Available online at www.sciencedirect.com
ScienceDirect
Image and Vision Computing 25 (2007) 1185–1193
www.elsevier.com/locate/imavis

The model for optimal design of robot vision systems based on kinematic error correction

Kanglin Xu *, George F. Luger

Department of Computer Science, University of New Mexico, Albuquerque, NM 87131, USA

Abstract

An active vision system is a robot device for controlling the optics and mechanical structure of cameras based on visual information to simplify the processing for computer vision. In this paper, we present a kinematic model for the optimal design of such active vision systems. We first build a generic kinematic model for robot structure error analysis using a Denavit–Hartenberg transformation matrix, differential changes for this transformation matrix and link parameters. We then extend it to analyze an active vision system using algorithms for estimating depth using stereo cameras. This model is generic and is suitable for analysis of any active vision system. Since we can employ it to analyze errors based on variations of link parameters when we use an active vision system to estimating depth, we can combine it with a cost-tolerance model to implement an optimal design for active vision systems. In this way, we can not only save manufacturing cost and implement *design for manufacturing* (DFM) but reduce or avoid calibration work for an active vision system. Our algorithm also works for a binocular head and on even more complex tasks. Based on our approach, we have created a software tool that functions as a C++ class library. We also demonstrate how to use this software model to analyze a real system *TRICLOPS*, which is a significant proof of concept.

Keywords: Active vision system; Differential transformation; Pose estimation; Design for manufacturing (DFM)

1. Introduction

A robot manipulator is a position oriented mechanical device. The accuracy of the manipulator's position in an application environment is dependent on the manufacturing accuracy and the control accuracy. Unfortunately, there often exists both manufacturing error and control error. Generally, robots must be calibrated to improve their accuracy. Calibration involves robot kinematic modeling, pose measurement, parameter identification and accuracy compensation. These calibrations are hard work and time consuming.

For an active vision system, a robot device for controlling the motion of cameras based on visual information due to measurement noise, the kinematic calibrations are much more difficult. As a result, most existing active vision systems are not accurately calibrated Shih [8]. To address this problem, many researchers select self-calibration techniques. In this paper, we apply a more active approach, that is, we reduce the kinematic errors at the design stage instead of at the calibration stage. Furthermore, we combine the model described in this paper with a cost-tolerance model to implement an optimal design for active vision systems so that they can be used more widely in enterprise.

We begin to build the model using the relation between two connecting joint coordinates defined by a DH homogeneous transformation. We then use the differential relationship between these two connecting joint coordinates to extend the model which relates the kinematic parameter errors of each link to the pose error of the last link. Given this model, we can implement an algorithm for estimating depth using stereo cameras, extending the model to handle an active stereo vision system.

* Corresponding author. Tel.: +1 505 835 6744.
E-mail addresses: klxu@cs.unm.edu (K. Xu), luger@cs.unm.edu (G.F. Luger).

0262-8856/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.imavis.2006.04.020

Based on these two models, we have developed a set of C++ class libraries. Using this set of libraries, we can estimate robot pose errors or depth estimation errors based on kinematic errors. Furthermore, we can apply these libraries to find the key factors that affect accuracy. As a result, more reasonable minimum tolerances or manufacturing requirements can be defined so that the manufacturing cost is reduced while retaining relatively high accuracy. Besides providing an approach to find the key factors and best settings of key parameters, we demonstrate how to use a cost-tolerance model to evaluate the settings. In this way, we can implement optimal *design for manufacturing* (DFM) in enterprises. Because our models are derived from the Denavit–Hartenberg transformation matrix, differential changes for the transformation matrix and link parameters, and the fundamental algorithm for estimating depth using stereo cameras, they are suitable for any manipulator or stereo active vision system.

The remainder of this paper is organized as follows. Section 2 derives the model for analyzing the effect of parameter errors on robot poses. Section 3 introduces the extended kinematic error model for an active vision system. It should be noted that this extended model is the main contribution of our paper and that we integrate the robot differential kinematics into an active vision system. Section 4 provides more detailed steps describing how to use our approach. Section 5 discuss some issues related to the design of active vision systems and DFM. Section 6 presents a case study for a real active vision system and cost evaluation using a cost-tolerance model. Finally, Section 7 offers concluding remarks.

2. Kinematic error model for a manipulator

A serial link manipulator consists of a sequence of links connected together by actuated joints [7]. The kinematical relationship between any two successive actuated joints is defined by the DH (Denavit–Hartenberg) homogeneous transformation matrix. The DH homogeneous transformation matrix is dependent on the four link parameters, that is, θ_i, α_i, r_i, and d_i. For the generic robot forward kinematics, only one of these four parameters is variable. If joint i is rotational, the θ_i is the joint variable and d_i, α_i, and r_i are constants. If joint i is translational, the d_i is the joint variable and θ, α_i, and r_i are constants. Since there always exists errors for these four parameters, we also need a differential relationship between any two successive actuated joints. This relationship is defined by matrix $d\,\mathbf{A}_i$ which is dependent on $d\theta_i$, $d\alpha_i$, dr_i, and dd_i as well as θ_i, α_i, r_i, and d_i. Given the relationship between two successive joints $\mathbf{A}_i$ and differential relationship between two successive joints $d\mathbf{A}_i$, we can derive an equation to calculate the accurate position and orientation of the end-effector with respect to the world coordinate system for a manipulator with N degrees of freedom (DOF).

In this section, we will first derive the differential changes between two successive frames in Section 2.1. We then give the error model for a manipulator of N degrees of freedom with respect to the world coordinate system in Section 2.2.

2.1. Differential changes between two frames

For an N DOF manipulator described by the Denavit–Hartenberg definition, the homogeneous transformation matrix $\mathbf{A}_i$ which relates the $(i-1)$th joint to ith joint is [7]

$$\mathbf{A}_i = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & r_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & r_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where s and c refer to sine and cosine functions, and θ_i, α_i, r_i, and d_i are link parameters. Given the individual transformation matrix $\mathbf{A}_i$, the end of an N DOF manipulator can be represented as

$$\mathbf{T}_N = \mathbf{A}_1\mathbf{A}_2\cdots\mathbf{A}_{N-1}\mathbf{A}_N \tag{2}$$

We will also use the following definitions. We define $\mathbf{U}_i = \mathbf{A}_i\mathbf{A}_{i+1}\cdots\mathbf{A}_N$ with $U_{N+1} = I$, and a homogeneous matrix

$$\mathbf{A}_i = \begin{bmatrix} \mathbf{n}_i & \mathbf{o}_i & \mathbf{A}_i & \mathbf{p}_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where $\mathbf{n}_i$, $\mathbf{o}_i$, $\mathbf{a}_i$ and $\mathbf{p}_i$ are 3×1 vectors.

Given the ith actual coordinate frame $\mathbf{A}_i$ and the ith nominal frame $\mathbf{A}_i^0$, we can obtain an additive differential transformation $d\mathbf{A}_i$

$$d\mathbf{A}_i = \mathbf{A}_i - \mathbf{A}_i^0 \tag{4}$$

If we represent the ith additive differential transformation $d\mathbf{A}_i$ as the ith differential transformation $\delta\mathbf{A}_i$ right multiplying the transformation $\mathbf{A}_i$, we can write

$$d\mathbf{A}_i = \mathbf{A}_i\delta\mathbf{A}_i \tag{5}$$

In this case, the changes are with respect to coordinate frame $\mathbf{A}_i$.

Assuming the link parameters are continuous and differentiable we can represent $d\mathbf{A}_i$ in another way, that is

$$d\mathbf{A}_i = \frac{\partial\mathbf{A}_i}{\partial\theta_i}d\theta_i + \frac{\partial\mathbf{A}_i}{\partial\alpha_i}d\alpha_i + \frac{\partial\mathbf{A}_i}{\partial r_i}dr_i + \frac{\partial\mathbf{A}_i}{\partial d_i}dd_i \tag{6}$$

Comparing (5) with (6), we obtain

$$\delta\mathbf{A}_i = \mathbf{A}^{-1}\left(\frac{\partial\mathbf{A}_i}{\partial\theta_i}d\theta_i + \frac{\partial\mathbf{A}_i}{\partial\alpha_i}d\alpha_i + \frac{\partial\mathbf{A}_i}{\partial r_i}dr_i + \frac{\partial\mathbf{A}_i}{\partial d_i}dd_i\right) \tag{7}$$

For the homogeneous matrix, the inverse matrix of $\mathbf{A}_i$ is

$$\mathbf{A}_i^{-1} = \begin{bmatrix} \mathbf{n}_i^t & -\mathbf{p}_i\cdot\mathbf{n}_i \\ \mathbf{o}_i^t & -\mathbf{p}_i\cdot\mathbf{o}_i \\ \mathbf{A}_i^t & -\mathbf{p}_i\cdot\mathbf{A}_i \\ \mathbf{0}_{1\times3} & 1 \end{bmatrix} \tag{8}$$

By differentiating all the elements of Eq. (1) with respect to θ_i, α_i, r_i and d_i, respectively, we obtain