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VISION BASED IN-SITU CALIBRATION OF ROBOTS WITH APPLICATION IN SUBSEA INTERVENTIONS

M.Sc. Thesis

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CALIBRAGEM VISUAL IN SITU DE MANIPULADORES ROBÓTICOS COM APLICAÇÃO EM INTERVENÇÕES SUBMARINAS

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Abstract

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The majority of today's industrial robots are programmed to follow a predefined trajectory. This is sufficient when the robot is working in a fixed environment where all objects of interest are situated in a predetermined position relative to the robot base. However, if the robot's position is altered all the trajectories have to be reprogrammed for the robot to be able to perform its tasks. Another option is teleoperation, where a human operator conducts all the movements during the operation in master-slave architecture. Since any positioning errors can be visually compensated by the human operator, this configuration does not demand that the robot has a high absolute accuracy. However, the drawback is the low speed and low accuracy of the human operator scheme. The manipulator considered in this thesis is attached to a ROV (Remote Operating Vehicle) and is brought to its working environment by the ROV operator. Every time the robot is repositioned, it needs to estimate its position and orientation relative to the work environment. The ROV operates at great depths and there are few sensors which can operate at extreme depths. This is the incentive for the use of computer vision to estimate the relative position of the manipulator. Through cameras the differences between the actual and desired position of the manipulators is estimated. This information is sent to controllers to correct the pre-programmed trajectories. The manipulator movement commands are programmed off-line by a CAD system, without need even to turn on the robot, allowing for greatest speed on its validation, as well as problem solving. This work includes camera calibration and calibration of the structure of the manipulator. The increased accuracies achieved by these steps are merged to achieve in-situ calibration of the manipulator base.

Key Words

Robotics; Calibration; Computer vision; SIFT; Pattern recognition; Automation; Stereopsis

Resumo

Augustson, Trond Martin; Meggiolaro, Marco Antonio (Advisor). **CALIBRAGEM VISUAL IN SITU DE MANIPULADORES ROBÓTICOS COM APLICAÇÃO EM INTERVENÇÕES SUBMARINAS.** Rio de Janeiro 2007, 143p. Dissertação de Mestrado – Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

A maioria dos robôs industriais da atualidade são programados para seguir uma trajetória pré-definida. Isto é suficiente quando o robô está trabalhando em um ambiente imutável onde todos os objetos estão em uma posição conhecida em relação à base do manipulador. No entanto, se a posição da base do robô é alterada, todas as trajetórias precisam ser reprogramadas para que ele seja capaz de cumprir suas tarefas. Outra opção é a teleoperação, onde um operador humano conduz todos os movimento durante a operação em uma arquitetura mestre-escravo. Uma vez que qualquer erro de posicionamento pode ser visualmente compensado pelo operador humano, essa configuração não requer que o robô possua alta precisão absoluta. No entanto, a desvantagem deste enfoque é a baixa velocidade e precisão se comparado com um sistema totalmente automatizado. O manipulador considerado nesta dissertação está fixo em um *ROV* (*Remote Operating Vehicle*) e é trazido até seu ambiente de trabalho por um teleoperador. A cada vez que a base do manipulador é reposicionada, este precisa estimar sua posição e orientação relativa ao ambiente de trabalho. O *ROV* opera em grandes profundidades, e há poucos sensores que podem operar nestas condições adversas. Isto incentiva o uso de visão computacional para estimar a posição relativa do manipulador. A diferença entre a posição real e a desejada é estimada através do uso de câmeras submarinas. A informação é enviada aos controladores para corrigir as trajetórias pré-programadas. Os comandos de movimento do manipulador podem então ser programados *off-line* por um sistema de CAD, sem a necessidade de ligar o robô, permitindo rapidez na validação das trajetórias. Esse trabalho inclui a calibragem tanto da câmera quanto da estrutura do manipulador. As melhores precisões absolutas obtidas por essas metodologias são combinadas para obter calibração in-situ da base do manipulador.

Palavras-Chave

Robótica; Calibragem; Visão computacional; SIFT; Reconhecimento de padrões; Automação; Visão estéreo

Summary

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List of Variables

A_q – Observation matrix used in quaternion rotation estimation

C_a – Observation matrix for plane estimation

$C_a^{`}$ – Observation matrix for arc coordinates projected onto the estimated plane

C_t – Observation matrix for translated coordinates used to estimate circle parameters

G_e – Non singular Identification matrix where the redundant errors have been eliminated.

T_n^0 - homogeneous matrix 4x4 that describes the orientation and position of the manipulator end-effector relative to its base as a function of the angles of the links θ_n and the generalized errors ε.

a_i – Denavit-Hartenberg parameter: length of the common normal between two adjacent links

a – quaternion vector

a_0, a_1, a_2, a_3 - quaternion vector components of a.

a_p - parameter for an estimated 3D plane

a_l - line parameter used to estimate a line through least square approximation

b - quaternion vector

b_0, b_1, b_2, b_3 - quaternion vector components

b_t – parameter used to estimate a circle from translated arc parameters

b_q – vector used in quaternion rotation estimation

b_l - line parameter used to estimate a line through least square approximation

b_p - parameter for an estimated 3D plane

c_l - line parameter used to estimate a line through least square approximation

c_p - parameter for an estimated 3D plane

c_r – estimated radius of projected circle

d_{mnop} – variable used in deduction of triangulation principles

d_p - parameter for an estimated 3D plane

d_i – Denavit-Hartenberg parameter: distance between the origin O_{i-1} and H_i

d_{int} – Intraocular distance between two camera centers

d_n – distance limit that denotes the maximum allowed distance from the nearest corresponding coordinate

$d_{r,i}$ – a coordinates' distance from the cluster center ${}^{1}_{R}\tilde{p}$

e_0 - matrix containing the edge angle of an image

i – complex quaternion unit vector

j – complex quaternion unit vector

k – complex quaternion unit vector

k – quaternion rotation axis given by **k** = [i j k]

n_p - normal vector for estimated plane

$\hat{p}$ - coordinate in the normalized in the normalized image plane

${}^{1}p$ - 3D coordinate set relative to the origin

${}^{2}p$ - 3D coordinate set corresponding to ${}^{1}p$ with a different reference frame

${}^{1}_{R}p$ – translated coordinate set, used in RANSAC algorithm

${}^{1}_{R}\tilde{p}$ – estimated center of the translated coordinate set ${}^{1}_{R}p$

q – quaternion vector

q_0, q_1, q_2, q_3 - quaternion vector components of q

$r_{e,i}$ – error ratio of a coordinate, denoting its position error relative to its distance from the center of the cluster.

$r_{\lim}$ – error ratio limit, denoting the accepted error ratio $r_{e,i}$

r_r – estimated radius of projected circle

$\hat{u}$ - normalized x-coordinate of an image relative to the image center

$\hat{v}$ - normalized y-coordinate of an image relative to the image center

$\check{u}$ - image x-coordinate corrected for radial distortion

$\check{v}$ - image y-coordinate corrected for radial distortion

u_t – output vector from least square estimate of a circle

v_p - least square vector estimated by a lest square of C_a

$\grave{x}_a$ - x coordinate of an arc projected onto plane

x_i – coordinate of joint i in the Denavit-Hartenberg notation

x_q – substitution parameter used in quaternion deduction

x_r – estimated x-coordinate of circle center

x_t – translated x-coordinate used to estimate circle parameters

x_{tri} – coordinate defining a point used in triangulation

y_a – y-coordinate of an arc projected onto plane

y_q – substitution parameter used in quaternion deduction

y_r – estimated y-coordinate of circle center

y_t – translated x-coordinate used to estimate circle parameters

y_{tri} –coordinate defining a point used in triangulation

y_i – coordinate of joint i in the Denavit-Hartenberg notation

z_i – coordinate of joint i in the Denavit-Hartenberg notation

z_{tri} –coordinate defining a point used in triangulation

C_a – observation matrix of arc coordinates relative to the laser tracker

$C_a^{'}$ – matrix containing the projected coordinates of C_a

G – matrix containing the edge magnitude of an image

G_x – matrix containing the edge magnitude in x direction of an image

G_y – matrix containing the edge magnitude in y direction of an image

S_x – Sobel filter mask for detecting edges in x direction

S_y – Sobel filter mask for detecting edges in y direction

L_o – observation matrix for camera calibration

M – projection matrix of the pin hole camera

M_v – projection matrix in vector form

${}^cO$ – camera reference frame

${}^wO$ – world reference frame

${}^cP$ – coordinate relative to the camera reference frame

${}^wP$ – coordinate relative to the world reference frame

Q – skew matrix used to calculate vector product

R – rotation matrix defining the relative rotation between two views

ΔX- difference between desired position of the manipulator end-effector and the actual position.

ΔX_t -matrix containing differences between desired position of the manipulator end-effector and the true measured position.

$\boldsymbol{J_t}$ - The matrix 6*m* x 6(*n*+1) formed by *m* Identification Jacobians, called the Total Identification matrix

α – magnification factor in x direction for the pin hole model [pixels]

β – magnification factor in y direction for the pin hole model [pixels]

α_i – Denavit-Hartenberg parameter: the angle between the joint axes in the right hand sense.

$\hat{\varepsilon}$ - vector containing the estimated generalized errors

$\varepsilon^{\cdot}$ - vector where the redundant errors are incorporated in the non redundant errors

$\varepsilon_{x,i}$ - Generalized error of joint *i* along *x*-axis

$\varepsilon_{y,i}$ - Generalized error of joint *i* along *y*-axis

$\varepsilon_{z,i}$ - Generalized error of joint *i* along *z*-axis

$\varepsilon_{p,i}$ - Generalized rotational error of joint *i* around x-axis

$\varepsilon_{s,i}$ - Generalized rotational error of joint *i* around *y*-axis

$\varepsilon_{r,i}$ - Generalized rotational error of joint *i* around *z*-axis

γ_1, γ_2 - multiplication factors that determines at what coordinate the closest mutual point is found for two lines in 3D

θ_i – Denavit-Hartenberg parameter: the angle between the x_{i-1} axis and the common normal H_iO_i measured along the *z*-azis

$\theta_{p,x}$ – estimated angle around the *x*-axis, between the normal plane and the reference frame.

$\theta_{p,y}$ – estimated angle around the *y*-axis, between the normal plane and the reference frame.

θ_{q} – quaternion rotation angle

θ_{x_0} - camera bias angle around *x*-axis

θ_{y_0} - camera bias angle around *y*-axis

θ_{z_0} - camera bias angle around z-axis

ζ – substitution variable used in estimation of quaternion rotation angle

ρ – substitution variable used in estimation of quaternion rotation angle