A concept for the simultaneous orientation of brightness and range images

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ABSTRACT: Within the scope of a common evaluation of brightness and range images, this article introduces a new area based approach to achieve the simultaneous orientation of both data types. The actual innovation is the combined least-squares adjustment. The adjustment is an extension of object space image matching with ranges as additional observations. The complete mathematic model is specified and discussed. For a representation of complex object surfaces, the simultaneous consideration of multiple surface patches is described. It is shown, that this concept is a generalization of the known methods for brightness and range image orientation, including approaches using area based and feature based primitives.

1 INTRODUCTION

Documentation of building facades is useful in a variety of applications such as architecture, cultural heritage, virtual reality and urban planning. Currently, the standard technique for data capture is terrestrial photogrammetry. Since several years terrestrial laser scanning is gaining importance. These techniques provide brightness images and range images of the facade. Range images directly deliver geometric information of the viewed object scene and brightness images the texture. Due to their different potential these data complement each other and also include redundant information. For instance, on the one hand the brightness images give visual information of the object scene and on the other hand indirect geometric information, i.e. through stereoscopy and image matching. Image matching is an ill-posed problem and needs good approximate values of the unknowns, which can be provided by a laser scanner. Hence, the fusion of both data types significantly increases the potential of optical measurement techniques. The orientation of the images is a prerequisite for any task involving the transformation between the different sensor data and is the focus of this paper.

For the orientation of range images taken from different positions corresponding entities have to be determined in the two data sets, and then correspondences between these entities must be established, e. g. by minimizing the Euclidean distances between them. Usually, the minimization is carried out within a least-squares rigid body transformation. For this task several approaches have been developed. One of the most famous approaches is the iterative closed point (ICP) algorithm introduced by Besl & Mc Kay (1992). The algorithm directly works with point clouds in object space. Because of the discrete handling of the object surface, the accuracy of the image orientation depends on the point density of the cloud.

Modifications of this algorithm were developed for multiple point cloud orientation and for increasing the accuracy and reliability of the results. One extension of this approach with regard to the surface description is given by Grün & Akca (2004). There, the discrete point cloud is represented as a patch-wise surface function. Neugebauer (1997) shows how to directly use range images to solve the orientation problem. The surface is implicitly specified in the range image as a function of the observed ranges; for an overview of further approaches concerning range data orientation see e. g. Grün & Akca (2004).

A general overview of the orientation of brightness images is given by Heipke (1997). In the context of this paper only object based image matching algorithms are relevant. These algorithms are published in detail in the literature, see e.g. by Heipke (1990), Schneider (1991) and Weisensee (1992). The functional model includes the sensor parameters, the image orientation and the parameter of the surface function. Kempa (1995) demonstrates the estimation of the image orientation beside the surface reconstruction.

One of the weaknesses of the listed approaches is the use of one single data source only. By combining brightness and range images an improvement in the evaluation can be achieved. Especially fixed relative orientations between imaging and range sensors are helpful.

In the next section, we describe the potential of brightness and range images. Limitations and advantages are briefly discussed. The main part of the paper contains an introduction of a new orientation concept combining brightness and range images in a single least-squares adjustment. The functional model of brightness and range values including the image orientation and surface parameters is described. The chosen unknowns within the adjustment are discussed, and the observation equations are given. The paper concludes with some remarks on the proposed concept. The approach proposed in this paper is presented on a theoretical basis only, the paper does not address applications examples, nor does it deal with the generation of initial values for the unknowns of the non-linear adjustment.

2 SENSOR AND IMAGE DATA

2.1 *Camera and brightness image*

Brightness images are delivered by photographic cameras and contain radiometric information of the object scene. Cameras are passive measurement systems. Light, emitted by an external source and reflected on the object surface, is received and registered by the camera sensor. For the orientation of brightness images geometric information of a surface element is needed. If this information is unknown, it has to be estimated within the orientation process. Therefore, the surface element has to be observed from at least two positions. Also sufficient structure in the radiometric signal is necessary. By including multiple images in the orientation process redundancy is produced and therefore the accuracy and reliability of the results is increased.

2.2 *Laser scanner and range image*

Range images are delivered by airborne and terrestrial laser scanners. Each picture element represents a triple of polar coordinates. The ranges are measured by recording the travel time of pulses from the sensor to the object surface and back. Limitations of the data acquisition occur in occluded areas, and for objects with no reflection or no reflection towards the receiver. Because of the relatively high acquisition time, a laser scanner generally can not be used as a hand-held system.

2.3 *Hybrid sensor*

Since the existence of laser scanners the combination of the scanning device with a camera sensor has been an attractive task. The goal is to provide simultaneously range data and brightness information of the object surface with identical viewing direction. The camera can either be integrated into the scanning device or mounted on top. For achieving correspondence between the sensors the eccentricity parameters have to be determined by system calibration.

This kind of sensor technology is developed to obtain directly coloured point clouds. Additionally, automatic orthophoto generation is possible. Since the relation between the radiometric image and the point cloud is given, differential rectification is feasible. The relative orientation between the sensors is usually considered as constant.

3 THE NEW ORIENTATION CONCEPT

In this section a new approach for the simultaneous orientation of brightness and range images is introduced. It is a general approach to orientate multiple images of multiple sensors with and without known relative orientation. The orientation concept is based on the combination of object based image matching and the exploitation of range images. The innovation is that the irradiances of the brightness image and the ranges are combined in a least-squares adjustment.

3.1 *The functional model*

For the model description the definition of the coordinate systems, the orientation of the individual sensors in object space, the transformation between sensor space and object space and the definition of the object surface must be introduced, see fig. 1.

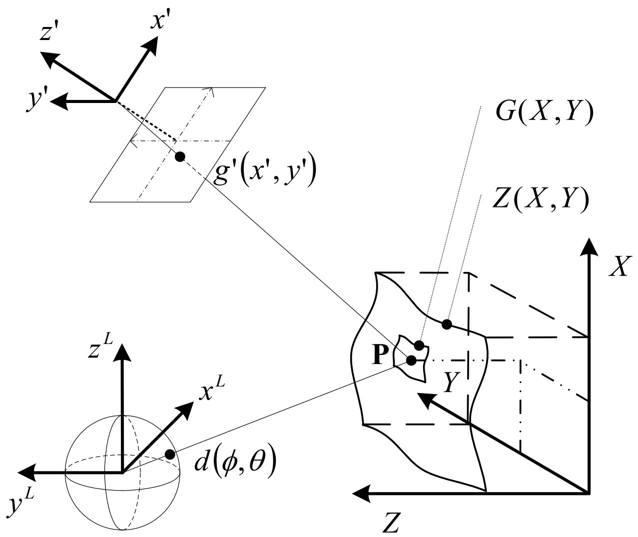

Fig. 1: Parameters of the functional model

In sensor space of the brightness image the coordinate system $[x', y', z']$ is defined with the origin in the projection centre. Concerning the range image the sensor system $[x^L, y^L, z^L]$ is defined in the centre of the terrestrial laser scanner. The object surface $Z(X,Y)$ is given in the object space coordinate system $[X, Y, Z]$. The exterior orientation of the sensor referring to the object space is given by $O^C(\mathbf{T}^C, \mathbf{R}^C)$ and $O^L(\mathbf{T}^L, \mathbf{R}^L)$. The parameters of the orientation consists of three translations $\mathbf{T}(t_X, t_Y, t_Z)$ and three rotations around the X,Y and Z axis, respectively, captured in the rotation matrix $\mathbf{R}(r_{11}, r_{12}, \dots, r_{33})$.

The relation of a brightness value $g'(x', y')$ to the corresponding grey value $G(X,Y)$ of a surface element (X,Y) in object space is outlined in fig. 1. The brightness is a function of the image coordinates. The image coordinates depend on the object coordinates and the image orientation through the collinearity equations.

$$g'(x', y') = G(X,Y) \tag{1}$$

with:

$$x' = -c \frac{r_{11}^C\left(X - t_X^C\right) + r_{21}^C\left(Y - t_Y^C\right) + r_{31}^C\left(Z(X,Y) - t_Z^C\right)}{r_{13}^C\left(X - t_X^C\right) + r_{23}^C\left(Y - t_Y^C\right) + r_{33}^C\left(Z(X,Y) - t_Z^C\right)} \tag{2}$$

$$y' = -c \frac{r_{12}^C\left(X - t_X^C\right) + r_{22}^C\left(Y - t_Y^C\right) + r_{32}^C\left(Z(X,Y) - t_Z^C\right)}{r_{13}^C\left(X - t_X^C\right) + r_{23}^C\left(Y - t_Y^C\right) + r_{33}^C\left(Z(X,Y) - t_Z^C\right)} \tag{3}$$

The range values of the laser scanner are expressed as distances d in a direction (ϕ,θ) relative to the $[x^L, y^L, z^L]$ system. ϕ is the horizontal angle between the x-axis and the direction of d, θ is the corresponding vertical angle. The observed range d is identical to the distance s between the observed surface point and the origin of the laser scanner:

$$d(\phi,\theta)=s \tag{4}$$

with

$$\phi=\arctan\left(\frac{y^L}{x^L}\right) \tag{5}$$

$$\theta=\arctan\left(\frac{\sqrt{(x^L)^2+(y^L)^2}}{z^L}\right) \tag{6}$$

$$s=\sqrt{(X-t_X^L)^2+(Y-t_Y^L)^2+(Z(X,Y)-t_Z^L)^2} \tag{7}$$

For the relation of a range value $d(\phi,\theta)$ to the surface function in object space, the transformation between the range image sensor system and object space system is necessary:

$$\begin{pmatrix} x^L \\ y^L \\ z^L \end{pmatrix}=\left(\mathbf{R}^L\right)^T\begin{pmatrix} X-t_X^L \\ Y-t_Y^L \\ Z(X,Y)-t_Z^L \end{pmatrix} \tag{8}$$

The eccentricity between the camera and the laser scanner coordinate system is given by:

$$\mathbf{e}=\mathbf{T}^C-\mathbf{T}^L \tag{9}$$

$$\mathbf{R}_C^L=\mathbf{R}^L\left(\mathbf{R}^C\right)^{-1}=\mathbf{R}^L\left(\mathbf{R}^C\right)^T \tag{10}$$

with $\mathbf{e}$ = eccentricity vector between the perspective centers of the camera and laser scanner; $\mathbf{R}_C^L$ = rotation matrix between the two coordinate systems. For hybrid sensors $\mathbf{e}$ and $\mathbf{R}_C^L$ may be known from a calibration step.

3.2 *Simultaneous consideration of multiple surface patches*

The introduced surface function parameterization of the previous chapter is not sufficient for the description of complex object surfaces. Thus, a more general parameterization is necessary. In this new orientation concept multiple surface patches are introduced, as it is shown in fig. 2. Each patch represents a part of the surface with its own surface function described in a local coordinate system $[X^{S_i}, Y^{S_i}, Z^{S_i}]$; with $i=1,\dots,n$. These patches are located in areas of geometric surface variation or good texture. The size of each patch can be chosen individually.

Unless given otherwise, the object coordinate system $[X, Y, Z]$ is defined through the first patch, and the orientations of the other patches with respect to the first one are described by the values $O^{S_i}(\mathbf{T}^{S_i}, \mathbf{R}^{S_i})$, which are known if the whole object surface is assumed to be given.

For instance, the transformation of the point $\mathbf{V}^{S_2}$ of the second surface patch coordinate system $[X^{S_2}, Y^{S_2}, Z^{S_2}]$ into the object space coordinate system is:

$$\begin{pmatrix} X_V \\ Y_V \\ Z_V \end{pmatrix}=\mathbf{t}^{S_2}+\mathbf{R}^{S_2}\begin{pmatrix} X_V^{S_2} \\ Y_V^{S_2} \\ Z_V^{S_2} \end{pmatrix} \tag{11}$$

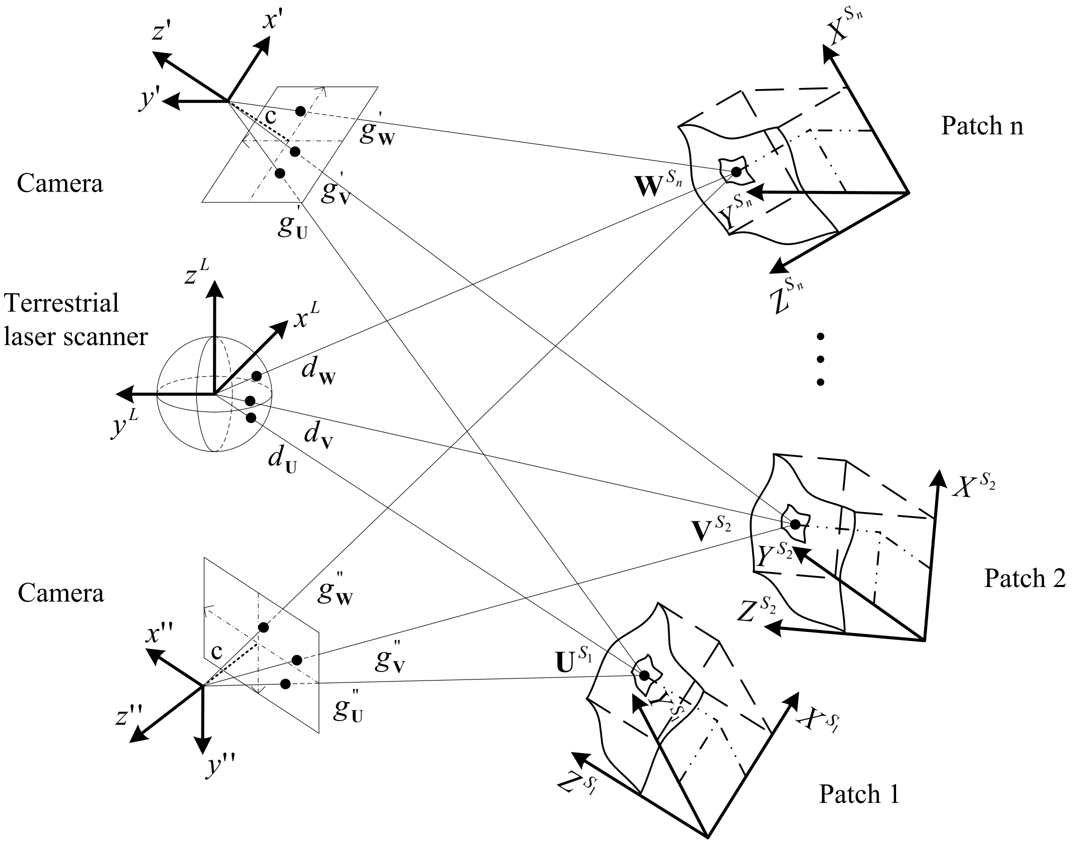

Fig. 2: Simultaneous use of multiple surface patches

3.3 *Adjustment approach*

In the following the object surface function is assumed to be known and the image orientations, as well as the grey values of the surface elements are considered as unknowns. The resulting non-linear observation equations read:

$$v_C = \hat{G}(X,Y) - g'\left(x'\left(\hat{O}^C\right), y'\left(\hat{O}^C\right)\right) \tag{12}$$

$$v_L = s\left(\hat{O}^L\right) - d\left(\phi\left(x^L\left(\hat{O}^L\right), y^L\left(\hat{O}^L\right)\right), \theta\left(x^L\left(\hat{O}^L\right), y^L\left(\hat{O}^L\right), z^L\left(\hat{O}^L\right)\right)\right) \tag{13}$$

with v_C, v_L = residuals of the adjustment.

Equations (12) and (13) have to be linearized with respect to the unknowns:

$$v_C = f\left(x_0\right) - \sum_{i=1}^{6} \frac{\partial g'}{\partial x'} \frac{\partial x'}{\partial O_i^C} d_{O_i^C} - \sum_{i=1}^{6} \frac{\partial g'}{\partial y'} \frac{\partial y'}{\partial O_i^C} d_{O_i^C} \tag{14}$$

$$\begin{aligned} v_L = f\left(x_0\right) + \sum_{i=1}^{3} \frac{\partial s}{\partial O_i^L} d_{O_i^L} - \sum_{i=1}^{6} \frac{\partial d}{\partial \phi} \left(\frac{\partial \phi}{\partial x^L} \frac{\partial x^L}{\partial O_i^L} + \frac{\partial \phi}{\partial y^L} \frac{\partial y^L}{\partial O_i^L} \right) d_{O_i^L} - \\ \sum_{i=1}^{6} \frac{\partial d}{\partial \theta} \left(\frac{\partial \theta}{\partial x^L} \frac{\partial x^L}{\partial O_i^L} + \frac{\partial \theta}{\partial y^L} \frac{\partial y^L}{\partial O_i^L} + \frac{\partial \theta}{\partial z^L} \frac{\partial z^L}{\partial O_i^L} \right) d_{O_i^L} \end{aligned} \tag{15}$$

with $f\left(x_0\right)$ = function of initial values for the unknowns.

The adjustment is then solved iteratively using the standard formulae. In case of known eccentricities of a hybrid sensor data set, the exterior orientation of the brightness images is replaced by the orientations of the laser scanner using equations (9) and (10).

4 DISCUSSION

This paper introduced a concept for the simultaneous orientation of brightness and range images. It is based on given approaches of area based image matching and range image exploitation. This concept represents a generalization of the individual orientation approaches. The observations correspond directly to the surface elements. The success of the orientation depends on the structure of the object surface in geometry and radiometry. The two types of data complement each other and it is sufficient, that only one of them provides adequate information at a given position on the object surface.

As a further generalization, the integration of corresponding features like discrete points is also possible. In this case, the image coordinates of the brightness and range images are considered as observations, and the brightness values are essentially used to localize the features. Furthermore, the registered intensity values of the laser scanner can be considered as additional observations in this simultaneous approach.

The next step of our work will be an investigation of the distribution of observations, respectively surface patches in object space. Also, the generation of approximate values, like the image orientation parameters, must be dealt with. Further, a strategy is necessary to determine the datum of the surface patch coordinate systems, if they are not given. Currently, we are busy implementing the described approach. First evaluations with synthetic data will be presented in the near future.

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