An Integrated Optical-Robotic Measurement System

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1. INTRODUCTION

This paper presents the results of an experiment designed to test a prototype integrated optical-robotic measurement system that is intended to measure the external profile of arbitrarily shaped cable connectors for subsequent manufacture of a jig to hold the connectors accurately in place during an automated cable-tree assembly and wiring process, see Figure 1. The desired measurement error tolerance is ±0.1 mm.

Integrating an industrial robot into the measurement system has the advantage that the measurement procedure can be automated. The main disadvantage is that accuracy, repeatability and calibration issues must be addressed. We have designed the measurement procedure, carried out by the robot, to be less dependent on absolute robot accuracy and instead rely on the lower limits: repeatability and relative accuracy. By matching the degrees-of-freedom (DOF) used by the robot at key stages in the process to the DOF of the measurement task, we remain closer to the lower limits of the robot accuracy.

2. APPARATUS AND PROCEDURE

The robot used in the measurement system is a KUKA KR-15/2 with a manufacturer stated repeatability of ±0.1 mm. Relying on the results from an earlier study [1], we can reach a repeatability of ±0.025 mm. This is done by taking heat-up effects of the robot into consideration.

When other factors, such as dynamics, are compensated for the repeatability may still be improved. Since the repeatability of a robot lower bounds its accuracy, the implication is that measurement tasks requiring accuracy of ±0.1 mm can be carried out by a measurement system that integrates a standard industrial robot, such as the KUKA KR-15/2.

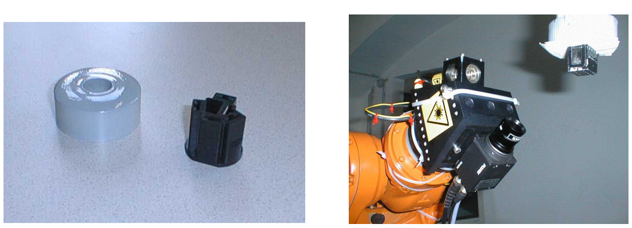

Figure 1. Cylinder and connector; Measurement head mounted to KUKA KR-15/2.

The measurement head is a custom design from the Institute for Automation at the University of Leoben. It employs the concept of laser light plane sectioning. A laser diode fitted with line optics creates a light plane. The laser plane intersects the connector. The trace of the intersection is visible and a CCD camera records its image. The camera and laser are inclined at 45° relative to each other. Moreover, the head is mounted to the robot tool flange such that the axis of symmetry of the camera and laser is incident on axis 6 of the robot. Figure 1 shows the mounted head in position to produce measurement data.

Procedure

The required measurement information for creating a scaled reconstruction and solid model of the exterior features of a cable connector between the planes perpendicular to the pin ends and the wire input portal is obtained by stacking a series of horizontal sections of the connector. The sections are obtained by projecting a laser plane onto the connector. The trace of the plane on the connector is viewed by the camera. Since there will always be some invisible features when seen from any particular vantage point, more than one view is necessary. It is our assumption that 8 views in the plane of the section are sufficient, separated by rotations of 45°about the z-axis of the robot base frame (perpendicular to the floor). The images are rectified and the result is a planar section of connector yielding all external profile features.

Once an initial robot assembly configuration is attained, the measurements for an entire section (i.e., the trace of the object being measured in the plane of the laser line) can be obtained. The plane of the laser line is chosen to be, and remains, parallel to the xy-plane in the robot base frame (i.e., the plane of the floor).

Work pieces are mounted in a fixture such that their longitudinal axis is perpendicular to the plane of the laser line. The laser diode light source is considered to be a point, P. The projected laser line, created with the line optics, is a line that does not contain P. The laser plane is determined by the line and point P.

The goal of each measurement is to obtain a segment of a planar section of the connector. This means that the measurement task requires, at most, 3 DOF. The robot has 6. Which should be used in obtaining multiple views of the section so that a composite image of the entire section can be reconstructed from the segments? By constraining the plane of the sections to be parallel to the principal xy-plane of the base, we eliminate 1 DOF. Moving the measurement head in a circle with a fixed radius, centred on the joint axis 1 eliminates another. Thus, once the initial assembly configuration has been established, only motions about joint axis 1 are required to obtain enough images for reconstructing a complete composite image of the section.

To calibrate the measurement head a calibration grid of known dimensions is required. All recorded laser traces lie in the laser plane. The camera is calibrated by superimposing the plane of the calibration grid on the laser plane. Employing some elementary projective geometry allows for the computation of a homogeneous transformation which can be used to map points, known in the image plane of the camera to the corresponding points on the known calibration grid. See [2] for a detailed explanation.

To suitably condition the raw data for each section we must determine a discrete set of point coordinates for each laser plane trace segment. This is done by locating the best *path* through the raw image using a suitable *centre-of-gravity* (COG) algorithm, see [3]. Each point set is then mapped to the Euclidean plane using the transformation obtained from the camera calibration procedure. We now require a suitable longitudinal axis upon which we can reassemble the 8 segments in one planar section, then stack the planar sections. The *reconstruction* axis is determined using a calibration cylinder, with roughly the same cross-section area as the connector, see Figure 1.

The raw image data of the plane traces on the cylinder are conditioned as above. We obtain a rectified coordinate set referred to some planar reference frame. The centres of the camera-distortion compensated arcs are determined using an improved version of the algorithm found in [4]. We translate the coordinates of the camera-distortion compensated connector segments so the arc centre coordinates are the reference frame origin, then rotate the new coordinates to remove the rotation angle of the first joint angle. Using the transformed section coordinates and robot angle offsets, we reconstruct the connector segments in the appropriate laser plane (z = constant). Figure 2 shows a raw image of the connector and a planar section reconstructed from 8 views.

3. RESULTS

The cable connector used in the experiment, shown in Figure 1, had a length of 24 mm. We decided that to demonstrate the validity of our approach obtaining 20 planar sections with a 1 mm separation would suffice.

We measured 20 different planar sections of the connector taking 8 images in each plane, for a total of 160 images. The first plane was near the measurement frame-connector interface. The remaining 19 sections were at 1 mm increments in the negative z-axis direction. Only 1 planar section of the calibration cylinder was measured. MATLAB programmes were written to rectify and reconstruct each section of the connector referenced to the cylinder section.

Note that in the raw images there are some outliers. The resulting unwanted data can be trimmed from the data set by eliminating the first and last 10% of data points in a segment; and eliminating data with an excessively steep slope, e.g. greater than 60°. However, this step is yet to be implemented.

The rectified image data is noisy. Two preliminary data filtering methods have been tested, without outlier removal. They are a 2D Butterworth filter and Fourier elliptical descriptors. We believe the latter method to be superior since FFT with efficient implementations are available in most programming environments.

To construct a solid model we proceed as follows. The data of individual segments in each layer are filtered using the FFT procedure. Thus, the data in the 8 segments in a section are seamlessly joined, and modelled mathematically. Using MATLAB, the 20 layers of the FFT filtered data were used to create a solid model. Figure 3 shows the wireframe thus obtained.

4. DISCUSSION AND CONCLUSIONS

Visual inspection of the reconstructed section, Figure 2, and the solid model, Figure 3 reveals the procedure we have developed can produce a solid model reasonably complete in desired external detail.

We conclude that these results show that an integrated robotic optical measurement system can be set up to measure cable connector external solid geometry. Moreover, the results suggest our procedure is a suitable tool for constructing solid models for CAM purposes. Until we have implemented a raw image data filter, no measurements will be made. This for the simple reason the data is, as yet, too noisy to obtain satisfactory dimensional tolerance. Due to this, we can assign no value to the dimensional accuracy of our solid model. This notwithstanding, we have good reason to believe that the required tolerance of ±0.1 mm can be attained in the automated manufacture of cable connector jigs.

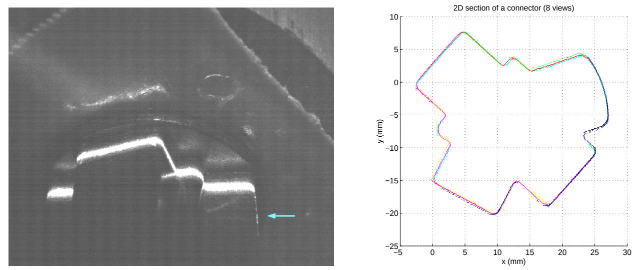

Figure 2. Camera view of laser plane trace on cable connector. The arrow points to data points with excessively steep slope; Reconstructed cable connector section in layer 0.

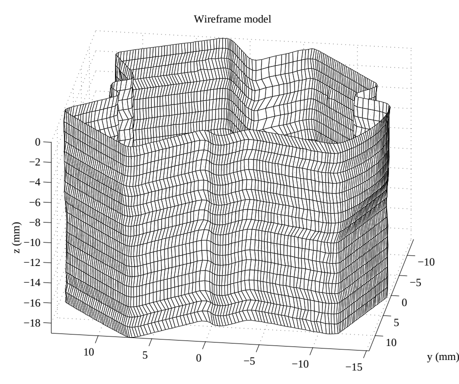

Figure 3. Wireframe model.

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