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Optical 3D Motion Measurement

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***Abstract* - This paper presents a CCD-camera based system for high-speed and accurate measurement of the three-dimensional movement of reflective targets. These targets are attached to the moving object under study. The system has been developed at TU Delft and consists of specialized hardware for real-time multi-camera image processing at 100 frames/s and software for data acquisition, 3D reconstruction and target tracking. An easy-to-use and flexible but accurate calibration method is employed to calibrate the camera setup.**

Applications of the system are found in a wide variety of areas; biomechanical motion analysis for research, rehabilitation, sports and ergonomics, motion capture for computer animation and virtual reality, and motion analysis of technical constructions like wind turbines.

After a more detailed discussion of the image processing aspects of the system the paper will focus on image modeling and parameter estimation for the purpose of camera calibration and 3D reconstruction. A new calibration method that has recently been developed specifically for the measurement of wind turbine blade movements will be presented. Test measurements show that with a proper calibration of the system a precision of 1:3000 relative to the field of view dimensions can be achieved. Future developments will further improve this result.

INTRODUCTION

In many areas of scientific measurement it is necessary to acquire information about the three-dimensional movement of one or more objects under study. When these objects are human beings we are dealing with biomechanical motion analysis which is a field where optical analysis of human movement has become a commonly used tool. The system that is discussed in this paper, PRIMAS -an acronym for Precision Motion Analysis System-, was originally developed for the purpose of this human movement analysis [1]. Recently however, there have been other applications beyond this scope. New application areas are real-time motion capture for 3D computer animation and virtual reality, and measurement of technical objects. Vibration and deformation analysis of full-scale wind turbine blades during real operation are a recent example of the latter type of applications.

In the following we will discuss the current implementation of the PRIMAS hardware and software as well as the modifications that are required to enable the measurement of wind turbine movements. Limitations related to the large dimensions of the measurement volume are the most important reason for these modifications.

HARDWARE

The PRIMAS system consists of dedicated hardware in a separate housing, which supports up to six CCD-cameras that operate pixelsynchronously at a frame rate of 100 Hz. The effective resolution of the CCDs is 288 lines by 604 pixels per line (non-interlaced). Each camera is equipped with an illuminator ring around the lens consisting of IR-LEDs that emit stroboscopic light with a short flash duration of 250 μs to prevent image blur in fast movements. The cameras use an electronic shutter with 250 μs exposure time and an infrared filter to reduce the influence of background light. By using spherical or disc-shaped retro-reflective targets or *markers* that reflect the infra-red light back into the camera lens a high-contrast image is obtained with bright marker images against a dark background. These markers are attached to the object under study at relevant landmarks.

In the hardware an adjustable threshold level is used to convert the analog grey-value image to a binary black-and-white image from which the marker image contour pixels are detected. At the correct setting of the threshold value there are only round or elliptic marker images visible without background disturbance. The contour pixel coordinates are subsequently used to calculate the midpoint $(x\ y)^T$ of each marker image with a 'centre of gravity' method:

$$x = \alpha_x \cdot \frac{\sum_i (x_i - \frac{1}{2} dx_i) \cdot dx_i}{\sum_i dx_i} \qquad (1)$$
$$y = \alpha_y \cdot \frac{\sum_i y_i \cdot dx_i}{\sum_i dx_i}$$

with x_i, y_i: pixel position of the trailing edge of a marker image on video line *i*;
dx_i: number of pixels between leading and trailing edge on video line *i*;
α_x, α_y: scaling factors to fit the result in a 15-bit integer number.

These calculations are performed in real-time by a firmware program that runs on an on-board processor. Finally the marker image coordinates are transported to a host PC through a high-speed serial interface cable and ISA-board. The resulting precision of the marker midpoints depends on the size of the image and is typically in the order of 0.1 pixel [2], [3]. When all six cameras are used, the maximum number of markers per camera that can be detected is about 30.

Data acquisition and system control are provided by a computer program that runs on the host PC. This program allows real-time graphical feedback of the captured data and in a calibrated setup with a limited number of markers real-time 3D reconstruction is possible. The recorded data are either stored on disk or -in real-time applications- output to a second computer.

MATHEMATICAL IMAGE MODEL

The marker image coordinates are modeled as images from the midpoints of the markers in space with coordinates $\mathbf{X} = (X\ Y\ Z)^T$ in the *reference coordinate system*. These marker coordinates can be expressed in a camera-related coordinate system with coordinates $\mathbf{X}_c = (X_c\ Y_c\ Z_c)^T$ by a rotation-translation transformation:

$$\mathbf{X}_c = \mathbf{M}^T (\mathbf{X} - \mathbf{X}_{cr}) \qquad (2)$$

where $\mathbf{M}$ is a [3×3] rotation matrix defining the camera orientation with respect to the reference coordinate system and $\mathbf{X}_{cr}$ is the position of the camera's projection centre.

Assuming forward central projection, the image coordinates $\mathbf{x} = (x\ y)^T$ of a point with position $\mathbf{X}_c$ in the camera coordinate system are given by:

$$x = x_0 - c_x \frac{X_c}{Z_c} + c_x \Delta_x$$
$$y = y_0 - c_y \frac{Y_c}{Z_c} + c_y \Delta_y \qquad (3)$$

where $(x_0\ y_0)^T$ is the position of the principal point;
c_x, c_y are scaled camera constants, and
Δ_x and Δ_y are lens distortion factors.

Equation (3) is the collinearity equation which is well-known in photogrammetry. It is the analytical model that is employed in parameter estimation procedures for calibration of the camera setup and 3D reconstruction of the marker positions.

CALIBRATION

Calibration is considered to be the estimation of the camera-dependent parameters that are present in the model (3). A full set of calibration parameters must be known for each camera to make 3D reconstruction possible. There are six *exterior* parameters ($\mathbf{X}_{cr}$ and three angles in $\mathbf{M}$) that change whenever the camera is moved and four *interior* parameters (x_0, y_0, c_x, c_y) in the model. Additionally there are parameters that describe the lens distortion, which are also counted as interior parameters. A sufficient lens correction model usually employs two radial symmetric polynomial coefficients, which leads to two more interior parameters to be estimated. Generally the interior camera parameters will only change when lens settings like focus and iris and modified.

The standard calibration method for PRIMAS [4], [5], [6] employs a planar calibration object with 48 markers at accurately known positions in a rectangular grid. This object is recorded in three or more different arbitrary positions and orientations by the cameras in the setup. The image coordinates of the markers on the calibration object now provide the information about the camera parameters. Apart from the camera parameters also the six orientation parameters of the calibration object relative to a reference position need to be estimated as 'nuisance parameters'.

Using the symbols θ for the parameter vector and $\mathbf{X}_p$ for the known marker coordinates on the calibration object, (3) can now be written as a function of these vectors:

$$\mathbf{x} = f(\mathbf{X}_p; \theta) \qquad (4)$$

Starting from an initial estimate provided by a linear approximation the parameters are refined with iterative corrections Δ_θ which are calculated with the Gauss-Newton method [7] from:

$$\left(\frac{\partial \mathbf{f}(\mathbf{X}_p;\theta)}{\partial \theta}\right)\Delta_\theta = \left(\mathbf{x}-\mathbf{f}(\mathbf{X}_p;\theta)\right) \tag{5}$$

Householder transformations are employed to transform the Jacobian matrix in (5) to upper triangular form, followed by backsubstitution to solve Δ_θ. Specific use is made of the sparse structure of the Jacobian to speed up computations and reduce memory requirements. The RMS residual error after convergence is typically about 0.1 pixel in x- and 0.07 pixel in y-direction.

3D RECONSTRUCTION

Once the calibration parameters are known, the 3D positions of unknown markers can be reconstructed from observed image coordinates of the same marker from at least two cameras. A linear least squares technique called the DLT (Direct Linear Transformation) [8] can be employed by re-writing (3) with DLT-parameters L_i which are calculated from the calibration parameters:

$$\begin{aligned} x - c_x\Delta_x &= \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \\ y - c_y\Delta_y &= \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \end{aligned} \tag{6}$$

By multiplying both sides of (6) with the denominator a linear matrix equation $\mathbf{A}_i\mathbf{X} = \mathbf{b}_i$ can be derived. Matrices $\mathbf{A}_i$ and vectors $\mathbf{b}_i$ from different cameras i are then combined into one equation $\mathbf{A}\mathbf{X} = \mathbf{b}$ to provide an overdetermined system. The estimator $\hat{\mathbf{X}}$ of $\mathbf{X}$ is now given by:

$$\hat{\mathbf{X}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} \tag{7}$$

The reconstruction precision that is achieved with this method depends on the precision of the image coordinates and on the number and arrangement of cameras. Typically this precision is 1:3000 RMS or better relative to the height of the measurement volume.

WIND TURBINE MEASUREMENTS

The PRIMAS system and software for calibration and 3D reconstruction as described above have been applied in a pilot project on the measurement of rotor blade deformation and vibrations in full-scale wind turbines [9]. This project was carried out in cooperation with G.P. Corten from the Netherlands Energy Research Foundation (ECN). The turbine that was subject of these measurements is the OARRF (Open Air Rotor Research Facility) of the IvW (Institute for Windenergy) of the TU Delft.

The advantage over conventional measurement techniques like the use of strain gauges and accelerometers is that optical measurement is contactless and non-invasive on the blades. Only the markers need to be attached like a sticker that does not influence the flow of air around the blades. For this project a total number of 9 markers with a diameter of 22 cm was used: 8 on the blades and 1 on the tower. This was expected to suffice for measurement of first and second order harmonics of blade vibrations in two directions. Torsion of the blades was not measured.

This project was unprecedented because of the large measurement volume in an outdoors application in contrast with previous applications indoors in a limited capture space. The diameter of the wind turbine under investigation was 10 m, the rotor axis was at 15 m above the ground. Two cameras were used at a distance of 20 m from the rotor with a mutual distance of 13 m as shown schematically in figure 1.

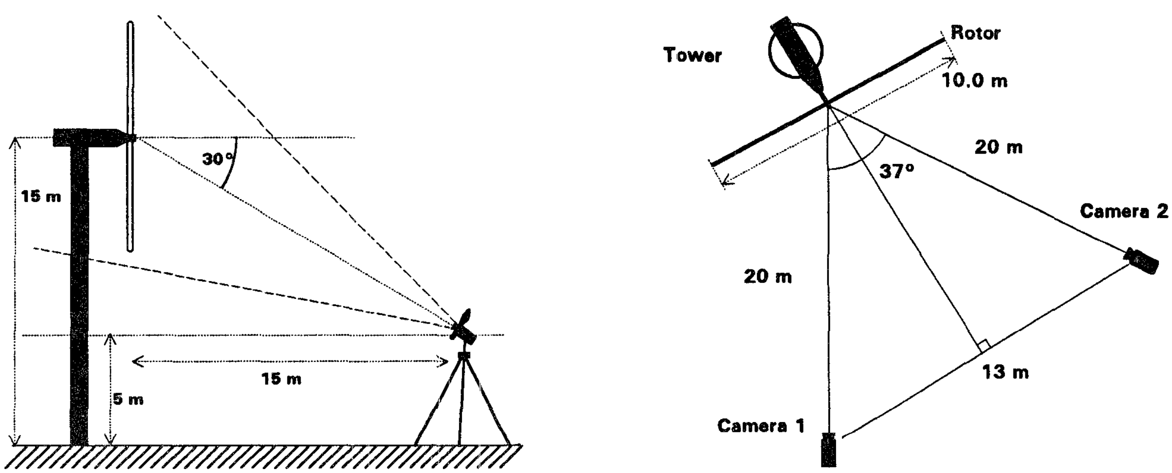

Figure 1 Schematic side view (left) and top view (right) of wind turbine and camera setup.

These conditions required an adapted illumination of the scene because of the long distance between cameras and markers and the relatively strong ambient light; high power (200 W) visible light stroboscopes had to be used instead of the infra-red LEDs. An additional advantage of the stroboscopes was the shorter flash duration of only 20 μs.

The unusual capture space also required a different calibration method; the calibration object was far too small for the standard method to be used. The markers on the turbine were used for calibration instead. A calibration data set was obtained by recording the turning rotor while turning the nacelle consecutively clockwise and anti-clockwise to obtain a 3D distribution of marker positions.

Although it is possible to calibrate the exterior camera parameters with independent unknown marker positions while the interior parameters are known from a preceding standard calibration [10], this method did not yield good results with the recorded calibration data set. Therefore the constant distance between the markers on the blades must be exploited as a priori knowledge. For this purpose a new calibration algorithm was designed.

The new algorithm is set up as a general calibration method that uses m_s markers on a stick with at least one known distance between the markers. The position of marker n on the stick, $\mathbf{X}_n$, is now parameterized by the position $\mathbf{X}_1$ of the first marker and two angles ϕ and ξ. The distance between markers 1 and n, D_{1n}, is either known or taken along as an extra parameter:

$$\mathbf{X}_n = \mathbf{X}_1 + D_{1n}\begin{pmatrix} \cos\phi \sin\xi \\ \sin\phi \sin\xi \\ \cos\xi \end{pmatrix} \tag{8}$$

with $\phi \in [0, 2\pi\rangle$, $\xi \in [0, \pi\rangle$ and $2 \leq n \leq m_s$.

By letting one camera (the *reference camera*) define the reference coordinate system, so that for this camera $\mathbf{X}_c \equiv \mathbf{X}$, only the exterior parameters of the other camera need to be estimated. The *stick parameters* $\mathbf{X}_1$, ϕ and ξ are estimated along as 'nuisance parameters'. By combining (8) with (2) and (3) the model is derived from which these parameters have to be estimated. Similar to the standard calibration method, the Gauss-Newton procedure is employed as the non-linear parameter estimation method, departing from an initial estimate that is determined manually.

RESULTS AND DISCUSSION

The 3D reconstruction results that were obtained with the parameters from the new calibration method were similar to those of the standard method; an RMS error of 3.5 mm on individual rotor marker positions was found, relative to the rotor diameter of 10 m. This agrees well with the 1:3000 precision mentioned earlier.

From the 3D marker positions angular displacements of the rotor blades relative to their zero-load trajectory were calculated. Details of this calculation and detailed results are not presented here but interested readers are referred to [9]. For movements perpendicular to the rotor plane (flap) a standard deviation of 0.1° has been found; for tangential movements within the rotor plane (lead/lag) this value was 0.06°.

From these results it is concluded that the system and the modified calibration software are a promising new tool for the analysis of rotor blade movements in large wind turbines. They offer a good prospect on successful application of PRIMAS to even larger commercial size wind turbines which often have a diameter of 40 m or more.

Future hardware developments will even improve upon the given precision results by providing more accurate marker image coordinates. The introduction of high-resolution CCD cameras and grey-level weighted midpoint calculation for PRIMAS are foreseen developments to achieve this improvement.

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