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Accurate light source position estimation for a laser triangulation measurement device using particle swarm optimization☆

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ABSTRACT

The two-dimensional object's position or object's edge position can be well estimated with simple triangulation techniques utilizing the projected shadow of the object edge by exposing the edge in different angles. This can be done using two bare Laser diodes projecting the object's edge in a different angle onto a CCD or CMOS sensor without the need of any additional optical elements such as collimation lenses. For simple triangulation methods, sensor- and Laser diode position play a very important role. The overall accuracy is mostly determined by the uncertainty of these positions. This paper presents a possible approach to determine the light source positions highly accurate. Because deterministic methods suffer when badly shaped error functions occur, stochastic methods can deliver very good results, ending up very close to the global optimum. When using particle swarm optimization (*PSO*) for determining the light source positions, it could be shown that the overall 2D X/Y object's edge position estimation error, which strongly depends on those positions, can be significantly lowered. The 2D edge position estimation error can be reduced from 407 µm down to 3.4 µm in X direction and from 280 µm to 8.3 µm in Y direction, using a standard sensor and two bare Laser diodes. It was possible to show the good convergence of the proposed PSO method, firstly by setting up a simulation and testing with simulated edge data. Later, simulation results could be verified with real measurement data. When using PSO, it can be pointed out, that the light source position can be determined within micro-meter accuracy, which effectively reduces the overall measurement error of the system.

1. Introduction

In many cases, common contact-less optical methods for determining 2D object's parameters use so-called shadow methods. The shadow of an opaque measurement object which is exposed by a light source, is projected onto a light sensitive sensor. Therefore, the object's projected edge position on the sensor can be obtained (Fig. 1). In result the position of an object, or geometrical object parameters, like thickness or diameter could be determined, given the position of several projected edges [1,2].

The idea of getting rid of very expensive additional optical elements which were needed for collimating the light source's light beam, is essential when setting up small measurement systems [3]. This also leads directly to savings in production costs, system dimensions, and reduced complexity of such measurement devices. A small measurement device could be well-integrated directly into applications like wafer production- or testing systems like it is proposed in [4].

The test setup proposes a linear CCD sensor array and two bare, off-the-shelf Laser diodes, placed in a distance of L_{iY} to the sensor. These two Laser diodes sequentially expose one single sharp edge of an opaque object onto the sensor. The shown setup relies on sequential exposure, therefore only one single edge is projected in one step by one single light source. Every single exposure will generate a shadow, a diffraction pattern respectively, which is projected onto the sensor (Fig. 1). By finding this projected edge position on the sensor, as well as due to the known the light sources positions, it is obvious that the objects edge position (X/Y) could be easily determined with triangulation methods.

In this paper, it is proposed that the very first pixel of the CCD sensor is placed in the X/Y coordinate origin at (0/0), and its orientation is in X direction only, therefore, the projected edge position on the sensor will also be only a function of X. This means that in an optimization step, an eventually existing sensor skew results in a shifted light source position after optimization, meaning a rotation about the origin

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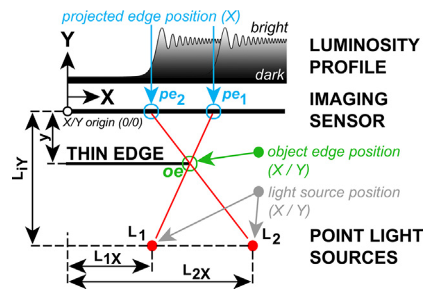

Fig. 1. Working principle for position measurements, projecting an object edge with two light sources onto a sensor.

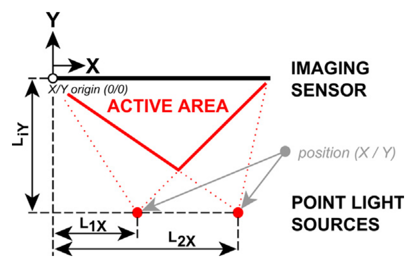

Fig. 2. Active 2D (X/Y) measurement area, by increasing the distance in between the two light sources the active measurement area gets smaller.

compensating the sensor skew angle. The object edge position is thereof determined in relative to the first sensor pixel.

The object's edge is also considered to be very thin, meaning a razor blade knife edge with an edge thickness of a few hundred nanometers (typical razor blade knife edge width $< 200\,\text{nm}$). This plays an important role, since the enhancement of the Laser diodes photometric stereo basis can increase the edge position estimation accuracy (see Section 4.3), but also scales down the measurement area (Fig. 2). This circumstance is also discussed in [2]. For 2D edge position measurements, it must be maintained that both light sources expose the same edge. Especially with thick objects and a wide photometric stereo basis, this problem can be nicely illustrated (Fig. 3). At first the light source L_1 will expose the object bottom edge, and in the second step L_2 is going to expose the top edge. Then the two projected edge positions would be used to estimate one particular object edge position. In any case, for the shown setup, the X/Y position of bottom or top edge cannot be determined with triangulation, because both light sources will always expose a different edge.

For all proposed considerations, it is now assumed that both light sources expose exactly the same edge. In the real measurement setup, the razor blade knife edge has indeed just a few hundred nm of edge thickness, which is thereof neglected, since the overall measurement accuracy is considered to be around some micrometers. Thereof the thickness of the razor blade as well as the edge shape of this very thin edge, is not even noticeable in the measurement results.

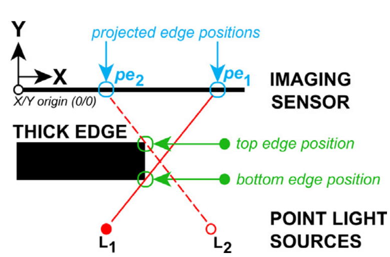

Fig. 3. The used light sources expose different edges, in result a two-dimensional X/Y edge position estimation is not possible.

In fact, when using triangulation methods, the object edge position estimation accuracy depends on the preciseness of the positions of L_1 and L_2 in the measurement setup. Also in [2] the uncertainty of that positions is stated to be critical. Because those light sources cannot be placed easily within micrometer precision in any setup, the uncertainty of that positions directly influence the estimation accuracy of triangulation methods.

In contrast to the proposed triangulation method, it was shown in [3] that in a orthogonal measurement setup using two separate image sensors it is also possible to determine the diameter of an object, without the need of knowing the light source position, although a divergent light beam is used. Indeed, this approach is feasible just for diameter measurements of circular objects. In case the measurement object is not circular, additional exposure information is not available, meaning just one single edge is exposed by one light source on the sensor. Thereof the light source position has to be known very accurate.

This work presents a novel approach to identify those positions. Particle swarm optimization, is used to determine this inaccurate parameters L_{iX} and L_{iY} in a way to significantly increase the accuracy of the estimated X/Y object edge position [5]. The proposed method is independent of the edge detector used (e.g. simple thresholding [1]) and can be envisaged to be used in combination with any suitable edge detector as proposed in [3] or [6]. The estimation accuracy of the objects X/Y edge position will be improved, regardless of the used projected edge detection algorithm. By defining a residual error as function of the projected edge position, the particle swarm optimizer can alter the particle positions to minimize the remaining residual projection error. In section III it is shown how a set of known object edge positions and corresponding projected edge positions (see pe_1 and pe_2 in Fig. 3) can be used to optimize L_{iX} and L_{iY}. The X/Y objects edge position estimation error is then reduced implicitly. In a real-world application, the projected edge is influenced by noise as well as Laser speckles, the geometrical setup, the used edge detector and the underlying edge projection model. Therefore, this projected edge position on the sensor is always detected with some error. The resulting error-function, which is going to be optimized, won't always have only a single flat or nicely shaped valley. Therefore, deterministic methods might not converge to the global optimum when optimizing L_{iX} and L_{iY}. In that case, stochastic methods like the proposed particle swarm optimization, can deal a lot better with badly shaped error functions which were strongly influenced by different sorts of noise.

2. Related results

The first indispensable step is determination of the projected edge position on the sensor, since this information is needed for estimation of the unknown objects edge position. When exposing an edge using narrowband point light sources, e.g. Laser diodes, a diffraction pattern will be generated. This pattern, which also strongly depends on the geometrical parameters of the measurement setup, will be projected onto the sensor (Fig. 4). By using the known solutions of Fresnel Integrals for an opaque half plane [7], which is the edge in this case, the Luminosity on the sensor can be described using (1–2). As it can be obtained by Eq. (1) (where $C(\zeta)$ is the Fresnel cosine integral and $S(\zeta)$ the Fresnel sine integral), the theoretical exposure intensity at any arbitrary point x on the sensor can be determined unambiguously (k is the wavenumber, y the distance in between the edge and the screen, x the position in X direction on the sensor).

Thereof follows the relative intensity at the projected edge's position on the sensor by 25% of I_0 (Fig. 4). By using that knowledge, it seems obvious that very simple thresholding will work for determining the projected edge position on the sensor [8].

$$I_{rel}(\zeta) = \frac{I_0}{2}\cdot\left\{\left[\frac{1}{2}-C(\zeta)\right]^2 + \left[\frac{1}{2}-S(\zeta)\right]^2\right\} \tag{1}$$