Buletinul Ştiinţific al Universităţii "Politehnica" din Timişoara

Seria ELECTRONICĂ şi TELECOMUNICAŢII
TRANSACTIONS on ELECTRONICS and COMMUNICATIONS

Tom 53(67), Fascicola 2, 2008

Triangulation Based 3D Laser Sensor Accuracy and Calibration

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Abstract – This paper describes properties of 3D laser sensors and the advantages and disadvantages of geometric setup of the camera and the laser source. These parameters are used to calibrate this setup to acquire 3D information with accurate distance measurements. With the described algorithm the three dimensional distance information can be obtained and the information can be merged to get a calibration transformation for future measurements.
Keywords: 3D laser scanning, laser range sensor calibration, 3D visualization

I. INTRODUCTION

Non-contact visual range measurement methods become more and more common because of their speed and efficiency. In industrial they allow us to obtain information about substances which may be hot, chemically aggressive, sticky or sensitive, provided that sufficient light is reflected from the surface. Like described in [1] visual data sources can be separated into active and passive sources. The most common passive data sources for industrial applications are still camera based systems. Cameras provide a 2-dimensional projection of a scene without depth information. With the help of two or more cameras and the known transformation between these cameras distance values can be determined [2]. Other active sensor solutions use defined light patterns which are projected to the scene. Unfortunately many camera based solutions suffers from surrounding lightning conditions and have a lower accuracy [3].
At the current state-of-the-art of industrial data acquisition active visual data sources like non- contact laser range sensors are superior to other industrial measurement methods regarding their accuracy, costs and robustness [3],[4]. Additionally active methods produce dense sampling points compared to passive methods. For active triangulation, the scene is illuminated by a laser source from one direction and viewed by a sensor from the other direction. For machine vision applications it is important to be efficient and robust. This is very important to get 3D information especially for industrial robotic applications. This paper describes influences in 3D laser range measurement setups. We focus on triangulation based setups and introduce an efficient calibration method in this paper, which is already used in different applications. In the first section an introduction to triangulation based distance measurement is made. The influence factors to the sensor accuracy are described in section 2. We focus on the geometric setup and introduce a calibration method to determine the calibration parameters.

A. *Triangulation based distance measurement*

The principle of triangulation bases on very simple geometrical constraints [1]. A triangulation based distance sensor usually consists of a light source and a receiving unit. The laser diode emits a laser beam towards the object and the surface of this object reflects this beam to the camera. If all extrinsic parameters (mainly angle and base distance between camera and laser) are known the distance to the object can be obtained.
Figure 1 shows the setup for a one dimensional distance measurement. The laser beam is reflected from the object to the CCD- Array. With known extrinsic parameters of the setup the distance to the

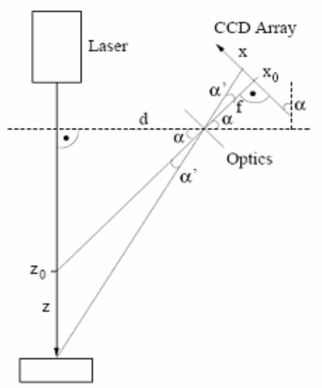

Fig. 1 triangulation principle of laser range sensors [1]

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object z can be calculated with the following equation.

$$z = d \cdot \frac{f \cdot \tan(\alpha) + x}{f - x \cdot \tan(\alpha)} - z_0 \quad (1)$$

The distance between the object and the sensor z mainly depends on the position x where the reflected beam intersects the CCD array. This principle is extended to two dimensions by using a CCD- or CMOS camera instead of an array. The laser beam is split by lens optics to a laser line. So the triangulation principle of 2.5D distance measurement setup is not limited to the distance measurement shown in figure 1. To determine unknown extrinsic parameters the arranged setups must be calibrated. The next section will introduce other possible setups and describe their advantages and disadvantages concerning their accuracy for 3D laser range measurements.

II. ACCURACY INFLUENCE FACTORS

The principle of the triangulation is extended in common laser range measurements using a high-resolution CCD/CMOS camera and a line projecting laser. With this extension a complete height profile of an object can be determined with the help of a camera from the displacement of a laser line. The height information of the object can be calculated from this laser displacement.

To get correct distance values of such a camera system the exact geometric construction, the environment and parameters must be known. So the factors with the greatest influence on the measuring precision and resolution are explained in the following. The accuracy of a triangulation based laser range sensor depends mainly on three factors:

- camera specifications
- laser specifications
- geometric setup

The camera influences the accuracy of the measurement by their resolution and optics. We assume the intrinsic parameters (e.g. focal length, lens distortions, depth of field, chip size) of the camera are known. These parameters can be obtained by camera calibration and manufacture specifications.

The right way of illuminating the objects to measure is also a critical factor for building a vision system that is efficient and robust. For best result it is important to shield out direct sun light and other ambient light from the field of view because many cameras do not use wavelength filters. The camera should provide a good image quality with a high contrast between the features that are interesting for the processing.

The laser light source parameters can not be changed beside of the focus. Most of the laser sources are classified with their output power (100mW and below), their resulting laser beam size and optics. The line optic of industrial lasers is specified by the fan angle/line length at a defined distance. This line sources emit a uniform laser line with a laser line width of a minimum of 0.1mm. This limits the resolution of a full scan in transportation direction.

The most important factor is the geometric setup respectively the distance between laser and receiving unit and the object distance. For large distances to the object the distance between laser and receiving unit must be increased. In turn this leads to a vulnerability of occlusions, therefore triangulation based sensor are commonly used in close range environments up to a few meters.

The camera is located in a certain angle to the laser with view direction to the projected laser line. In general, if the object is flat the laser line in the camera image is smooth. A higher object is depicted in the camera like a step(Fig. 2). The geometric setup is very important therefore this will be explained in detail in the next subsection.

A. Geometric setup

The closer the camera is located to the object, the higher is the measurement accuracy and the resolution respectively. But with a closer distance to the object a high-quality suitable camera lens is needed. This is important for small field-of-views to achieving a good vision measurement with sharp images and low distortion. Considering the geometric setup of the camera and the laser, the camera and the laser should be mounted in that way that the laser illuminates the object from one direction, and the camera views the object from another direction.

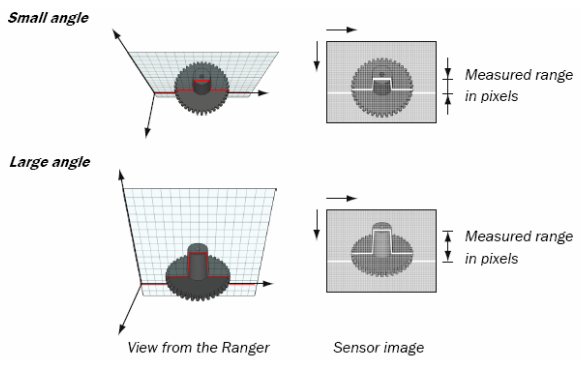

Fig. 2 camera view of different angles [5]

In addition, if the camera looks at the object in a small angle (see Fig. 2), the measurement pixel range is small too. This leads to a lesser height resolution in general. The larger the angle of the camera is, the larger is the measured range in pixels. Smaller angles leads to bad sampling and large angles lead to occlusions. In most cases the angle ranges from 15° to 65° referring to Fig. 4 (reversed ordinary setup).

The geometric setup between laser and camera is the probably most important influence factor on the measuring precision and height resolution of the

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camera system. Mounting the camera and the laser in the right way depends on different requirements and environmental characteristics. At first the object itself influences the setup by its surface features. The types of objects range from transparent, glossy to matt in every color with different shapes. Additionally the type of measurement plays an important role because common distance measurements can be combined with grayscale and scatter measurements. Each measurement requires defined resolutions and region of interests. In order to counter these different types of requirements there are at least four main principles for mounting the camera and the laser according to [5]:

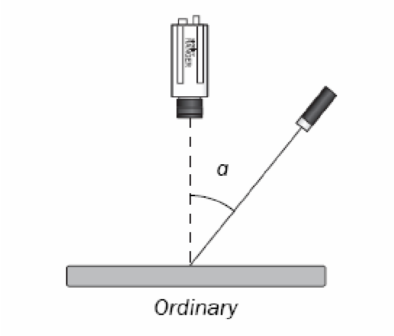

Fig. 3 Ordinary setup [5]

The *ordinary setup* shown in Fig. 3 achieves the maximum height resolution. In this setup the camera is placed over the object perpendicular to the direction of movement and he laser project a laser line from the side. This geometry gives the highest resolution but suffers from miss-register. The laser line in the camera image does move to a different y coordinate, if the distance value changes. This requires a higher computational complexity to reconstruct the distance measurement information.

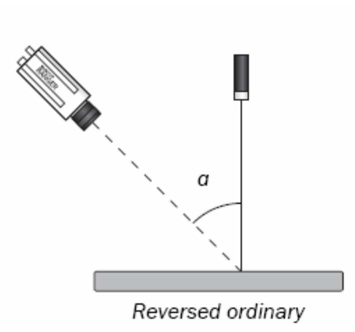

Fig. 4 Reversed ordinary setup [5]

In the *reversed ordinary setup* (Fig. 4) the laser is mounted over the object and the camera is located in the same direction but moved with a certain angle looking at the projected laser line. This measuring set-up has a good height resolution and does not suffer from miss-register, so this setup is the most common one. This setup is similar to the Ordinary setup, but the placement of the laser and the Ranger has been switched.

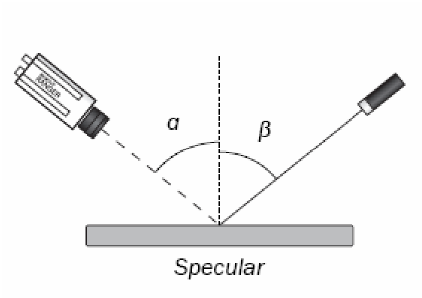

Fig. 5 Specular setup [5]

For the *specular setup* the camera and the laser are mounted on opposite of each other. Through the high intensity of light emitted by the laser the specular setup (Fig. 5) is useful for dark or matte object surfaces. As a disadvantage occlusion areas arise in front of and behind the object. The setup offers a lesser height resolution and is often used for surface analysis applications.

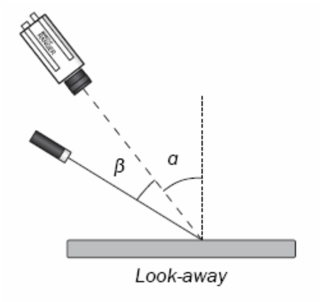

Fig. 6 look away setup [5]

Like the specular setup *the look away setup* is not suitably for range measurement applications. The camera and the lighting are mounted on the same side. A strong light source is needed and also occlusions occur with this setup, but this setup avoids reflections and can be used for surface analysis and inspections.

III. OBJECT SCANNING

We describe in this section how a laser range sensor measures range by using triangulation. This means that the object is illuminated with a laser line from one direction, and the camera is measuring the object from another direction. Each time the camera makes a measurement one profile of the object is recorded and stored. If the object is moved from measurement to measurement the entire object can be scanned. The result of a measurement is a height profile, containing one value for each measured point along an object surface. In most of the applications the object is placed on a conveyor belt and is moved in a linear way. The height profiles of the object are recorded piecewise (Fig 7). After the acquisition these profiles are merged together to a complete 3D model. This process is shown in the Fig. 7 with a reversed ordinary setup.

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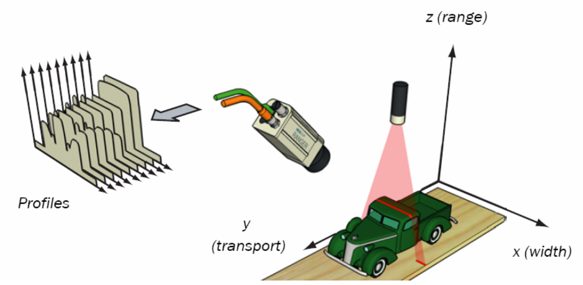

Fig. 7 object scanning with reversed ordinary setup [5]

The result is a collection of profiles, where each profile contains one profile at a certain location along the transportation direction. The term "scan" is here a synonym for a collection of profiles acquired by the camera. The camera sends the profiles to a computer. The computer stores the profiles and processes the profile data for the application.
Here the left-handed coordinate system is placed in such a way that y is the transportation direction (Fig. 7). The speed of transportation is connected to the acquisition speed of the camera. So the accuracy in y depends mainly on the camera shutter speed and the speed of transportation. The camera shutter speed is often controlled by the exposure time parameter. The exposure time can be adjusted for example in the parameter file of the camera. The higher the exposure time is the higher is the total amount of light falling on the image sensor. The total amount of light on the image sensor in the camera is influenced by the focal ratio or f-number which gives information about the focal aperture of the camera. The f-number is the focal length divided by the aperture diameter of the lens of the camera and is a dimensionless quantitative measure of speed. The f-number [6] is the reciprocal value of the relative opening and the relation of the focal length and aperture diameter. The more the lens aperture is open, the higher is the fraction of light is and the brighter is the taken picture. This increases the robustness for the laser line detection but reduces the camera speed. If the scanning process is as slow as possible the minimum of the resolution is limited by the laser line width, so most applications achieve a y-resolution of about 0.1mm. The resolution in x is mainly defined by the camera characteristics respectively the chip resolution and the optics like the distance resolution.
The distance resolution in z depends on the angle between the laser and the camera. If the angle is very small, the location of the laser line does not vary much in the sensor images even if the object varies a lot in height. But if the angle is large, a small variation in height would be enough to move the laser line in the camera image (Fig. 2). But a large angle leads to occlusions. Occlusion occurs when there is no laser line for the camera to detect in the sensor image. This happens in to different ways. The first type of occlusion is the "camera occlusion". This happens when the laser is hidden by the object. A "laser occlusion" occurs when the laser cannot properly illuminate parts of the object(Fig 11). Adjusting the angles of the Ranger and the laser can reduce the effect of occlusions.
To make the best measurement the laser line and the camera lens should be adjusted optimally. In addition to the geometric order of the measurement system the characteristics of the camera play an important role in the analysis of the measuring precision for the x and z coordinates. In order to understand the concept, when a picture gets sharp or blurred, we have to adjust the depth of focus. The depth of focus is described by the optical laws. A lens maps the objects to the chip area in the focal plane (Fig. 8).

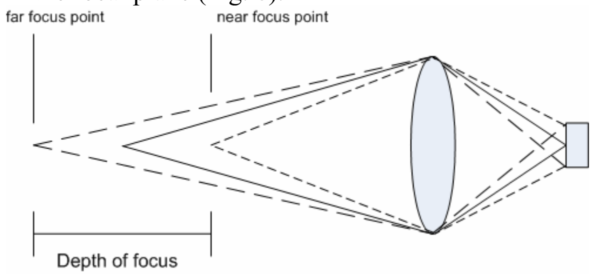

Fig. 8 camera depth of focus

The optimal focus point is more or less a dot-like object. This point between the far and near focus point in Fig. 8 is projected to the image plane behind the lens according to the laws of geometrical optics. If the focal plane is exactly in the intersection point of the three beams (the solid beam in Fig.8), then the object is shown sharply. All other objects outside the optimal depth of focus are consequently blurred points (even the dotted beams Fig. 8). The depth of focus is calculated with the so called circle of confusion which is defined by the maximum diameter for a light emitting point in a scene (see [6], [7]) .The size of the tolerable circle of confusion is given by the pixel size of the camera. Beside this the calculation of depth of focus considers values of object distance, image distance, focal length to fulfill the laws of geometric optics. Because of the fact, that the focal length or lens properties are not known in real setups, the object is placed to the target position in front of the camera and the camera is focused for this setup manually without exact calculation before. The setup is verified by exact calculation of the depth of focus with special software[8] afterwards. Depending on application there is a certain tolerance range for the depth of focus.

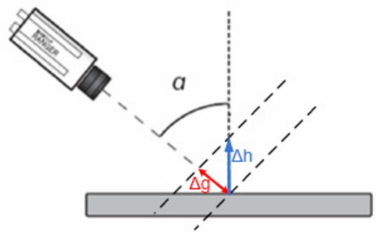

Fig. 9 Depth of focus and height resolution

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For the special purpose of the laser triangulation the depth of focus can be converted to a depth of height (Fig. 9). The laser line is shown sharply on the object surface in this field. For laser triangulation the term of depth of focus can also by applied to the laser source. Depending on the laser beam size and laser line optics the width of laser line is defined at the objects surface. For an optimal setup we assume the laser source is optimally focused for the used distance. With this setup we can measure the distance to the object. To find the parameters to calculate the height of an object we need to know the extrinsic parameters of the setup. These parameters are determined in the calibration process.

IV. CALIBRATION

Like already described the height measurement accuracy depends primarily on the geometric position of the camera. In our calibration we choose a reverse ordinary setup (see Fig. 4). The position of the camera is not fixed for the measurements. The distance and the angle α are variable to ensure the flexibility for many application cases. The angle of the camera is measured from the normal of the transport direction to the axis through the center of the lens. The previous chapters show how the height profile information of the laser line can is acquired from the camera. These values do not contain the actual height of the object but the height of the laser line as a number of pixels. The points along the laser line are given as x coordinate according to Fig. 7. The x axis must have the same direction for the sensor image coordinate systems and the world coordinate system. The location of the point in z (distance to the camera) must be calculated by the brightest pixel in one column of the picture. The location of a point along the transport direction (y coordinate) is represented by the sequence number of the measurements. To get calibrated measurements (e.g. coordinates and heights in millimeters) we have to transform the point information from the sensor coordinate system (row, column, profile number) to world coordinates (x,y,z). This transformation depends on some factors, for example the distance between the camera and the object, the angle between the camera and the laser, and properties of the lens. The task of the calibration process is to find the transformation between these two coordinate systems and is described in this section. The calibration process connects the height profile acquired from the camera with the real size of a reference object. We use an object laying on a conveyor belt like shown in Fig 7. One measurement results in a profile. This original profile is an idealized rectangle (left in Fig. 10) of our rectangular reference object. Depending on the geometric setup the resulting measurement consists of a deformed profile.

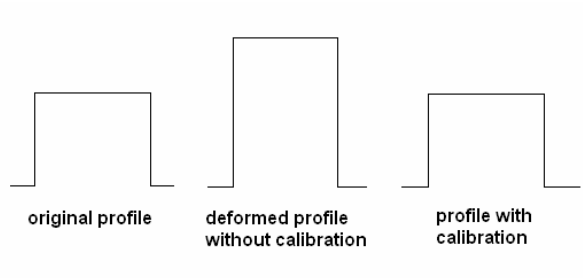

Fig. 10 reference object profiles

The calibration corrects the distortion between the heights and width of the measured profile to the object in its real height and width. The calibration algorithm consists of different steps and have to be done only once for the setup. If the camera has to be moved for any reasons, the calibration measurements must be made again. If an unknown object is scanned with the calibrated setup, the measurement results are multiplied with the scaling factors and the object is represented correctly.

A. Determine the scaling factors

To correct the distortion two scaling factors are calculated. The measurement setup consists of a rectangular object laying on a conveyor belt like shown in Fig. 7. The calibration process [9] consists of the following steps:

- The reference object is put in the camera field of view and the image is acquired
- The profile of the laser line is extracted
- The scaling factors are calculated

The calibration method bases on a rectangular calibrating object, with known height and width.

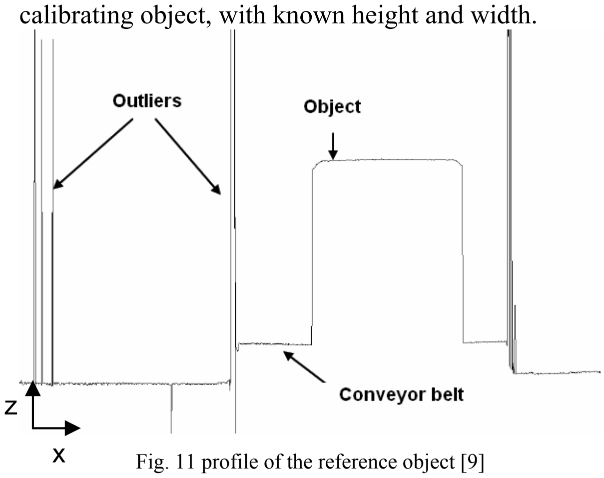

Fig. 11 profile of the reference object [9]

After the image is acquired the height profile is extracted. Therefore the maximal brightness value for each column in the image is selected. The profile is the array of the x position with the maximum grayscale level in every column. We have to filter this signal to be able determine the object size robustly. The original measurement signal also contains some outliers. These outliers lead to wrong edge detections because of their high gradients. These outliers occur in the recognition process of the laser line. In some cases the algorithm can not determine the right value

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in the column because the laser line is hidden from the camera view, so a completely wrong height value will be determined because of other reflections. If the minimum brightness threshold of the laser line is not reached, the x value in this y column is set to the maximum value which is shown in Fig. 11. The derivation values of these outliers are possibly higher than the derivation values of the edges. For this reason a measurement filter which filters the outliers from the signal is necessary. A median filter is a very good non-linear digital filter for extreme outliers and is often used in signal and image processing. A window is used to select *n* values from the signal. The values in the window are sorted into numerical order. The number of window values is always odd, so the center value (median value) of the window is selected as the resulting output value. The edge of our rectangle signal is not smoothed the median is an edge-preserving filter. Another advantage of the median filter over averaging filters lies in his nonlinearity. The height of the outlier does not have any influence on the result value. A 10 times greater value of the outlier provides the same result as one with 1000 times greater value. We implement a median filter in the calibration with a window size of 17 values. With this window size we can avoid outliers up to eight pixels without consequences for the measuring. This leads to a smoothed measurement signal of the reference rectangle shown in Fig 10.

To be able to determine the object width the edges of the rectangle must be detected and then their distance must be calculated in the first step. The signal is treated as a mathematical function. The high height difference at the edge of the rectangle can be determined with a derivation. The gradients at the edges are very high so the edge can be determined by the derivation of the signal and applying a threshold for the minimum and maximum gradients.

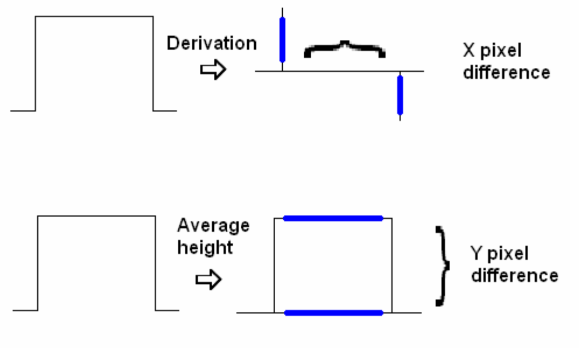

Fig. 12 edge detection in height profile

After the edges of the measurement signal are known, the object height is determined. We average the signal between the two detected object edges. To avoid possible rounded corners or signal delays, we reject a fixed number of pixels at the boundaries of the mean average value section between the edges. The result is the absolute height of the laser line between the two object boundaries. For the determination of the object height the lower object boundary still must be detected. The reference object is removed from the view of the camera so that the laser beam is projected on the bottom of the conveyor belt. The height value of the same measurement section is determined in the same way and the height of the bottom of the conveyor belt is measured. After this the calibration factors can be determined as follows:

$$X_{Calcib} = \frac{object\ width\ (in\ mm)}{number\ of\ pixels\ (X)} \quad (2)$$

$$Y_{Calcib} = \frac{object\ height\ (in\ mm)}{number\ of\ pixels\ (Y)} \quad (3)$$

The calibration factor defines the width and height of a pixel to the corresponding millimeter units. By multiplication with the calibration factors the camera distortion disappears and the object profile can are reprocessed true to scale independently of the camera position.

V. CONCLUSION

We described the role of the geometric setup of triangulation based laser range sensor and their effect on the resulting accuracy. With this background we introduced an efficient and simple calibration method. The preprocessing of the measurements as well as the calibration of the camera helps to resume a correct model of the scanned object in the computer. We counter occlusions by an efficient median signal filter and described a simple calibration for the laser range sensor setup. Additional cameras with further signal processing for grayscale measurement can be combined with laser line acquisition to improve the outlier detection. With a minimum of computational cost we are able to include this calibration in 3D laser range acquisition systems, which are used in several fields of research or industrial systems.

ACKNOWLEDGEMENTS

This work was supported by the company VMT (Pepperl+Fuchs Group). The authors would like to thank M. Otesteanu, K. Wilding and P. Peternek for their support.

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