New developments in Multimedia Photogrammetry

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Abstract:

Applications of photogrammetry, where the beam from an object to the sensor passes several optical media with different refractive indices, are called multimedia photogrammetry. This presentation describes a fast and versatile algorithm for the strict geometric modelling in multimedia photogrammetry, which can easily be implemented as a module into spatial resections, intersections or bundle solutions. The solution is restricted to the standard case of multimedia photogrammetry, where the object is situated in a liquid, the sensor is positioned in air, and a plane-parallel glass plate divides these two media. In combination with the choice of a suitable local coordinate system, this environment can be modelled very efficiently and the computational effort connected with the twice-broken beam can be reduced significantly. A further strong reduction of the computational effort has been achieved by downloading the geometric effects of the multimedia environment into a two-dimensional lookup-table and thus avoiding time consuming iterative solutions.

Integrated into a bundle adjustment program with self calibration, the refractive index of the liquid (or even of the refractive indices of the liquid and the glass plate) can also be introduced as an unknown and determined simultaneously. In practical tests the refractive index of a medium could be determined with a standard deviation of 0.15 $^{0}/_{00}$, which is better than the accuracy of most commercial refractometers.

1. Introduction

Problems of multimedia photogrammetry have been addressed by a number of authors in the past. Rinner (1948) addressed the relative orientation underwater imagery on stereo plotters and introduced the term 'two-media-photogrammetry'. Höhle (1971) and Okamoto/Höhle (1972) showed an analytic solution and performed the step from two-media to multimedia photogrammetry by replacing the straight lines of the central perspective model by polygons; their solution was implemented for the two-media case on an analytical plotter by Konecny/Masry (1970). An overview on theory and technique of multimedia photogrammetry has been given by Wrobel (1975). Kotowski (1988) developed an algorithm for ray tracing through an arbitrary number of parametrized interfaces, which was implemented into a bundle program. A number of publications report applications, e.g. in cartography (mapping in shallow water, Elfick/Fryer, 1984), archaeology (surveying of ship wrecks, Höhle, 1971), industry (survey in nuclear power plants, Przybilla et al., 1988) and fishing (measuring the shape of fishing nets, Zwart, 1987). Fryer and Fraser (1986) deal with the calibration of underwater cameras.

The geometric influence of waves on aerial imagery through the surface of shallow water has been treated by Okamoto (1982); this influence, which is very difficult to be modelled exactly, can be avoided in most close range photogrammetry applications by imaging through a glass window.

A disadvantage of many strict solutions presented in the past is the increased computational effort connected with the geometric complexity of multimedia environments; most algorithms require iterations, multiplying the computational effort. When coordinates of millions of objects have to be determined (e.g. in 3-D particle tracking velocimetry, Maas, 1992), this issue becomes important. For that reason a simplified (but nevertheless strict) solution will be shown in the following, which can be downloaded into a two-dimensional lookup-table and is thus computationally very efficient. The solution is restricted to the 'standard case' of multimedia photogrammetry (three media: object in liquid, sensor in air, and a plan-parallel transparent plate dividing the other two media); it is based on Snell's Law and can be considered a module in the collinearity equation, which allows for a simple implementation in spatial resections, intersections or bundle solutions.

2. Multimedia module

The multimedia module computes a radial shift of each object point relative to the nadir point of the respective camera (figure 1), which can be used as a correction term in the collinearity equation. If the X-Y plane of the coordinate system is chosen parallel with the plane interface glass/liquid (or with the air/glass interface), a relatively simple model becomes possible. The procedure is shown in figure 1: If the point $P(X, Y, Z)$ in object space is shifted to $\bar{P}(\bar{X}, \bar{Y}, Z)$, the collinearity condition can be applied for P using the object coordinates of the shifted point $\bar{P}$. Only a radial shift by ΔR ($\Delta R > 0$ if $n_2 > n_1$ and $n_3 > n_1$) parallel to the X-Y plane has to be computed for each point relative to the nadir point of each camera. Thus, rays from different cameras C_j to an object point P are calculated with straight beams from different virtual object points $\bar{P}_j$ with the broken beams still intersecting in P.

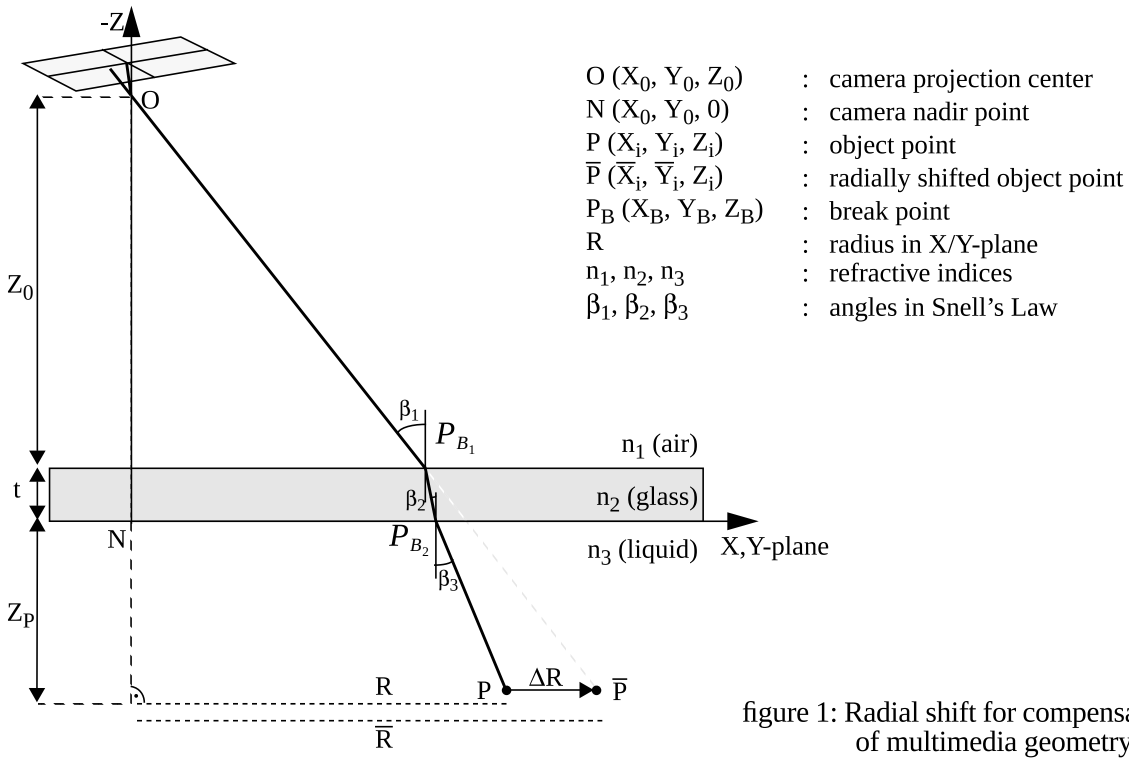

figure 1: Radial shift for compensation of multimedia geometry

From figure 1 can be derived:

$$Z_0 \cdot \tan\beta_1 + t \cdot \tan\beta_2 + Z_p \cdot \tan\beta_3 = R \qquad \overline{R} = (Z_0 + t + Z_p) \cdot \tan\beta_1 . \tag{1}$$

With Snell's Law

$$n_1 \cdot \sin\beta_1 = n_2 \cdot \sin\beta_2 = n_3 \cdot \sin\beta_3 \tag{2}$$

the system describing the multimedia geometry is complete. Equations (1), (2) can only be solved iteratively due to the trigonometric functions. If P is chosen as a first approximation for $\overline{P}$ and

$$\overline{R}_{(0)} = \sqrt{(X_P - X_0)^2 + (Y_P - Y_0)^2} \quad , \tag{3}$$

the angle of incidence in the medium n_1 in the first iteration becomes

$$\beta_1 = \operatorname{atan}\left(\frac{\overline{R}_{(0)}}{Z_0 + t + Z_p}\right) . \tag{4}$$

From Snell's Law one gets the angles of incidence and refraction in the other two media:

$$\beta_2 = \operatorname{asin}\left(\frac{n_1}{n_2} \cdot \sin\beta_1\right) \quad , \qquad \beta_3 = \operatorname{asin}\left(\frac{n_1}{n_3} \cdot \sin\beta_1\right) \tag{5}$$

and the correction for $R_{(0)}$:

$$dR = R - (Z_0 \cdot \tan\beta_1 + t \cdot \tan\beta_2 + Z_p \cdot \tan\beta_3) \quad . \tag{6}$$

The equations (3) - (6) are used iteratively

$$\bar{R}_{(1)} = \bar{R}_{(0)} + dR \qquad => \beta_1, \beta_2, \beta_3 \qquad => dR \qquad \text{etc.}$$

until $dR < \varepsilon$ (e.g. with the iteration criterium $\varepsilon = 0.001$ mm).

Transforming back from polar coordinates to the cartesian system, one obtains the coordinates of the radially shifted point $\bar{P}$

$$\bar{X}_P = X_0 + (X_P - X_0) \cdot \frac{\bar{R}}{R} \quad , \quad \bar{Y}_p = Y_0 + (Y_P - Y_0) \cdot \frac{\bar{R}}{R} \quad , \quad \bar{Z}_P = Z_P \, . \tag{7}$$

The collinearity condition for cameras C_j can then be used with the radially shifted point $\bar{P}_j$ ($\bar{X}$, $\bar{Y}$, Z) instead of P (X, Y, Z).

This model can also be deducted from Kotowski's model under the foregoing simplifications. A similar model has been presented by Philips (1981), who vividly uses the term 'apparent places' known from astronomical geodesy. Also Kludas and Thomas (1990) use a similar procedure for their implementation of a three-media module in an analytical plotter; however, they circumvent the time consuming iterations by an approximate solution.

3. Multimedia Lookup-Table

The convergence of the iterative scheme of equations (3) - (6) can be accelerated considerably by introducing an overcompensation-factor ($ocf \approx 1.1 \ldots 1.8$) for the calculation of ΔR. The choice of *ocf*, however, depends on the refractive indices, the ratio of the path lengths in liquid and air and on the incidence angle itself, so that a constant *ocf* can only represent an average state. A consequent extension of this idea is the implementation of the radial shift into a lookup-table. Due to the restriction to the standard case of multimedia photogrammetry (which covers more than 90% of the applications in close range photogrammetry) and the choice of the local coordinate system, the input parameters for this lookup table are only the depth coordinate Z_i of an object point in the liquid and the radial distance R of the object point from the nadir point. The output of the lookup-table is the radial displacement factor $\bar{R}$/R. If the lookup-table is initialized sufficiently dense, a linear interpolation will yield results which can be considered a strict model. The computational effort necessary for the initialization of these two-dimensional lookup-tables (one per camera station) will be compensated by the reduced processing time in the determination of mass points, where the only additional operations with respect to the one-media case are an interpolation in the multimedia lookup-table and one multiplication per measured image point.

4. Simultaneous determination of the refractive index

As an additional option, the multimedia bundle allows for the introduction of the refractive index of the liquid as an unknown to be determined simultaneously. This can become necessary when coordinates of an object in a liquid with unknown refractive index have to be determined. The option can also be used as a tool for the analysis of a liquid itself. The refractive index of water, for instance, depends significantly on temperature and salinity, so that the multimedia bundle can be used for indirectly estimating these parameters.

In a practical test imaging a calibration field inside a fluid cell (figure 2), the refractive index of the fluid could be determined with a standard deviation of 0.00015, which is better than the accuracy of most commercial refractometers (Kliem/Streck, 1977). This allows for example for the determination of the salinity of water with a standard deviation of ~0.05%.

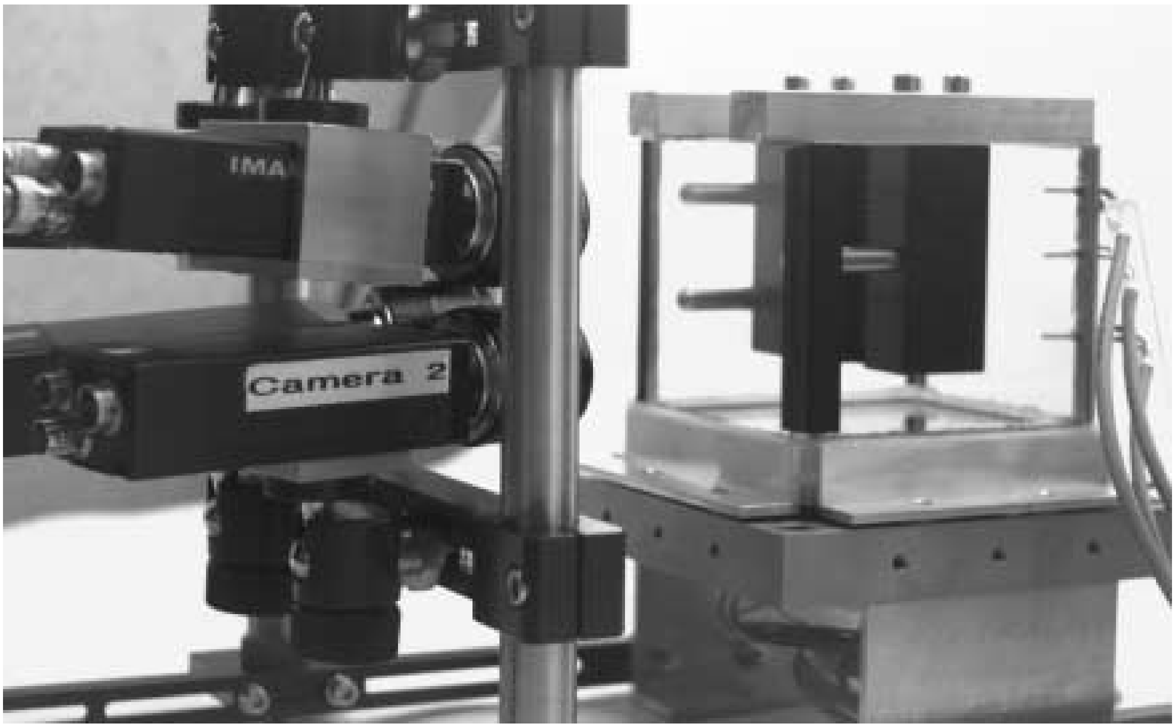

figure 2: experimental setup the examination of Marangoni convection

5. Further influences of the multimedia environment

Besides these exactly modelled effects the multimedia environment causes some problems which are not contained in the mathematical model but do have a non-negligible influence on the accuracy of results:

- Inhomogenities of the refractive index (due to local temperature differences, salinity etc.) cause deviations from the strict mathematical model, which can often not be modelled. When fluids of different refractive index are mixing, one will have to intersect almost inpredictably bent beams rather than twice broken beams, and even the visibility can be limited.
- Deviations from the planeness of the glass walls falsify the incidence angles. This point will be the major source of error in many applications.
- The network geometry is deteriorated by the smaller intersection angle of rays due to the fact that rays are broken towards the optically denser medium. This causes larger errors in the depth coordinates.
- Diffusion and absorption in liquid cause an extinction of light and reduce the image

contrast.

- The dispersion e.g. in water is much larger than in air. The variance of the refractive index in water over the visible spectrum of light is 1.4% in contrast to 0.008% in air (Hoehle, 1971). This leads to colour seams at the edges of imaged objects which will appear as blur in black-and-white images. Moreover, special care has to be taken when using lightsources with different spectral characteristics in one application.

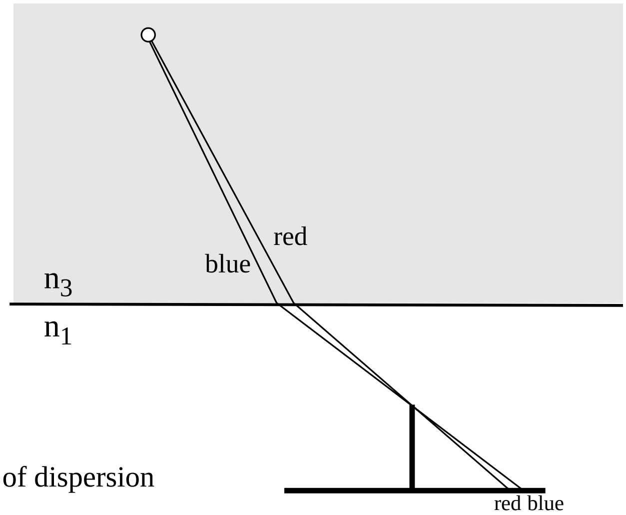

figure 3: effect of dispersion

- The diffraction is not rotationally symmetric when a convergent camera arrangement is chosen in multimedia photogrammetry (Meid, 1991).
- The optical system (liquid - glass - air - camera lens) passed by each ray is not corrected for aberrations if lenses are corrected for the use in air. This leads to a degradation of image quality, especially as the cameras are arranged convergently.

All these effects cause a degradation of image quality of multimedia images and systematic errors that are only partly contained in the mathematical model of multimedia bundle adjustment with self calibration. This fact will necessarily lead to larger errors in the coordinate determination of underwater objects as compared to applications in air. Depending on the quality of the transparent medium separating liquid and air, the homogeneity of the refractive index and the depth of an object in water, σ_0 of multimedia bundle adjustment computations was between 0.47 and 1.2 micron in practical applications using CCIR-norm CCD camera equipment, rather than 0.25 ... 0.35 micron in applications in air.

6. References

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