Object orientation measurement system without zero drift

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Abstract. The need for zero drift and accurate object pose estimation is very common in today’s industry. Implementing optical measurement system allows to overcome certain problems, that are inherent to inertial navigation systems (INS). These problems include size and weight of high accuracy systems of the type and zero drift, low dynamic range. Method, described in this article is based on the fiducial markers recognition. The markers were located on investigated object, their positions were estimated on four images, captured by four digital cameras, connected to the PC. The Results, obtained by four cameras, were processed by developed algorithm, allowing to conduct pose estimation with an accuracy of 0.2 degrees in 3 degrees of freedom.

1. Introduction

The need for high accuracy object pose estimation is very common in automation and robotic industry. Systems, capable of determining an object pose, can be divided into several groups, according to the fundamental measurement technique: ultrasonic, radio, magnetic, optical and inertial systems.

Ultrasonic (and acoustic systems in general) and radio location systems are based on the determination of a signal propagation time [1-2]. Signal, emitted by one or number of emitters, is received, and based on signal propagation delay object is located or it’s pose is estimated. Major disadvantage of these methods is low accuracy of marker position estimation. Widely known ultrasonic location methods in addition require alignment of the receivers and emitters within their radiation patterns, which can not be guaranteed in all object orientations. Optical and inertial systems are the most perspective for the task.

Inertial navigation and orientation systems include usually three accelerometers, gyroscopes and magnetometer [3-4]. The main disadvantage of these systems is gyroscope zero drift and accelerometer temperature dependence, these uncertainties can reach several degrees and increase with time, so INS can not be used in high accuracy tests that last for substantial amount of time.

Optical pose estimation methods are well known and can be divided into few categories: laser based scanning methods [5], time-of-flight methods, and photogrammetric methods. Laser and LIDAR based systems are quite complicated and require complicated processing. Time-of-flight cameras are rare and expensive.

Photogrammetric systems are based on object pose estimation through visual image processing. Fiducial marker capturing approach can be used in the case. With this approach the object pose can be estimated with high accuracy.
The object pose estimation principle based on object known points projection on the image plane was proposed in [6]. The main goal was to find correspondence between the coordinates of certain points of the object in real world and their projections on the camera image plane. This correspondence then can be approximated by transformation matrix with some error. Transformation matrix is determined during the calibration procedure, when the pictures of the object with known geometry (chessboard target) are taken and points with known coordinates in real world (squares intersection) are detected on captured images. Estimated parameters include intrinsic matrix, that contain focal lengths of the lens and principal point coordinates, distortion matrix, and extrinsic matrix, which determine object position in camera coordinate system.

In this work ArUco markers were used [7] (figure 1). Markers are square shaped with pixel array inside or the square. Marker pose is estimated from square corners projections and marker are identified with the information, contained in pixel array. By marker pose estimation and identification, object pose determination can be implemented.

![Figure 1. Examples of ArUco markers used in experiments.](image)

2. Measurement technique

The relation between three dimensional real world point’s coordinates and corresponding two dimensional image point’s coordinates can be described by equation (1):

\[
A = M \cdot (RT) = \begin{pmatrix}
    f_x & 0 & c_x & r_{11} & r_{12} & r_{13} & t_{14} \\
    0 & f_y & c_y & r_{21} & r_{22} & r_{23} & t_{24} \\
    0 & 0 & 1 & r_{31} & r_{32} & r_{33} & t_{34}
\end{pmatrix} \begin{pmatrix}
    x_w \\
    y_w \\
    z_w
\end{pmatrix}
\]

here \(M\) is camera matrix, \(c_x, c_y\) are principal point coordinates (point of intersection of optical axis and the image plane); \(f_x, f_y\) are lens focal lengths; \(R\) is rotation matrix; \(T\) is translation vector; \(r_{11}, \ldots, r_{33}\) are rotation matrix components; \(t_1, t_2, t_3\) are translation vector components.

As a result of the object pose estimation a rotation matrix is obtained that describes rotation between real world coordinate system \(O_wX_wY_wZ_w\) and camera coordinate system \(O_cX_cY_cZ_c\). \(O_{wl}X_{wl}Y_{wl}Z_{wl}\) coordinate system represents the object coordinate system after certain rotation in the moment image capture. Figure 2 describes these coordinate systems mutual positions.

To obtain an object pose in the real world coordinate system the reference frame is captured by all cameras in initial object position, the corresponding rotation matrix \(R_0\) is calculated. To simplify the notation, we will use the rotation matrixes instead of translation matrixes (since the object in experiments rotates) and three dimensional coordinates instead of homogeneous coordinates. Then in the initial moment of time coordinates in the camera coordinate system can be determined from world coordinate system by equation (2)

\[
\begin{pmatrix}
    X_c \\
    Y_c \\
    Z_c
\end{pmatrix} = \begin{pmatrix}
    X_w \\
    Y_w \\
    Z_w
\end{pmatrix} R_0,
\]

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Figure 2. Camera coordinate system and object coordinate systems before and after rotation.

here \((x_w, y_w, z_w)^T\) are coordinates of a certain vector in the real world coordinate system \(O_wX_wY_wZ_w\), \((x_c, y_c, z_c)^T\) are coordinates of the same vector in the camera coordinate system \(O_cX_cY_cZ_c\), \(R_0\) is initial rotation matrix.

After the rotation measurement frames are captured, the current rotation matrix \(R(t)\) is calculated for each camera. So coordinates in the camera coordinate system can be determined from world coordinate system by equation (3)

\[
\begin{pmatrix}
  x_1c \\
  y_1c \\
  z_1c
\end{pmatrix} = \begin{pmatrix}
  x_w \\
  y_w \\
  z_w
\end{pmatrix} R(t),
\tag{3}
\]

here \((x_w, y_w, z_w)^T\) are coordinates of a certain vector in the real world coordinate system \(O_wX_wY_wZ_w\), \((x_1c, y_1c, z_1c)^T\) are coordinates of the same vector in the camera coordinate system \(O_cX_cY_cZ_c\), \(R(t)\) is current rotation matrix.

Given that the camera coordinate system does not move and vectors \((x_w, y_w, z_w)^T\) in equations (2) and (3) are the same vectors, the rotation matrix that describes the object rotation in the real world coordinate system is:

\[
\begin{pmatrix}
  x_1c \\
  y_1c \\
  z_1c
\end{pmatrix} = \begin{pmatrix}
  x_c \\
  y_c \\
  z_c
\end{pmatrix} R_0^T R(t) = \begin{pmatrix}
  x_c \\
  y_c \\
  z_c
\end{pmatrix} R'(t),
\tag{4}
\]

here \(R'(t) = R_0^T R(t)\) is the rotation matrix that describes object rotation in the real world coordinate system. It is known that the most convenient way to describe a rotation of an object is to use quaternions. For given rotation matrix quaternion components can be evaluated by the Sheperds method [8].

3. Measurement setup

For the evaluation of the proposed technique experiments were conducted using high accuracy equipment. Experimental setup is shown in figure 3. The optical goniometer GS-5 was used as the reference turn indicator with the accuracy of 5 arc-seconds. An object was made by CNC machining from synthetic resin. Printed markers were glued onto object in machined pockets to improve marker placement accuracy. Marker size was 20x20 mm. Images were captured by 4 Logitech C920 cameras.
Figure 3. Experimental setup.

The distance from the object to the camera system was 550 mm. It was calculated based on cameras field of view. Projection of the object occupied 90% of camera’s field of view. The goniometer allows for accurate control of only one rotation angle. Thus to obtain experimental results, for three dimensional rotation, and angular velocity measurement, rotation mount of *Meade LX980 telescope* was used with accuracy of 5 arc-minutes.

With the use of the goniometer accuracy of turn angle around the $O_wZ_w$ axis $\phi$ was determined in the range of $0–180$ degrees. The Meade rotation mount was used to determine the accuracy of the inclination angle $\theta$ in the range of $-25^\circ$...$+25^\circ$ and angular velocity measurement accuracy.

Figure 4 shows the pose estimation error of $\phi$ angle from the goniometer experiments (a), $\theta$ estimation error from the rotation mount experiments (b) and one of the captured images of the object during experiments (c).

Figure 4. The pose estimation error of $\phi$ angle from the goniometer experiments (a), $\theta$ estimation error from the rotation mount experiments (b) and example of an experimental image for pose estimation (c).
4. Conclusions
This paper describes high accuracy optical system for real time object pose estimation. The system consists of 4 digital cameras, and number of ArUco markers placed on the object of interest. Mathematical apparatus was developed for object pose estimation in real world coordinate system. Experiments were conducted for measurement error estimation using optical goniometer GS-5 and Meade rotation mounts as a reference turn measurements systems. The proposed system allows real time rotation quaternion estimation based on the ArUco markers. With the accuracy of 0.2º for turns around vertical axis and accuracy of 1º for turns around horizontal axis.

We compared the results with the existing systems specifications. As an example of radio-frequency positioning systems, Decawave and Ubisence [9] systems can be mentioned. This system has declared accuracy of about ± 10 cm. An example of ultrasonic systems is described in [10], the measurement error is declared to be several millimeters. It is also worth considering that ultrasonic systems require finding transmitters and receivers located and orientated according to their radiation patterns, which is not always possible with an arbitrary orientation of the controlled object. As an example of an inertial system, the Xsense system can be mentioned. The MTi-G-710 type sensor [11] has three three-axis gyroscopes, an accelerometer and a magnetometer on board. The sensor has a sensitivity of 0.05º, a zero-setting error of 0.2º/s and a zero drift of 10º/h. The main drawback of such systems is the presence of zero drift, which does not allow them to be used for long-term measurements.

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