Data Fusion Between a 2D Laser Profile Sensor and a Camera

M. Wagner[1], P. Heß[1], S. Reitelshöfer[2] and J. Franke[2]
[1] *Nuremberg Campus of Technology, Nuremberg Institute of Technology, Fürther Straße 246c, 90429, Nuremberg, Germany*
[2] *Institute for Factory Automation and Production Systems, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany*

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Abstract: This paper describes a color extension of a 2D laser profile sensor by extracting the corresponding color from a camera image. For these purpose, we developed a routine for an extrinsic calibration between the profile sensor and the camera. Based on the resulting translation and rotation vectors a belonging pixel can be calculated for each profile point. Consequently, the color for each profile point can be extracted from the image. This approach is used to extend the geometric data of a robotic based 3D scanning system by color data.

1 INTRODUCTION

The range of applications for industrial robots extends. Especially small and medium-sized enterprises focus on small quantities and consequently a high flexibility. Thus, workpiece related robot programming is used with increasing frequency for typical robotic tasks, such as handling, processing or inspection. In most cases, an already existing CAD-model is used for this purpose, but for some applications the scanning of individual workpieces can be necessary. This is a fast way to get an accurate 3D model of the real workpiece, especially from unknown objects.

Laser scanners are commonly used for the scanning of workpieces. They are very efficient in extracting geometric information, but one main drawback of laser sensors is their lack of capability in capturing textures of objects. Thus, common 2D laser profile sensors do not have color information implied. In this paper, we present an extension of a common 2D laser profile sensor with color information by extracting them from a camera image. One possible way to fuse the data is to detect the laser profile in the image and fit it to the measured profile, but the visibility of the laser depends strongly on the color and the surface of the scanned object. In addition, it means a lot expenditure to fit the profiles. The selected approach avoids these disadvantages, by fusing the data of the two sensors through the transformation between the base coordinate systems. Thereby, the position of the profile points in the image can be calculated regardless of the visibility of the laser.

To find correspondences between the points of the profile sensor and the pixels of the camera image the geometric transformation between the sensor frames needs to be determined by a calibration. First, an intrinsic calibration of the used camera is done for this purpose. The second calibration step is the extrinsic calibration between the profile sensor and the camera. Based on the resulting calibration parameters, a calculation of the corresponding pixels can be realized. Finally, the color is determined from the image.

The subsequent content of this paper is structured as follows. The related work in the field of extrinsic calibrations between a camera and a laser scanner is presented in the following section. Furthermore, the approaches for the sensor calibration and the color extraction are described in detail. The fourth section deals with the accuracy investigation of the realized approach. A short conclusion is at the end of the paper.

2 RELATED WORK

The consideration of the related work is separated in two sections. Initially, a short summary of 3D workpieces scanning through industrial robot arms is given. The state of the art in sensor fusion between laser scanners and cameras follows afterwards.

2.1 Robot-based Workpiece Scanning

The reconstruction of 3D shapes can be done with a multitude of sensors and approaches. Thus, many contact or non-contact sensors, such as radiation-,

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light- or image-based sensors, are on the market–either they are three-dimensional sensors or they are one- or two-dimensional sensors moved by hand or by machine. One flexible machine for doing this motion is an industrial robot arm. By linking the measurement points with the robot positions, 3D point data can be derived.

For robotic based workpiece scanning non-contact sensors are mainly used. Due to the requirement for a high accuracy and a close range triangulation-based sensors are preferred. Thus, 2D laser profile sensors are frequently used for scanning workpieces by moving the sensor by a robot arm (Larsson and Kjellander, 2006; Borangiu and Dumitrache, 2010; Li et al., 2011; Shen and Zhu, 2012). These scanning systems for example are used for a reverse engineering process, as shown in (Larsson and Kjellander, 2006). A workpiece scanning for subsequent processing has been pursued in (Borangiu and Dumitrache, 2010). Most of the approaches use an additional rotation table on which the workpiece is placed to improve the reachability. In our approach, the system is extended by moving the workpiece with a second robot arm (cf. Figure 1) to improve the reachability furthermore and to include the robot-related workpiece position in the scans for following processing steps.

The realized scans with all of these robotic-based systems include only the geometric information, what is sufficient for many applications. No color information is included, but for example for object recognition or realistic model building it can be necessary. Therefore, they need to be obtained by additional sensors.

2.2 Sensor Fusion

Not for every application a perfect individual sensor is available. Thus, multiple sensors need to be used frequently to achieve all of the necessary data. To combine the data of multiple sensors an extrinsic calibration between the sensor coordinate systems must be done first. Therefore, related reference points visible in all of the data sets need to be obtained.

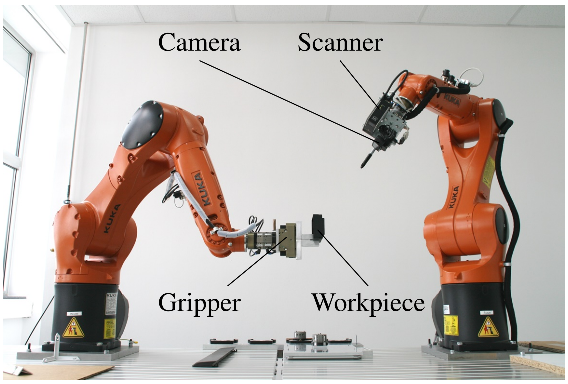

Figure 1: Robot set-up for workpiece scanning.

Many approaches for the fusion of a camera and a 2D or 3D laser scanner have been realized in the past. The main application is navigation for mobile robots (Zhang and Pless, 2004; Mei and Rives, 2006; Scaramuzza et al., 2007; G. Li et al., 2009; Nunez et al., 2009) or vehicles (Garcia-Alegre et al., 2011; Osgood and Huang, 2013). Object recognition–also for mobile robots (Klimentjew et al., 2010) or vehicles (Mohottala et al., 2009)–is a frequent application, too. In addition, other applications, for example model building or medical applications, are considered (Cobzas et al., 2002).

Some of the realized extrinsic calibration methods use manually selected reference points, as shown in (Cobzas et al., 2002) or in (Scaramuzza et al., 2007). More intuitive approaches use calibration objects for an automatic reference point detection. Approaches with known and with unknown objects are realized. Most of them use a calibration plane to detect references. Thus, for example in (Zhang and Pless, 2004) and in (Mohottala et al., 2009) a checkerboard in different poses has been used. The approach realized in (G. Li et al., 2009) uses the edges of a plane and in (Nunez et al., 2009) only the corners of a rectangular object, such as a pattern, are used. Another way is the use of patterns with geometrical extensions, as shown in (Klimentjew et al., 2010). In this approach, a typically checkered pattern is extended with a 3D structure to get reference points in both data sets. The corners or walls of a room can be used as well (Mei and Rives, 2006). Some approaches use specific single objects as reference points. Thus, in (Osgood and Huang, 2013) small white discs are placed in the laser plane and detected through the reflection in the camera image, for example. In (Navarrete et al., 2013) small catadioptrics are used and the laser intensity information is converted to a 2D image which is fused with the camera image.

To the best of our knowledge, no approach for a color extension of a short ranged 2D laser profile sensor has been realized, yet.

3 APPROACH

The color extension of the robotic-based 3D scanning system is based on the data fusion between the geometric position data from the profile sensor and the belonging color data from the camera image. This process is done in four main steps (cf. Figure 2).

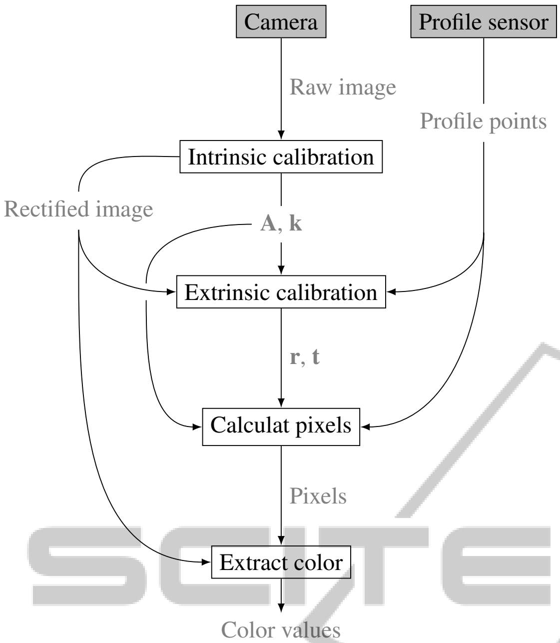

Figure 2: Color extension routine.

First, the used sensors need to be calibrated intrinsic to ensure the accuracy of the measurements. The used profile sensor is already calibrated by the manufacturer. Thus, only the camera needs to be calibrated intrinsic to achieve a rectified image. The resulting intrinsic camera parameters and the rectified image is used for the following extrinsic calibration between the camera and the profile sensor by getting matched image and profile points. The extrinsic calibration results the transformation between the two sensors. With the intrinsic and the extrinsic parameters a belonging pixel can be calculated for each profile point. In the last step, for each profile point a color is extracted from the rectified image.

The main steps of the color extension routine are described in the following subsections in detail.

3.1 Intrinsic Calibration

Before the fusion of the two sensors data, each of the sensors need to be calibrated intrinsic. As already mentioned before, the used 2D laser profile sensor is already calibrated intrinsic by the manufacturer. Therefore, this step does not need to be considered. However, this does not apply for the camera.

As already shown by (Tan et al., 1995), classic camera calibration methods use complicated calibration objects, with known 3D coordinates. Newer calibration methods either seek calibration cues from the scene or only require simple calibration objects. A common method is the calibration by a planar pattern published in (Zhang, 2000). By moving either the camera or the pattern and detecting the pattern in the image in multiple poses, the intrinsic parameters can be calculated. They consist of the intrinsic matrix

$$\mathbf{A} = \begin{bmatrix} f_x & \gamma & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

and the distortion vector $\mathbf{k} = (k_1 \ \ k_2 \ \ p_1 \ \ p_2)^{\mathrm{T}}$. We use this approach with a typical 9×6 chessboard. The implementation is based on the open source library OpenCV.

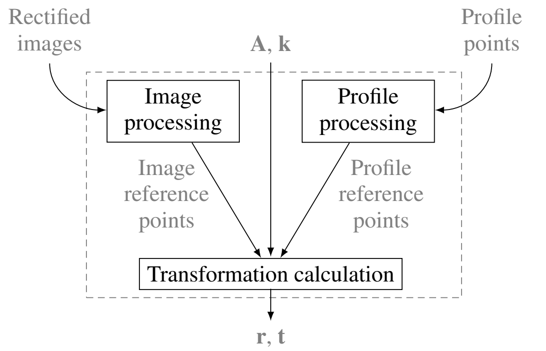

Figure 3: Extrinsic calibration routine.

3.2 Extrinsic Calibration

The realized extrinsic calibration routine is shown in Figure 3. Before calculating the transformation between the sensors, each sensor data is processed to achieve the reference points. Afterwards, the translation vector $\mathbf{t} = (t_x \ \ t_y \ \ t_z)^{\mathrm{T}}$ and the rotation vector $\mathbf{r} = (\theta_x \ \ \theta_y \ \ \theta_z)^{\mathrm{T}}$ are calculated from the reference points and the intrinsic camera parameters.

In our approach, any planar calibration object fitting in the measurement range of the profile sensor is usable. The exact color and size of the object is not important. As reference points the corner points of the profile and the end points of the laser line inside of the image are detected.

3.2.1 Profile Processing

Starting from the fact that only the calibration object is in the range of the profile sensor, we achieve the profile reference points by taking the two profile points with the smallest and the largest x-value.

To make sure that all reference points are measured correctly, the trapezium shaped measuring range is limited as follows (cf. Figure 4). First, the values are limited to a z-range, that is a little bit (e.g.

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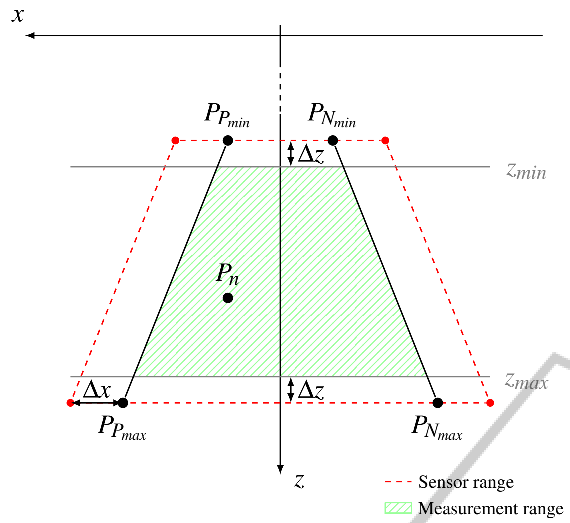

Figure 4: Range limitation for the profile sensor.

five times the z-resolution) smaller than the z-range of the sensor, to ensure that no reference points close to the boundary of the sensor-range are taken. Thus, the z-range borders are shifted about Δz and only points inside of these borders are used furthermore. In the next step, the x-value of the reference points is controlled by calculating the two scalar products:

$$d_P = (P_{P_{max}} - P_{P_{min}}) \cdot (P_n - P_{P_{max}}) \tag{1}$$

$$d_N = (P_{N_{min}} - P_{N_{max}}) \cdot (P_n - P_{N_{min}}) \tag{2}$$

Thereby, the sensor range is reduced on both sides about Δx. If $d_P > 0$ and $d_N > 0$, the reference point P_n is inside of the limited range and can be used for calibration. A calibration object close to or even outside of the profile sensor measurement range results negative values. Thus, these points are not saved for calibration.

3.2.2 Image Processing

The laser appears in a visible line on the calibration object. The visibility of the laser depends on the material and the surface of the scanned object as well as the viewing angle. Therefore, we reduce the camera image to a binary image with values that are in range of a color spectrum matching to the laser line color. The spectrum is selected individually by choosing ranges either for the HSV (hue-saturation-value) or the RGB (Red-Green-Blue) parameters. Furthermore, an erosion and a dilation is done on the binary image to clearly stand out the laser line. In the next step, a line fitting procedure using least squares method is done, resulting the linear equation. The two end points of the line are achieved by determining the bounding box and calculating the points of intersection between the box and the linear equation.

To ensure that all image reference points are collected correctly, the image frame is also reduced by a small stripe. Thus, only points inside of the reduced frame are accepted. If the calibration object is positioned close or even outside of the image frame, no reference points are saved.

3.2.3 Transformation Calculation

The transformation between the profile sensor and the camera consists of translations in the three dimensions and rotations around the three axis, represented by a translation vector **t** and a rotation vector **r**. The calculation of the transformation between the two sensor coordinate systems is done by an iterative method based on Levenberg-Marquardt optimization. This method has already successfully been used in several previous approaches for sensor fusion (Cobzas et al., 2002; Zhang and Pless, 2004; Scaramuzza et al., 2007; Mohottala et al., 2009). In order to solve the established equation systems $N \geq 3$ reference points are necessary. Since we have two points per measurement, at least two measurements are required. From the N corresponding reference points in the profile P_{Ref_n} and in the image I_{Ref_n} as well as the intrinsic camera parameters **A** and **k** (cf. Section 3.1) the translation **t** and the rotation **r** finally result.

3.3 Pixel Calculation

Both used sensors only offer two-dimensional information. Thus, the profile points $P_n = (p_x \;\; 0 \;\; p_z)^{\mathrm{T}}$ and the image points $I_n = (i_x \;\; i_y \;\; 0)^{\mathrm{T}}$ contain only two variables. The relationship between the data points can be described by the following equation:

$$I_n(i_x, i_y) = \mathbf{R} \cdot P_n(p_x, p_z) + \mathbf{t} \tag{3}$$

Using this geometric relation, a belonging pixel for every profile point could be calculated. The rotation matrix **R** can be derived from rotation **r** determined through the extrinsic calibration (cf. Section 3.2) as well as the translation **t**. The resulting pixel corresponds the projection of the profile point onto the image plane.

3.4 Color Extraction

Several approaches are possible for the extraction of the color values from the camera image. The most obvious one is the extraction directly from the calculated pixels. However, with visible laser sensors the

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object is discolored by the laser in these areas. Thus, the laser needs to be turned of temporary, for example through pulsation. But this takes time, which is disadvantageous especially in a full 3D scan. This drawback can be avoided by coloring the entire point cloud after the scan. Therefore, multiple images could be necessary to color all sides of the point cloud. But in this case, the color information is not already usable during the individual profile shots. Our third approach avoids both disadvantages by approximately determining the color values from neighboring pixels. For this purpose, for each profile point two neighbor points $N_n = (p_x \ \pm\delta \ p_z)^{\mathrm{T}}$ with a distance δ in y-direction are used to calculate the corresponding pixels by:

$$I_n(i_x, i_y) = \mathbf{R} \cdot N_n(p_x, \pm\delta, p_z) + \mathbf{t} \tag{4}$$

The offset must be chosen large enough that the laser is not hit anymore. The corresponding color value is then averaged from the color values of the two nearby pixels. Thus, the color values can be quickly obtained on-the-fly, with the disadvantage of an inaccuracy.

4 EXPERIMENTS AND RESULTS

As mentioned in Section 3.2, any planar calibration object fitting in the measurement range of the profile sensor is usable for our approach. As example we use Lego bricks with different colors in order to investigate the influence of the color (cf. Figure 5). The used camera is a Logitech 920c with a resolution of 1920×1080 and a frame rate of 30 fps. The used laser profile sensor is a Micro-Epsilon scanCONTROL 2600-100 with a range from 125.0 mm to 390.0 mm in z-direction. The x-range of the sensor is between ± 28.5 mm and

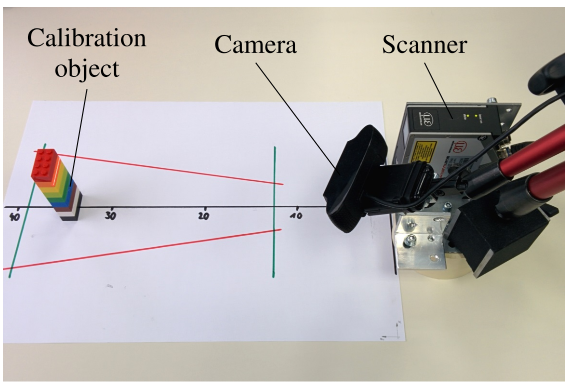

Figure 5: Experimental set-up for sensor fusion.

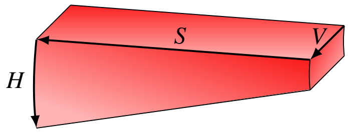

Figure 6: Exemplar color spectrum ($H: 339° - 351°$, $S: 29.8 - 87.2$ %, $V: 98.0 - 100.0$ %) for line detection.

± 71.0 mm. Inside of this range the sensor is measuring 640 points per profile with a z-resolution of 12 μm. Through the adjustable shutter time the sensor can be set well to different surfaces.

For the individual color of the calibration object a specific color spectrum is selected through a color dialog or through a pipette, by clicking on to image pixels. Thus, one of the lightest pixels and one of the darkest pixels of the laser line is selected to achieve a good spectrum. An example spectrum is depicted in Figure 6.

To illustrate the correctness of the calibration, stepped Lego bricks with different colors along the profile are used, as shown in Figure 7. The profile point based calculated pixels are colored purple inside of this image. It becomes apparent, that the calculated points are close to the actual laser line. Based on the calculated pixels the color information is extracted from the camera image and the corresponding color profile is visualized in Figure 8, showing the color changes at step transitions.

In order to make a concrete statement about the accuracy of the calibration, the belonging pixel for each profile reference point and furthermore the distance between the pixel and the corresponding end of the detected line is calculated. From the sum of the distances of all used reference points the average pixel error is calculated.

Twenty calibrations with two experimental set-ups

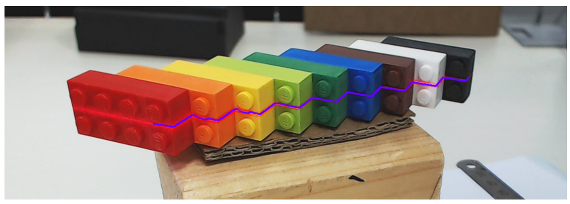

Figure 7: Multi-color example for color extraction.

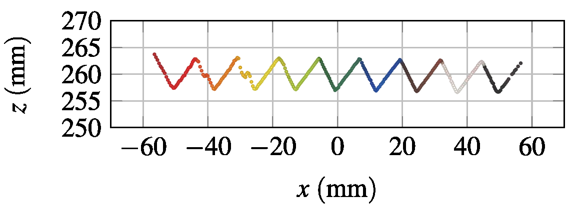

Figure 8: Resluting colored profile for Multi-color example.

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have been performed. The first set-up is shown in Figure 5 and in the second set-up the camera is mounted as close as possible to the profile sensor. Thereby, either two, five or ten object positions scattered inside of the reference areas were used. However, an increased number of reference points has no significant influence on the results. Thus, a number of $N = 4$ reference points is sufficient. The resulting mean values and the standard deviation values for each parameter are shown in Table 1 and 2.

Table 1: Parameter estimation for first experimental set-up.

t (mm)	σ (mm)	**r** (deg)	σ (deg)	*Error* (pixel)	σ (pixel)
72.3995	0.8716	34.4061	0.1101		
80.1886	0.3726	-22.9854	0.2741	0.9349	0.1891
20.5744	0.4808	-3.4034	0.1325		

Table 2: Parameter estimation for second experimental set-up.

t (mm)	σ (mm)	**r** (deg)	σ (deg)	*Error* (pixel)	σ (pixel)
1.9726	0.0445	-9.2074	0.0310		
-32.7163	0.1503	-5.9926	0.0370	0.8696	0.0721
-18.5722	0.3498	-89.2548	0.0621		

The realized approach achieves stable solutions and consequently a good repeatability. The validation shows low standard deviation values for the transformations ($\sigma < 1\text{mm}, \sigma < 0.3°$). A good absolute accuracy is also achieved with average pixel errors below the resolution of the camera (1 pixel). This error occurs partially by rounding errors that can hardly be avoided.

The calibrated sensors are used for workpiece scanning with two robot arms (cf. Section 2.1). Figure 9 shows a partial reconstruction of some Lego bricks held up by a gripper. Due to the contained color information, it can be clearly distinguished between the individual bricks and the gripper.

(a) Scene (b) Point cloud

Figure 9: Example for a colored reconstruction.

So far, the coloring needs approximately 4 ms per profile point. Future work will be focused on the time optimization of the process. In addition, an improvement of the reference point distribution, by splitting the profile sensor measurement range in sections and a partial restriction on one reference point per section, is prospected.

5 CONCLUSIONS

In this paper, a color extension for a 2D laser profile sensor by getting the color information from a camera is presented. For this purpose, a sensor fusion between the two sensors has been realized. Therefore, a flexible calibration routine has been created. Indefinite planar calibration objects are usable with this approach regardless of their color. The accuracy of the approach is confirmed through experiments. A pixel error close to the resolution of the camera has been achieved.

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