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A 3-D Scanner Capturing Range and Color: Design and Calibration

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Abstract

We present a simple, low-cost and easy to reconfigure 3-D color-range scanner - CRS, which is able to capture the geometry and color of the measured object. The CRS utilizes a scanning laser sheet and the triangulation principle to acquire the geometry of the measured object. The projected laser stripe is detected using a matrix array pixel processor MAPP2200, which makes the scanner system compact and eliminates the need for any additional signal processing hardware. The color values for each 3-D point are acquired using a standard color CCD camera. For accurate range measurements and color value acquisition the physical geometry of the scanning system has to be determined and camera-to-camera calibration made between MAPP2200 and CCD camera. In-house camera calibration toolbox for MATLAB is used for both of these tasks. To maximize portability the CRS is connected to the RS-232 port of the host computer and can be easily controlled by using simple ASCII commands. Finally we show some 3-D images taken with CRS.

1 Introduction

In mobile robotics, the ability to acquire three-dimensional information from an environment and to have color information about surrounding objects makes the robot vision system more suitable for complex tasks, such as environment modeling [1] and object recognition [2]. At present, there are only a few commercial 3-D scanners available, and only some of them capture the color of the object. These systems tend to be expensive and/or their reconfiguration is difficult, which limits their use in robotics.

The CRS was designed for robotics research at the University of Oulu. It will be mounted on a Nomad XR4000 mobile robot and its main function is to acquire 3-D data for robot control, environment modeling and object recognition. The CRS is based on an active structured light measurement technique [3][4], and it can hence also be used in featureless environments. The CRS is implemented using commercially available parts and a simple digital controller, which makes CRS reconfigurable and easy to implement.

The calibration of the 3-D scanner [5] is a critical task and is also addressed in this paper. We present a accurate calibration procedure, which makes no assumptions about the measurement geometry.

2 CRS

The main components of the CRS are shown in Figure 1. A 256x256 element MAPP2200 sensor [7] is used to extract the projected laser profile from the object’s surface. A CCD camera gets the color values for each range point and the beam splitter makes these two sensors share a common optical axis for accurate color mapping.

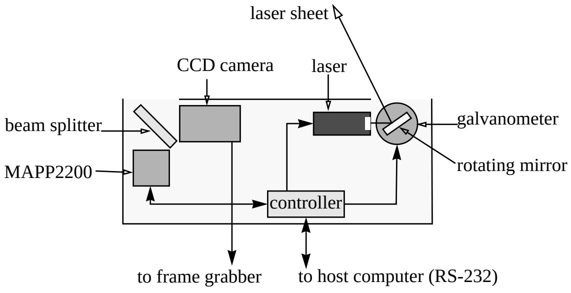

Figure 1. The main components of the CRS.

A laser module with a cylindrical lens produces the laser sheet, which is projected onto the scene using a galvanometer controlled mirror. A Simple TMS230C50 DSP-based digital controller is used to control the measurement system, excluding the CCD camera, which is independent of the other CRS components.

All important aspects of the system can be reconfigured: The measurement geometry of the CRS can be adjusted to new tasks, new system features needed at different tasks, like obstacle avoidance, can be added into the embedded software running in the DSP, and both the MAPP2200 and the CCD camera use standard c-mount optics, which are easy to replace for new applications.

The CRS uses a triangulation principle [3] to acquire range measurements from the object. The MAPP2200 sensor detects the laser profile reflected from the object's surface and gives the 2-D image coordinates for profile points at sub-pixel accuracy. Using a known imaging geometry 3-D coordinates can be reconstructed out of these 2-D image coordinates.

The colors for the 3-D measurement points are defined by mapping the MAPP2200 image coordinates onto the color image taken by the CCD camera. The mapping parameters are defined in the calibration phase.

We use an in-house MATLAB calibration toolbox [6] and nonlinear least-square estimation to find out the imaging geometry and color mapping parameters for the CRS.

The CRS communicates through the RS-232 connection, sending status information and 2-D image coordinates and receiving commands and configuration data. The CRS uses simple ASCII commands to control the system and to obtain image data. The acquisition time for the CRS, including the data transfer time, is currently about 15 seconds for a 256x256x512 range image. Acquisition time could be reduced by using the USB instead of the RS-232, which is the major bottleneck in system performance. We still use the RS-232 connection, however because of its simplicity and portability. Figure 2 shows the CRS in its current configuration.

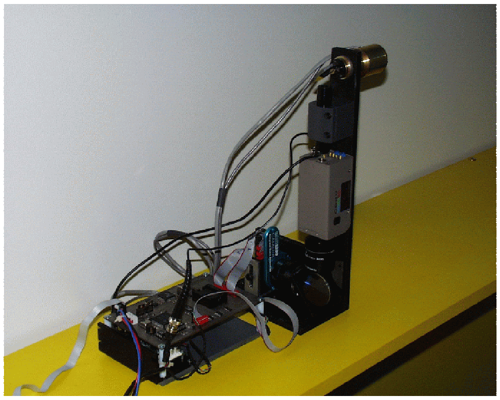

Figure 2. The CRS.

3 Calibration

Calibration is made in three phases. In the first phase, both the MAPP2200 sensor and the CCD camera are calibrated for geometrical distortions. In the second phase, the model parameters of the physical measurement geometry are estimated and in the third phase, camera-to-camera mapping from the MAPP2200 to the CCD camera is solved. In the next three subsections we will briefly describe the calibration procedure for the CRS.

3.1 Camera Calibration

Geometric camera calibration is required for correcting the spatial errors in the MAPP2200 sensor and CCD camera images. Both devices are accurately calibrated using the method described in [6].

3.2 Estimating the measurement geometry

The model parameters of the physical measurement geometry shown in Figure 3 are:

$$w = \left[x_0 \ y_0 \ z_0 \ \omega_0 \ \varphi_0 \ \kappa_0 \ v \right]^T$$

where the first six are the transformation parameters of the coordinate system of the galvanometer scanner with respect to the MAPP2200 coordinate system. The parameter v is used to map the desired angle φ to the correct galvanometer input voltage V_{ig} and vice versa. $\varphi = \varphi_0$ when $V_{ig} = 0$. Next, we will briefly describe this calibration phase. See Figure 3 for the calibration setup.

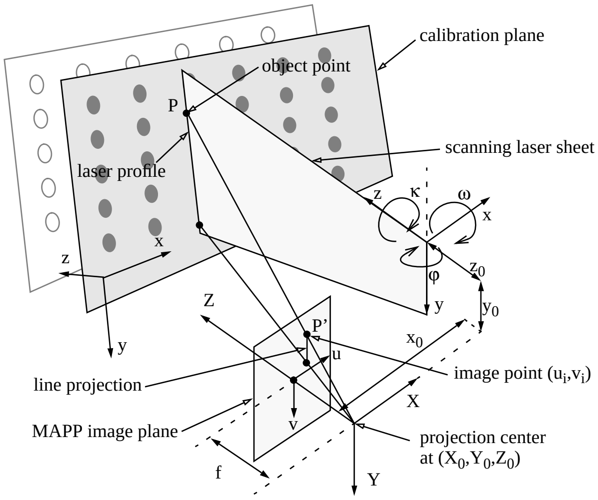

Figure 3. CRS model and calibration setup.

We use a planar calibration object with a black background and white circles as shown in Figure 4. First, we take two sets of measurement data at two different locations of the calibration plane, by sweeping the plane with a laser sheet and saving the MAPP2200 image coordinates of the projected lines at the current input voltage V_{ig} of the galvanometer. We assume here that the input-output mapping of the galvanometer is linear, which is practically true of high-quality galvanometers. We repeat the sweep three times using the same galvanometer positions: 15 different positions at about 2^o steps. The final data set consist of the average of these three sweeps.

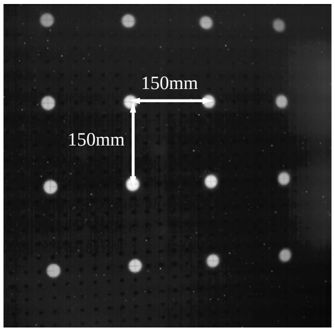

Figure 4. MAPP2200 image of the calibration plane.

Before relocation of the calibration plane, we take one gray-scale image from it with MAPP2200. We use the image and the calibration toolbox to define the 3-D location of the calibration plane in the MAPP2200 coordinate system. Having two data sets and two accurate calibration plane locations, we can estimate the unknown parameters using non-linear least-square estimation in MATLAB. For this estimation, we use the following error function

$$J = \sum_{i=1}^{N} \frac{|Au_i + Bv_i + C|}{\sqrt{A^2 + B^2}}$$

where A, B and C are the parameters of simulated line projection of the laser stripe to the MAPP2200 image plane, calculated using the current parameter estimates, galvanometer input voltage and knowledge about calibration plane location, (u_i, v_i) are the coordinates of the measured stripe point on the MAPP2200 image plane and J is the sum of distances between all measured stripe points and related line simulation. During the estimation, the distance error between the measured profiles and simulated projections is minimized.

3.3 Color Mapping

In order to have a color value for each range point, we have to map the MAPP2200 image coordinates, i.e. stripe points, to the color image taken by the CCD camera. This mapping consist of rotation, translation and scaling from the MAPP2200 image to the CCD image. We took an image of the calibration plane with both of these devices and selected the same four or more white circles from the images. We then calculated the centroids of these circles and applied an estimation method to minimize the mapping error of these centroid locations, and to find the mapping parameters.

4 Accuracy

In order to test the accuracy of the CRS, we placed the calibration plane on the scene and scanned it. We then calculated the centroid locations of the white circles from the reflectance image. Because the reflectance image is in perfect registration with the range image, the centroid locations can be used to index the correct 3-D point from the range image. We used these 3-D locations of the circles and their known mutual distances on the calibration plane to evaluate the accuracy of the CRS and the goodness of the calibration.

Direction	Actual [mm]	Max [mm]	Min [mm]	Std dev [mm]
X	150.0	149.39	148.28	0.5904
Y	150.0	151.34	149.95	0.6992

Table 1. Accuracy evaluation at average distance of 1.1m.

We calculated the 3-D distance errors in horizontal and vertical direction between adjacent circles on the calibration plane. The average distance of the circles in Z-direction was 1102.8 mm. Table 1 summarizes the evaluation and shows the validity of the calibration method.

The error introduced at the calculation of the centroid locations of the calibration circles was not considered in this evaluation, which may slightly bias the evaluation results.

5 Results

Figure 5 shows a CRS image taken at resolution 512x256x512. This image is a combination of range and reflectance images without color information.

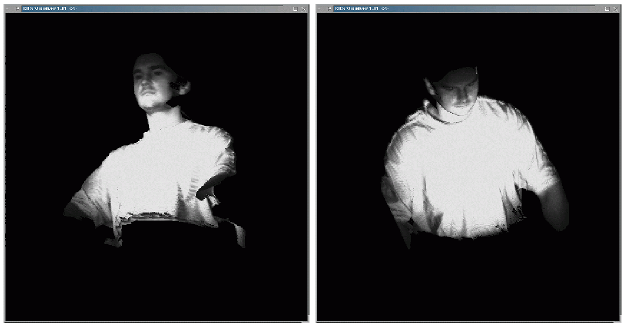

Figure 5. A combination of range and reflectance images.

The image quality is good and there is no systematic distortions on it, which indicates successful calibration. Some occlusion can be seen on non-convex parts of the image. This image was taken using the horizontal sheet of light.

Figure 6 shows a CRS range image on the left and same image with colors on the right. This image is taken at resolution 256x256x512 using the vertical sheet of light. In this image occlusion can be seen more clearly near the hands of the person. The color image on the right shows how CRS combines range and color. This ability is useful in many applications such as object recognition, environment modeling and creation of realistic surface models for virtual reality.

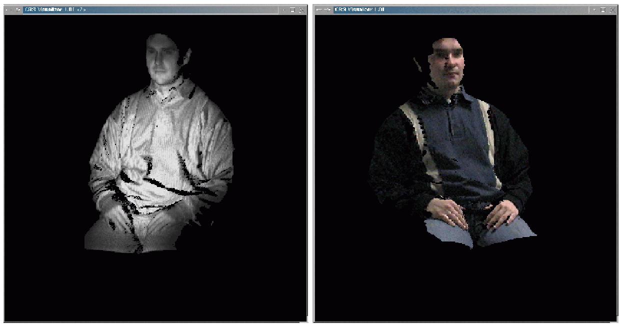

Figure 6. A combination of range and color images.

6 Conclusion and Future Work

In this paper we presented CRS, a 3-D scanner capable of capturing both range and color. The main design idea, was the reconfigurability, at both hardware and software levels, and simple implementation.

Calibration issues were also addressed. The accurate calibration method was proposed and evaluated. The in-house calibration toolbox for MATLAB was used in all the three semi-automatic phases of the calibration procedure. In future, the range image acquisition time could the reduced using a USB instead of RS-232 connection to the host computer, and the measurement resolution could also be enhanced by using the new 512x512 element MAPP2500 chip.

References

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