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Knife Edge Diffraction for Spatially Extended Light Sources

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Abstract – **The position of an object’s edge can be determined from its shadow projected onto a CCD or CMOS sensor without any additional optical elements such as lenses. Nevertheless, in many applications a collimated Laser light beam is used to illuminate the measured object. Since laser diodes are often complicated in handling, and mostly need additional expensive Laser driver hardware, new approaches were considered. Spatially extended light sources such as off-the-shelf LEDs could be used for edge detection in combination with diffraction pattern analysis, without the need of any additional collimation optics for illumination. Results and applicability for simple position measurement are discussed.**

Keywords **– CCD Sensor, Knife Edge Diffraction**

I. INTRODUCTION

So-called shadow methods for position measurement use a shadow of the measurement object projected onto a light sensitive detector with a collimated light beam to determine the measured object’s edge position. The idea of getting rid of very expensive additional optical elements for collimating a light beam, can lead to savings in production cost of such measurement devices. The proposed approach of using off-the-shelf LEDs could be used for measurement tasks in different industries, where small and lightweight measurement systems were required.

Both linear and area CCD or CMOS sensor arrays are applicable for such position measurements and available in a wide range of pixel sizes and sensor lengths as well as comparable in performance. Measurement accuracy and area for position measurements is limited by the sensors pixel size, pixel count and resulting overall sensor length.

The position of an object, or geometrical object parameters, like thickness or diameter [1] could be determined from the position of the projected edges (Fig. 1). For this paper the use of a linear CCD sensor is assumed and in addition some assumptions were made. The sensor is placed in Y direction, therefore, the projected edge position on the sensor will also be only a function of Y. The X/Y position of the light sources and the X Position of the edge is considered to be known. As it can be clearly seen the projected object’s edges will generate a shadow

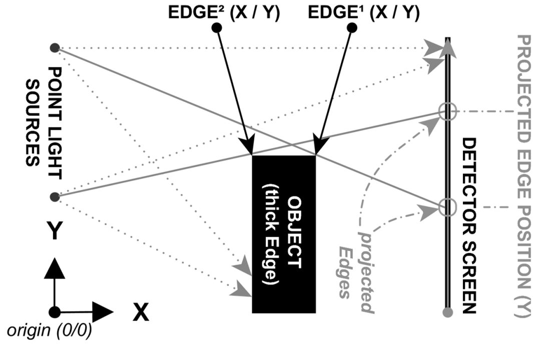

Fig. 1 principle of projecting object’s edges with two light sources

projection, to be more precise, an illumination profile, projected onto the sensor. This shadow projection, which depends on some geometrical parameters of the measurement setup, is also strongly influenced by the used light source type. The shown setup relies on sequential exposure, therefore only one single edge is projected in one step by one single light source. Simultaneous multi-source edge exposure will not be considered in this paper. The projected edge positions are always considered with respect to some reference point (origin) in the measurement area and for the simulations the edge position is always centred in Y direction to the sensor to get comparable results.

For this paper the object’s edge will always be considered as very thin, assuming a straight knife edge. In this case, several methods exist that the X distance does not necessarily has to be known. The X/Y position of this knife edge can be determined by using two light sources (Fig. 2) and triangulation methods [2]. The preciseness of locating the projected edge position (Y) on the light sensitive detector, determines the overall accuracy of this X/Y position estimation. In fact, when LEDs were used, which are no longer narrowband point light sources, finding the exact Y position of the projected edge on the detector screen is the most challenging part, since simple thresholding for finding the projected edge position may not be sufficient any more [3]. The edge projection, the projected illumination profile respectively, along the Y direction on the sensor depends on several parameters,

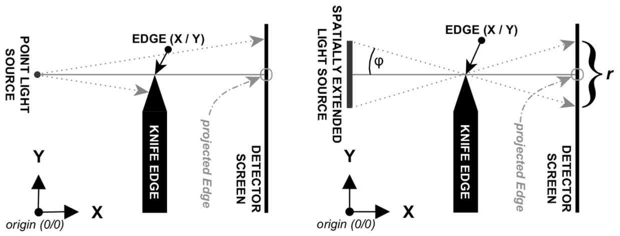

Fig. 2 straight knife edge projection with one point light source (left), and one spatially extended light source (right)

caused by the measurement setup, as well as limitations given by the sensor, like spatial- and amplitude resolution.

Depending on the size of the light emitter, the illumination profile on a detector screen will be very different. If using a narrowband point light source, the edge projection will be more or less sharp, therefore thresholding could be used. Otherwise, if an spatially extended light emitter e.g. a LED is used, the projected edge will be much broader and not really sharp (Fig. 2). This paper will shortly discuss some important system parameters which influence the illumination profile, that is seen by the sensor, the most and show how a diffraction pattern caused by a spatially extended light source could be modelled. This paper will focus on modelling the illumination profile caused by a LED on a CCD sensor as well as determining the projected edge position on the sensor, since the exactness of this position determines the achievable accuracy of a X/Y object position estimation.

II. RELATED RESULTS

As mentioned before, the task of determining the projected edge position accurately is not trivial and there are several aspects to consider when taking a closer look at the illumination profile on the sensor. For different light sources therefore two straight forward theoretical solutions could be obtained.

A. Theoretical knife edge diffraction for point light sources

The evaluation of the Fresnel integrals leads to one possible solution for an infinitely distant placed point light source. Solving Fresnel's equations shown in section IV leads to following observation. The projected edge's position, is only dependent on Y because the sensor is placed in that direction. Therefore, this position on the sensor can be determined by finding the corresponding pixel on the sensor where the exposure reaches 25% of the settled luminosity (Fig. 3). A simple binary search algorithm would easily find the desired pixel index in the entire pixel data in only a few steps. Since this approach is first of all not very robust in terms of unwanted additive noise, and furthermore it is only applicable in a really constrained manner since the distances in the measurement setup (light-source to edge and edge to detector screen) are important. As stated in [4] the size of the light emitting

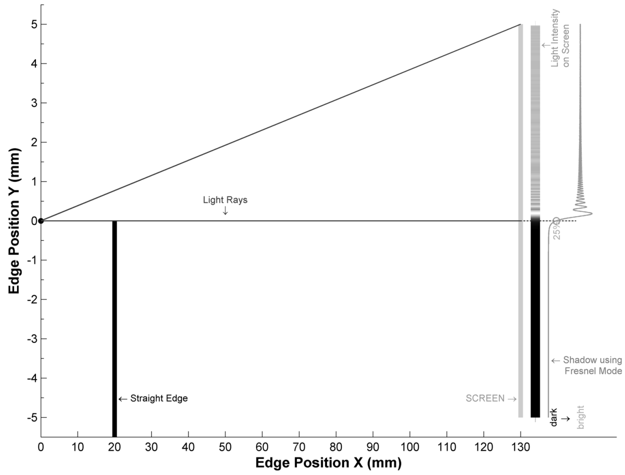

Fig. 3 theoretical illumination profile - shadow projection on a screen caused by a straight knife edge using Fresnel's integrals

area, if it's not dot-like, will play an significant role when trying to find this projected edge position since this straight forward solution is not applicable any more.

B. Theoretical knife edge projection for spatially extended light sources using geometrical models

Simple geometrical models were introduced in [5]. Some methods for determining the exact projected edge position for geometrical models are in detail discussed there. If using surface light emitters such as halogen or fluorescent lamps, simple geometrical models could be used for modelling the lights intensity on the detector screen. It is assumed that the light rays only propagate in a straight line, therefore the lights intensity on the detector rises linearly from dark to bright, only depending on the size of the light emitting area. Often light is not only emitted by one single area because in most cases a reflector is used to utilize the backward spreading light, which could normally not be used (Fig. 4). Most LEDs have some reflecting white housing with the semiconductor chip placed in the middle. The more advanced geometrical solution superimposes the reflected light rays from the white housing and the rays which incide on the screen directly emitted from the LEDs chip (Fig. 5). In section IV (C) this illumination profile is illustrated and described more in detail. This sensor illumination profile depends on several parameters like primary (chip) and secondary (reflector) light source size, measurement distances etc. which were described more in detail in section IV. Finding

Fig. 4 typical LED housing with the LED chip placed in the middle and white, light reflecting material around the chip

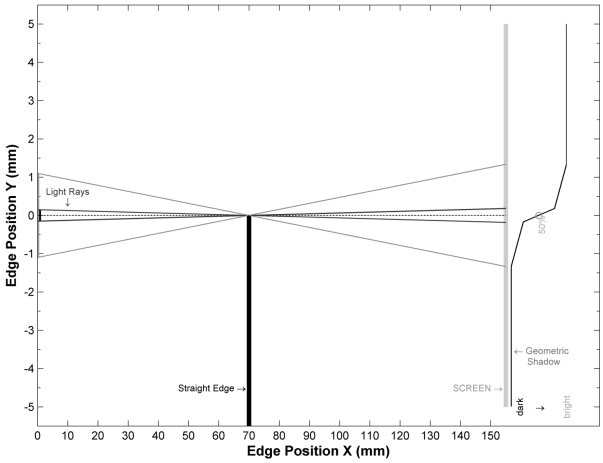

Fig. 6 illumination profile - geometrical shadow projection on a Screen caused by a straight knife edge and superimposed spatially extended light sources, e.g. LED chip with reflector

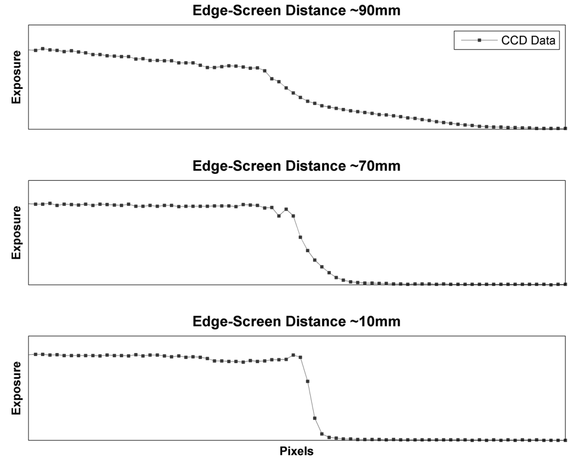

Fig. 5 multiple exposure data (illumination profile) when projecting a straight knife edge onto a CCD sensor with 63.5µm pixel size, using a standard LED

the projected edge's Y position, when assuming this geometrical model, will mean that the projected edge position on the sensor can be determined by finding the corresponding pixel on the sensor where the exposure reaches 50% of maximal luminosity. For that purpose, it is imaginable that without a detailed model knowledge thresholding could be an appropriate method for finding the projected edge position.

The light's intensity on the screen, regarding the sensor's exposure time, plays an important role in many high speed measurement applications. Therefore, high power LEDs may be used for exposure. Only if the light emitter has enough optical power output, the need of additional optical elements for collimating the light beam is obsolete. Most high power LEDs come with a chip size of less than 1mm² but still much bigger than a standard power LED. The light emitting area of a high power LED is, on the one hand far too large to use Fresnel's diffraction model which is only valid for point light sources, and on the other hand way too small to only use a simple geometrical model. To cope with that problem, a new method to model high power LED sized light emitters is introduced in IV C.

III. MEASURED KNIFE EDGE DIFFRACTION WITH SPATIALLY EXTENDED LIGHT SOURCES

As it can be seen in real measurement data (Fig. 6), and also stated in [5], the geometrical solution is suitable for some kind of big light emitters. If the edge is far away from the screen the illumination profile more or less looks like expected with a simple geometrical solution. When the edge is near to the sensor like in our measurement setup, and the light emitter is LED-like sized, some interesting observations can be made. When the edge moves towards the screen it seems that diffraction effects play a significant role. This behaviour is discussed in section IV-C in more detail. What can also be seen in Fig. 6 that the small hump at 70mm edge-sensor distance, completely disappears when moving towards the sensor (10mm distance). This can be explained by the integrating behaviour of the CCD sensor pixel. Since for this measurements, a sensor with 63.5 µm pixel size was used, the small hump disappears when its width shrinks below the size of one single pixel.

IV. DESCRIPTION OF THE USED METHODS

In this section follows the mathematical description of the proposed methods, which were used in before. Additionally, a new modelling approach for high power LEDs called enhanced knife edge projection for spatially extended light sources is going to be introduced.

A. Theoretical knife edge diffraction for point light sources

The theoretical intensity on the sensor for a single wavelength, which means a really narrowband point light

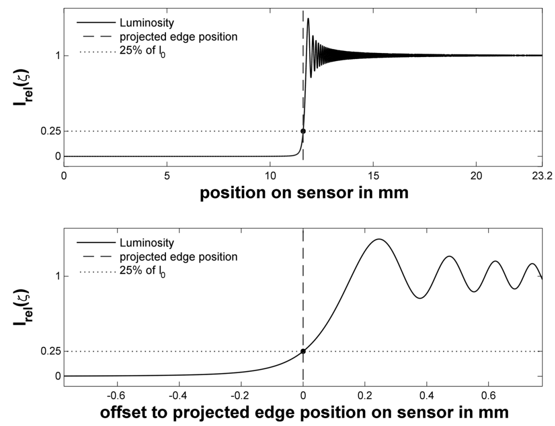

Fig. 7 simulation of a diffraction pattern generated by an infinitely distant point light source and a sharp edge, whole sensor exposure (top) and extract of the edge's projection detail (bot)

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

$$\zeta = \sqrt{\frac{k}{2 \cdot x}} \cdot y, \; y_{sensor,i} = \pm (i \cdot \alpha) \quad (2)$$

source, can be calculated by using the known solutions of Fresnel Integrals for an opaque half plane [6], which is the edge in our case (1-2).

As it can be obtained by equation (1) (where C(ζ) is the Fresnel cosine integral and S(ζ) the Fresnel sine integral), the theoretical intensity at any arbitrary point y on the sensor can be determined unambiguously (k is the wavenumber, x the distance from the edge to the screen, and y the position in Y direction on the sensor). This enables us to determine the light intensity, the exposure value given by the sensor respectively, for every single pixel of the sensor. For the calculation it is proposed that the measurement setup is made in a way, that Fresnel's solutions were accurate enough. This means the wave fronts incide towards the edge in a planar way and furthermore the sensor does not have to be too distant from the exposed edge, since then Fresnel's solutions are then not valid any more. Also if the light source has a broader spectrum the solution will not be accurate. If all boundary conditions were satisfied by the measurement setup, the relative luminosity of each sensor pixel could be approximated using equations (1-2), where *i* is symmetrical to the projected edge position (e.g. ranging from -10 to 10). Thereof also follows the relative intensity of 25% of I_0 at the projected edge's position on the sensor (Fig. 7), since C(0) and S(0) were zero.

B. Theoretical knife edge projection for spatially extended light sources using geometrical models

For geometrical projections the use of simple trigonometric methods is suitable (3). The size of the projected shadow (*r*), to be more precise, the width of the exposure value rising linearly from 0 to full intensity can be modelled for each spatially extended light source separately. Then the Intensity for each pixel can be calculated by linear interpolation in between the boundaries given by the projected edge position (*pe*) and *r*. All other pixels would have a relative Intensity of 0 or 1.

$$\varphi = -\tan^{-1}\left(\frac{[y_{source} - y_{edge}]}{x_{edge}} \right) \quad (3)$$

$$r = x_{sensor} \cdot \tan(\varphi) \cdot 2 \quad (4)$$

$$I_{rel} = \left[0,..,0, \text{interpol.}\left(\left[pe - \frac{r}{2} .. pe \frac{r}{2} \right], 0, 1 \right), 1, .., 1 \right] \quad (5)$$

Therefore, this shadow width, called *r*, only depends on the distances light-emitter to edge and edge to screen as well as the size of the area where the light is emitted from. With the idea, proposed in section II B two different sized light

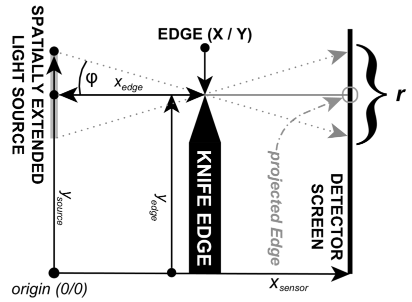

Fig. 8 setup for a spatially extended light source, the shadow width r depends on the y and x distances of the source and the edge

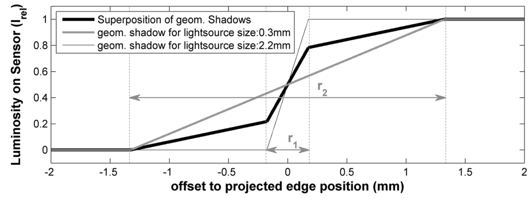

Fig. 9 geometrical shadow projections of two different sized, spatially extended light sources and the superimposed geometrical shadow projection (xsensor:155mm, xedge:70mm)

source sizes ($y_{source1,2}$) could be modelled, to consider the LED chip itself and some integrated reflector. By superimposing the intensity of this two sources at each pixel an intensity distribution on the sensor, like it is shown in Fig. 9, can be achieved.

C. Enhanced knife edge projection for spatially extended light sources combining theoretical knife edge diffraction for point light sources and geometrical models

Both presented methods, theoretical knife edge diffraction for point light sources and spatially extended light sources using geometrical models are not sufficient for a spatially extended light source (see real measurement data shown in Fig. 6). The idea was to combine both methods in a way that the effects on seen on the CCD sensor, caused by a spatially extended light source like a LED, could be somehow described. It can be envisaged,

$$I_{rel} = \left[0,..,0, \text{interpol.}\left(\left[pe - \frac{r}{2} .. pe \frac{r}{2} \right], 0, 1 \right), 1, .., 1 \right] \quad (5)$$

$$I_{rel,i} = I_{rel}(\zeta) * \text{box}(1, r_i) \quad (6)$$

$$I_{rel\text{-}sensor} = \sum_i m_i \cdot I_{rel,i} \quad (7)$$

$$\text{with} \sum_i m_i = 1 \quad (8)$$

that for each point of the spatially extended light source, where light is emitted, a point light source could be modelled, which in fact generates a diffraction pattern.

Therefore, for an arbitrary number of point like sources, placed on the light emitting area of the spatially extended light source, a superimposed diffraction pattern is projected on the Detector. Moreover, when taking a closer look at Fig. 8, it is obvious that instead of modelling a various number of point light sources on the emitter side, the single projected diffraction pattern caused by one single point light source will only appear shifted in its y position as often, as many sources were modelled, in between the given boundaries by r. To give a handier example we now consider all distances X and light source sizes to be known, using equations (3-5). This delivers the width r, in between its limits the so-called shifted diffraction pattern will occur. Since it is proposed that the pattern is always the same, but only shifted by a number of pixels, calculating the diffraction pattern only once is sufficient and then convoluting the pattern with a rectangular shaped box filter with its width of r. This operation does the superimposing of a shifted pattern inherently. For the areas near the boundaries, given by r this assumption will produce an error, but the computation is much more simple. As mentioned before, several light source sizes (see Fig. 5), e.g. due to reflections on the LED housing, could be modelled resulting in different shadow widths, filter lengths r_i, respectively (5-6). Since the reflected light might have not the same intensity as the light which is inciding the sensor directly, i times different factors m should be considered (8). The result is a superimposed luminosity pattern on the sensor (7), which does not necessarily look the same as the Fresnel's solution for only a single light source would suggest.

V. NOVELTIES IN THE PAPER

Since most high precision measurement devices use laser diodes and optical elements for creating collimated light beams [2], the approach with spatially extended light sources seems really new. In [4] it was shown that it is possible to use LEDs instead of laser diodes, since the chip size of standard power LEDs is small enough that the use of Fresnel's solutions deliver good results. The problem with the use of standard power LEDs is, that this will result in long exposure times of a CCD sensor. Since the measured object's edge should not move during a single exposure, it is necessary for many applications to keep the exposure time as short as possible. Only high power LEDs with appropriate chip size will achieve this requirement. As shown in Fig. 6, some suitable high power LED will cause CCD exposure data which is not necessarily similar to the diffraction pattern given by Fresnel's solutions. Because in most cases standard LEDs were used, they could be modelled as point light sources. Since this assumption does not hold for high power LEDs this paper proposes a novel approach for modelling and understanding the effects caused by spatially extended light sources like high power LEDs, which can be recorded by a light sensitive Detector.

VI. RESULTS

The enhanced knife edge projection model leads to the following solution (Fig. 10). For this simulation setup, the projected edge position is at position 0mm. When considering one standard high power LED, like it was used for our measurement setup in Fig. 6, the chip size is 0.3mm times 0.3mm and the reflector size was 2.2mm in diameter. When considering that the shadow length (r) will be much longer for the bigger sized secondary light source it seems feasible that in Fig. 10 the diffraction pattern completely disappears for that source due to the long box filter. The superposition (using $m_{1,2} = 0.5$) delivers the shown result.

Since the sensor pixel shows some integrating behaviour, all details smaller than the pixel size will mostly disappear. The detail shown in Fig. 6 shows how the small hump, caused due to diffraction effects, suddenly disappears, when moving the edge towards the sensor. This relies on the fact that a diffraction pattern changes its spatial expansion, since the pattern strongly depends on the distance between edge and sensor. Only evaluating Fresnel's solution at one single center point of one pixel will not take any integrating behaviour of a sensor pixel into account. Therefore, this integrating behaviour of the sensor pixel can be taken into account by again applying a box filter with the length of one pixel to the simulated signal $I_{rel\text{-}sensor}$ which can be in advance calculated with any arbitrary resolution using Fresnel's solutions (e.g. 1/10 of the pixel size). Additionally, when tweaking the parameter m for every source a little bit, since the distribution will not be exactly one half for the direct and reflected light rays, the simulated result differs only a bit from the real exposure data, generated by the CCD sensor (Fig. 11). Of course, there are differences in the simulated data, especially when taking a look at the areas when the sensor data is close to zero and 100. There some additional

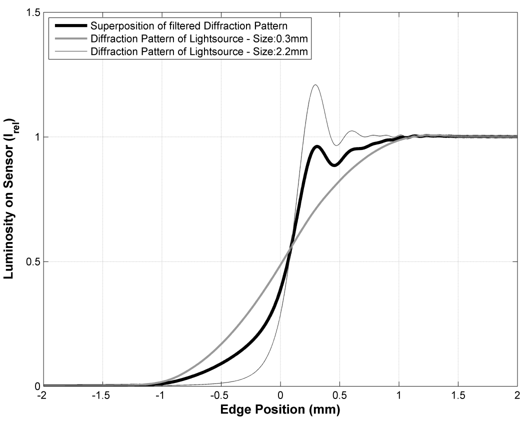

Fig. 10 enhanced knife edge projection for a spatially extended light source (e.g. LED), superimposed shadow projections.

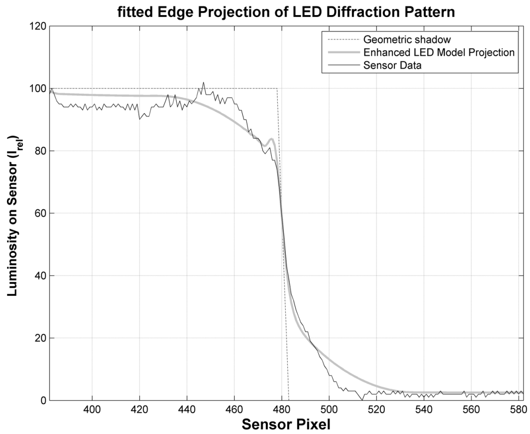

Fig. 11 improved combination of geometrical model and Fresnel's solutions compared with the simple geometric shadow of one single light source and real sensor data

problems occur. The result of the simple convolution is not really valid near the boundaries given by *r*. Also the luminosity distribution of the LED is not really homogenous over the whole sensor length, and maybe more than only one reflecting element should be modelled. It is imaginable that the use of more complex filters, could deliver more accurate results, which should be fit even better than the actual simulation results do. For determining the Y position of the projected edge simple thresholding can be used. A closer look shows that the thresholding level for determining the projected edge position in the overall pixel data is different for every proposed model. As mentioned in the sections before, when Fresnel's solution are suitable, the thresholding level can be set to 25% of I_0. If geometrical solutions satisfy the measurement setup, because the light source might be big, the thresholding level can be set to 50% of I_0. Since the application might use high power LEDs the threshold level will strongly depend on the distance in between edge and sensor as well as the light source size, since it can be seen that the filter length *r* influences the threshold level too. This behaviour can also be seen in Fig. 10, when we only take a look for each single light source without superimposing. The edge is projected in that sample at position 0mm. A long filter (light source size: 2.2mm) will rise the threshold level to near 0.5 times I_{rel}. A short filter (light source size: 0.3mm) will rise the threshold level only around to 0.3 times I_{rel}. The threshold level which should be used to determine the exact position of the projected edge is then given by the superimposed intensity at position 0mm and this level changes when the edge sensor distance is altered. As well, for all proposed methods this distance has to be known. But there are several methods existing for determining this, in most cases, unknown distance. Nevertheless, the combination of both models (geometrical and Fresnel's model) is somehow closer to real measurement data as either model for itself. With some improvement of important parameters this solution can be compared with real measurement data (Fig. 11). Thereof follows that there is a strong dependence of the threshold level used for determining the projected edge position Y, and the X edge position in the measurement area. The proposed model could be used to adapt the threshold level when the X distance of the edge is known.

VII. CONCLUSIONS

It was shown that the simulation results were strongly correlating with real measurement data in a measurement setup with a single LED and CCD Sensor. To achieve these promising solutions only a very simple geometrical model, and in addition, Fresnel's solutions were used for taking diffraction effects into account. The newly introduced approach seems to deliver pretty good results, since the small "hump" as seen in the real measurement data is also produced by the enhanced knife edge projection model for spatially extended light sources. The simulation and real measurements showed that in such a setup with a high power LED, taking only one single threshold level in the whole measurement area for finding the projected edge position, might not deliver accurate results since this level depends on several parameters. To use this method in a practical way for measurement devices, especially the simple box filter in the enhanced knife edge projection model should be adopted. Also some existing methods for determining the, in most cases, unknown distance between edge and sensor can be envisaged. Actual research is ongoing by gathering much more measurement data to also fine tune some parameters.

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