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Improving contour based pose estimation for fast 3D measurement of free form objects

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ABSTRACT

This paper introduces new techniques for pose estimation of free form objects with an optical 3D measurement system. The approach of pose estimation based on contour features was extended by utilizing projected features, which allows to overcome estimation limitations due to the lack of features on free form objects. The principles of combining contour features with projected markers are explained and results comparing different sizes, geometries and densities of projected markers are provided.

1. Introduction

Pose estimation is an important task in computer vision and is often needed for optical metrology. It is used to determine the pose of an object in a reference coordinate system. Applications are locating objects in a machine workspace, in mobile robotics or in the area of measurement. The goal is to establish a mapping between an object coordinate system and a reference coordinate system. In metrology, the pose of an object has to be known to compare its geometrical features to a reference.

One application relying on pose estimation is inverse fringe projection (IFP), which can be used to determine geometry defects of an object [1] with respect to its ideal CAD model. IFP is an enhanced method of structured light metrology, where the projection pattern is generated according to the nominal geometry and the objects pose. Therefore, the pose of the object has to be known accurately in order to generate an individual inverse fringe pattern.

Many free form objects cannot be clamped in a well defined pose and it is difficult to fix a coordinate system to the object. A lot of those objects have no or only few features with which their pose can be easily estimated. Pose estimation using contour features has already been subject to research [2], yet it suffers from high standard deviations estimating the z-coordinate when using cameras with large focal lengths. In [3] contour features are utilized to find a good initial pose. Another approach is to compare the observed 2D image to known images of the object as shown in [4], which again can be used to compute an initial pose. Lv et al. demonstrate in [5] the usage of a ladar device for pose estimation by fitting 3D points to an object model.

This paper motivates extending contour based pose estimation by projecting additional features onto the object to achieve more accurate results. The 3D coordinates of these features are measured with the projector-camera system and this information is integrated in the pose estimation.

Section 2 explains the basics of pose estimation, while Section 3 details the principles of state of the art contour based pose estimation of free form objects. Afterwards Section 4 presents the new approach using projected features. Results of the experiment evaluation are given in Section 5.

2. Pose estimation basics

Pose estimation is used to determine an objects pose in a reference coordinate system. The goal is to estimate all six degrees of freedom of an objects rotation and translation in a reference coordinate system. Preserving the distances and angles between points, this transformation is called rigid body motion. In this work we use the homogeneous extension of 3D vectors so that the transformation $\boldsymbol{P}$ from one coordinate system into another is a real valued 4×4 matrix with six degrees of freedom. The transformation of a point $\boldsymbol{x}$ to its image point $\boldsymbol{x}'$ into another coordinate system is $\boldsymbol{x}' = \boldsymbol{P}\boldsymbol{x}$ and

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$$P = \left(\begin{array}{c|c} R & t \\ \hline 0_{1\times 3} & 1 \end{array}\right) \quad (1)$$

with the 3×3 rotation matrix $\boldsymbol{R}$ and the translation vector $\boldsymbol{t}$.

With pose estimation we try to determine the elements of $\boldsymbol{P}$ so that the matrix transforms points in the object coordinate system to the camera coordinate system.

3. Contour features for pose estimation of free form objects

Rosenhahn et al. [2] use contour features for pose estimation by extending each pixel of the contour to a ray through the center of the camera. The 3D contour of the objects model, e.g. a CAD-file, is than iteratively transformed, to minimize the distance to those rays. As shown in Eq. (1) there are twelve parameters to be determined, which have only six degrees of freedom. This makes pose estimation a non trivial task. The space of transformation matrices is a Lie-Group so we look for the parameters in the corresponding Lie-Algebra. An element of this algebra is called a twist which has six parameters ($\boldsymbol{\omega} \in \mathbb{R}^3, \boldsymbol{v} \in \mathbb{R}^3$)

$$\hat{\xi} = \left(\begin{array}{ccc|c} 0 & -\omega_3 & \omega_2 & \\ \omega_3 & 0 & -\omega_1 & v \\ -\omega_2 & \omega_1 & 0 & \\ \hline & 0_{1\times 3} & & 0 \end{array}\right) \quad (2)$$

The transformation from the Lie-Algebra to it's Lie-Group is the exponential function, so

$$\boldsymbol{P} = \exp(\hat{\xi}\theta) = \sum_{k=0}^{\infty} \frac{(\hat{\xi}\theta)^k}{k!} \approx \boldsymbol{I} + \hat{\xi}\theta = \boldsymbol{P}' \quad (3)$$

is a linearization of the pose estimation problem. Having our rays in pluecker form [6]

$$\begin{pmatrix} 0 & -n_2 & n_3 & -m_1 \\ n_2 & 0 & -n_1 & -m_2 \\ -n_3 & n_1 & 0 & -m_3 \end{pmatrix} \boldsymbol{x} = \boldsymbol{0} \quad (4)$$

with the normalized direction of the ray $\boldsymbol{n}$, the momentum $\boldsymbol{m}$, we can substitute $\boldsymbol{x}$ with our transformed point on the objects 3D contour $\boldsymbol{P}'\boldsymbol{x}$. This can be rearranged as a system of equations that can be solved for our twist parameters $(\boldsymbol{v}, \boldsymbol{\omega})$:

$$\begin{pmatrix} 0 & n_3 & -n_2 & -x_2n_2 - x_3n_3 & x_1n_2 & x_1n_3 \\ -n_3 & 0 & -n_1 & -x_2n_1 & -x_1n_1 - x_3n_3 & x_2n_3 \\ n_2 & n_1 & 0 & x_3n_1 & x_3n_2 & -x_1n_1 - x_2n_2 \end{pmatrix} \theta \begin{pmatrix} \boldsymbol{v} \\ \boldsymbol{\omega} \end{pmatrix} = \boldsymbol{m} - \boldsymbol{x}'. \quad (5)$$

With those parameters and the Rodriguez formular [7]

$$\boldsymbol{P} = \exp(\hat{\xi}\theta) = \begin{pmatrix} \exp(\hat{\boldsymbol{\omega}}\theta) & (\boldsymbol{I} - \exp(\hat{\omega}\theta))(\omega \times v) + \omega\omega^T v\theta \\ \boldsymbol{0}_{1\times 3} & 1 \end{pmatrix}, \ \boldsymbol{\omega} \neq \boldsymbol{0} \quad (6)$$

with

$$\exp(\hat{\boldsymbol{\omega}}\theta) = \boldsymbol{I} + \hat{\boldsymbol{\omega}}\sin(\theta) + \hat{\boldsymbol{\omega}}^2(1 - \cos(\theta)) \quad (7)$$

we get an approximation of the rigid body motion, with which we can transform the model and continue with the next iteration. To find matches between a ray and a point on the 3D contour state of the art techniques of the Iteratively Closest Points (ICP) algorithms are used [8]. The algorithm is similar to a gradient descent and can be summarized as follows:

1. Transform object model (3D contour) to the initial pose.
2. Find matches between 3D rays from the image and points on the 3D contour.
3. Calculate linearized twist parameters $(\boldsymbol{v}, \boldsymbol{\omega})$ and convert to rigid body motion $\boldsymbol{P}'$.
4. Transform model.
5. Go to 2 until convergence.

4. Improving results with projected features

One disadvantage of pose estimation via contour features is that the objects pose has only little effect on the contour, if moved along the optical axis of the camera. This is especially true for long focal lengths. For telecentric optics there is no depth change at all. Depending on the geometry of the object even rotation might have only little effect on the contour in the camera frame. Using a structured light measurement system with a camera and a projector, this paper proposes projecting features onto the object's surface to improve the quality of the estimated pose.

Knowing the internal and external parameters of the camera and the projector and having the pixel position of a projected marker in both systems, we can calculate the 3D position of that marker. Having a cloud of those markers given in camera coordinates, we add the distance between those markers and the closest point of the object's surface to our system of equations. With that approach we can solve for our pose parameters with different kinds of features (contour or projected) in one system of equations.

4.1. Point–point constraint

With a 3D marker $\boldsymbol{x}$ and the corresponding point on the surface $\boldsymbol{x}'$ we can minimize the distances with $\boldsymbol{x} - \boldsymbol{P}'\boldsymbol{x}' = \boldsymbol{0}$ which gives us

$$\boldsymbol{x} - \boldsymbol{P}\boldsymbol{x}' = \boldsymbol{0} \Longleftrightarrow \boldsymbol{x} - \begin{pmatrix} x'_1 - \theta\omega_3 x'_2 + \theta\omega_2 x'_3 + \theta v_1 \\ \theta\omega_3 x'_1 + x'_2 - \theta\omega_1 x'_3 + \theta v_2 \\ -\theta\omega_3 x'_1 + \theta\omega_1 x'_2 + x'_3 + \theta v_3 \\ 1 \end{pmatrix} = \boldsymbol{0}. \quad (8)$$

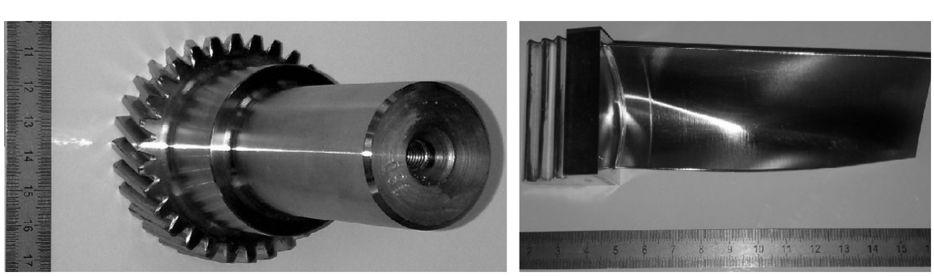

Fig. 1. Objects for experiments: pinion shaft (left), compressor blade (right) with a centimeter ruler.