuous phase distributions, phase with noise, etc. For measuring a surface with step feature, the geometric features of holes, and irregular reflectivity of quasi-specular, noises like local shadow, unlighted background, under-sampling in the fringe patterns, etc., there are some immeasurable parts in just a single-view, i.e. where the phase data obtained are unreliable. In order to get rid of the invalid data, an automatic segmentation technique according to the threshold of the histogram of modulation distribution has been proposed. And an improved maximum entropy algorithm based on the modulation-background co-occurrence matrix for thresholding has been presented too. This method attempts to utilize the information of both modulation and background of the fringe patterns, evaluates two-dimensional entropies based on the co-occurrence matrix to conduct segmentation of

phase map, and finally identifies the valid measurement areas of the object. Accordingly the unreliable phase data are cancelled in the single-view measurement. In order to compensate for the lacked 3 - D coordinates of the points in the invalid areas, multi-view measurements in different directions combing surface connection are available.

2. Calibration technique of fringe projection system

The old projected fringe system and calibration methods had bad maneuverability, inferior accuracy and are pain-taking, because they must satisfy some requirements. After comprehensive analysis and detailed deduction of the general geometry of measurement system had been performed, a new calibration method for the 3 - D measurement system has been presented. By importing the camera lateral calibration technique, in which the neural networks are built to correct the error terms of the lateral coordinates, the precision lateral coordinates distribution of the captured image corresponding to the reference plane is obtained. In order to get the data serving the calibration, a calibration gauge with white-black checker pattern is employed. The corners of the checker patterns are regarded as control points and its corresponding pixels in the image are extracted with sub-pixel accuracy. Based on it, the phase distribution of the whole calibration gauge is obtained by the least-square fitting to the phases in the white squares according to the theoretical distribution function, and the phase-to-depth and pixel to lateral coordinate mapping relationship are simultaneously

calibrated through only one operation. All these elevate the maneuverability of the system calibration and measurement accuracy. What's more, the system needn't satisfy the restricted conditions again as old one.

3. Multi-view connection method based on virtual cylinder

The principle of the multi-aperture overlap-scanning technique (MAOST) is to make the adjacent sub-apertures partially overlapped, and then their relative location and orientation can be obtained through the overlapped area. Therefore, the sub-apertures can be transformed to a global coordinate system. The iterative algorithm of multi-aperture overlap-scanning technique in cylindrical coordinates is mainly used in connecting measured surface of quasi-rotation objects. Its key is that the tangly coordinate transform equations in cylindrical coordinates are linearized and the error movement calculation and coordinates transformation are performed in an iterative way. But there are some difficulties in measuring the more complex surface, such as concave, or surface composed of patches, and surfaces that are not G1 connected, etc. A novel multi-view connection method algorithm aiming at such shape measurement of complex surface is suggested in the dissertation. A virtual cylinder is introduced, which is determined by the overlapping areas between views; the approximate rotation axis of the local surface coincides with the axis of the virtual cylinder. Thus the original cylindrical coordinate system could be transferred to a proper position, where the

transferred z-axis coincides with the axis of the cylinder, which making the previous connecting techniques in cylindrical coordinates available for measuring a more complex surface in the fictitious cylindrical coordinate system. This method enlarges the application of connecting various surfaces, such as those surfaces with non-single rotation axis. It provided the theoretical foundation for connection of three-dimensional complex shape, especially to obtain the whole surface tested from different views, which containing invalid measurement areas.

4. Utilization of measurement technology

On the basis of the techniques above, our lab has developed successfully the Optical Three-dimensional Sensing and Reconstruction System based on fringe projection technique, which composed of a specimen machine for data acquisition, a 3 - D measurement software for customer, and surface model & rapid prototype manufacture sub-system. The measurement results and reconstructions of several real parts show that the instrument system has achieved the demands described in the task specification, and realized integrating data capture, preprocessing with CAD/CAE/CAM system. Its achievement promotes the utilization of 3 - D optical measurement technology.

Key words reverse engineering, fringe projection, phase segmentation, system calibration, multi-view connection technique, virtual cylinder

目　录