A 3-DIMENSIONAL CAMERA CALIBRATION ALGORITHM FOR UNDERWATER MOTION ANALYSIS WITH REFRACTION CORRECTION CAPABILITY

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INTRODUCTION

The DLT (Direct Linear Transformation) algorithm, the most frequently used calibration algorithm, is based on the so-called collinearity condition; i.e. the object, image, and projection center form a straight line. This condition, however, does not hold in an underwater analysis setting due to the nonlinear image deformation caused by refraction at the water-air interface (Figure 1) [1]. The immediate outcome of the image deformation is an increased calibration/reconstruction error when compared to its above-water counterpart.

Reconstruction accuracy can be improved to a certain extent by maintaining large interface-object distance and/or camera-interface distance [1], by using localized sub-volumes (localized DLT) [2], or by manipulating the characteristics of the calibration frame [1]. Although these methods are useful, the ultimate solution is to use a calibration algorithm that has the refraction correction capability. The purposes of this study are (a) to develop a calibration algorithm that allows refraction correction, and (b) to test its applicability through a simulation.

METHODS

A comprehensive refraction model was developed with 12 experimental factors incorporated (Figure 1): position and orientation of the calibration frame with respect to the interface plane (6), camera position and orientation with respect to the interface plane (3), and the internal factors of the camera (3). Due to the complexity imposed by the nonlinear refraction equation, no simple direct solution is available and a special optimization strategy must be developed.

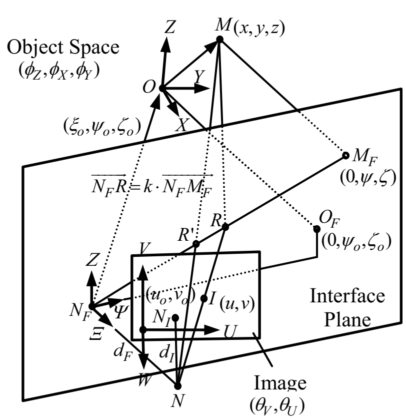

Figure 1. Refraction Model with 12 Experimental Factors

The new method proposed in this study is mainly based on the collinearity among the refraction point (R in Figure 1; not the object), image point (I), and the projection center (N). The coordinates of the refraction point were described as a fraction of the coordinates of point M_F by a ratio k (Figure 1). Although k is a high-order function of the position and angle factors, it was considered as a constant in the cost function for simplicity. As a result, the interface-to-calibration-frame distance was optimized separately from the others since this factor is involved only in the computation of ratio k. All other factors are present in the cost function and can be computed through an iterative approach using the Newton method. The interface-frame distance was optimized based on the calibration error. A converged set of experimental factors were obtained for every level of interface-to-frame distance. The distance that shows the smallest calibration error was selected as the optimal interface-frame distance.

A simulation was performed to assess the performance of the new algorithm. A 3 m x 1 m x 1m calibration frame with 56 control points was used. An arbitrary set of experimental condition was used (interface-frame distance = 4.0 m, camera-interface distance = 0.8 m, etc.) to generate the image coordinates of the control points. A series of calibrations were performed based on the real-life coordinates and the simulated image coordinates.

RESULTS AND DISCUSSION

Only 7 distance and internal camera factors were subject to optimization in this paper. Calibrations were repeated with various initial values. In all cases the distance and camera factors fell within 2 cm of the actual values used in the simulation. In terms of calibration error, the new algorithm outperformed the DLT algorithm considerably. Moreover, the calibration error showed a quadratic pattern with the minimum value coming from the optimized interface-frame distance. The calibration error increased when random errors were introduced to both the real-life coordinates and the image coordinates. However, the algorithm consistently generated stable (converged) solutions.

CONCLUSIONS

The new algorithm was deemed applicable in the underwater analysis. Due to its refraction correction capability, the algorithm will be useful especially in situations with poor experimental conditions, such as short camera-interface distance and interface-frame distance. Distortion correction also means considerably less extrapolation error outside the control volume.

REFERENCES

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