# Early Experimental Tests on a Vision System for Robot Mechanical Calibration

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***Abstract:*** *Early experimental results on algorithm for the kinematic calibration of a robot arm are presented. The technique is based on the recordings of a couple of television cameras. A target is located on the last link of a robot arm and its trajectory is recorded by the telecamera; the joint positions, obtained from the encoder, related to each of the couples of frames, is also recorded. By analysing a number of couples of frames, it is possible to compute the Denavit and Hartemberg parameters. The method needs a previous camera calibration.*
*Early experimental results on the camera model are also described.*

***Keywords:*** *Robot kinematic calibration, Vision system*

## I INTRODUCTION

Vision systems represent a very suitable tool in many robotic applications. In some previous investigations [1÷5], the robot arm calibration possibility, by means of a couple of cameras, was theoretically investigated. The main aim of these studies was to find a suitable technique by means of which it could be possible to obtain both vision system calibration and robot arm mechanical calibration; this with a flexible and non invasive tool.
The method has been developed starting from results by other Authors [7÷10] on vision systems.

## II CAMERA MODEL

A camera model was studied to use vision system in robotic application.
The developed model describes the relation between coordinates (u,v) of robot end-effector expressed in pixels, in image plane, and end-effector coordinates in the robot joints space.
The relation that synthetizes the model is following:

$$\{u,v\} = \frac{1}{\{N\}^T \cdot \left[T_n^0\right]\{\tilde{w}\}_n} [K] \cdot [T]\left[T_n^0\right]\{\tilde{w}\}_n \tag{1}$$

where:

$\{u,v\}$: vector with end-effector coordinates expressed in pixel in image plane;
$\{\tilde{w}_n\}$: end-effector homogeneous coordinates in robot frame n, for a generic robot with n d.o.f;
$[T_n^0]$: Denavit-Hartenberg robot transformation matrix from base frame to end-effector frame;
$[T]$: transformation matrix from camera frame to robot base

frame;

[K]: matrix with geometric and optical camera parameters;

{N}: vector with expression of optic axis in robot base frame.

## II CAMERA CALIBRATION

Camera calibration in the context of three-dimensional machine vision is the process of determining the internal camera geometric and optical characteristics (intrinsic parameters) and/or the 3-D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters). In many cases, the overall performance of the machine vision system strongly depends on the accuracy of the camera calibration.

In order to calibrate the tele-cameras a toolbox, developed by Christopher Mei, INRIA Sophia-Antipolis [11], was used.

By means of this toolbox it is possible to find the intrinsic and extrinsic parameters of two cameras that are necessary to solve the stereoscopic problem.

In order to carry out the calibration of a camera, it is necessary to acquire any number of images of observed space in which a checkerboard pattern is placed with different positions and orientations, Fig 1.

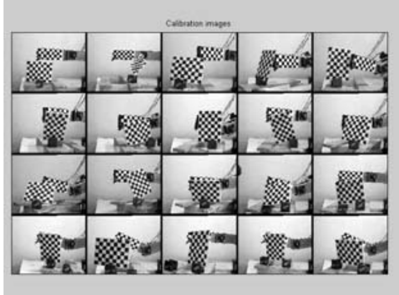


Figure 1

In each acquired image, after clicking on the four extreme corners of a checkerboard pattern rectangular area, a corner extraction engine includes an automatic mechanism for counting the number of squares in the grid. This points are used like calibration points, Fig. 2.

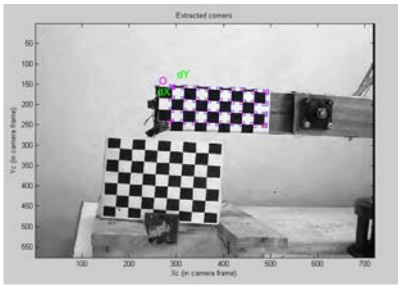


Figure 2

The square dimensions **dX**, **dY** are always kept to their original values in millimeters, and represent the parameters that put in relation the pixel dimensions with observed space dimensions (mm).

After corner extraction, calibration is done in two steps: first initialization, and then nonlinear optimization. The initialization step computes a closed-form solution for the calibration parameters based not including any lens distortion.

The non-linear optimization step minimizes the total reprojection error (in the least squares sense) over all the calibration parameters (9 DOF for intrinsic: focal (2), principal point (2), distortion coefficients (5), and 6*n DOF extrinsic, with n = images number).

The calibration procedure allows to find the 3-D position of the grids with respect to the camera, like shown in Fig. 3.

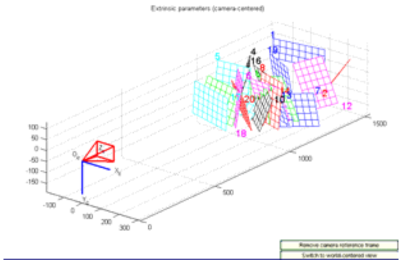


Figure 3

With two camera calibration, it is possible to carry out a stereo optimization, by means of a toolbox option, that allows to do a stereo calibration for stereoscopic problem.

The global stereo optimization is performed over a minimal set of unknown parameters, in particular, only one pose unknown (6 DOF) is considered for the location of the calibration grid for each stereo pair. This insures global rigidity of the structure going from left view to right view. In this way the uncertainties on the intrinsic parameters (especially that of the focal values) for both cameras it becomes smaller.

After this operation, the spatial configuration of the two cameras and the calibration planes may be displayed in a form of a 3D plot, like shown in Fig. 4.

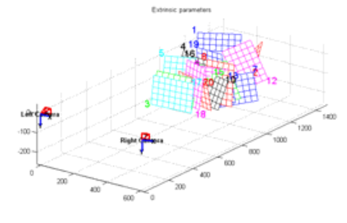


Figure 4

In Tables 1 and 2 there are results of stereo calibration for a vision system with two cameras.

| ***Intrinsic parameters of left camera*** | |
|---|---|
| | |
| *Focal Length* | |
| [1187.35528 1273.31194] ± [6.25360 6.43330 ] | |
| *Principal point* | |
| [344.49625 274.90866] ± [17.28778 16.05893 ] | |
| *Skew* | |
| 90.00000 ± 0.00000 degrees | |
| *Distortion coefficients* | |
| [-0.37195 0.40748 0.00028 0.00420 0.00000 ] ± [ 0.03898 0.15427 0.00218 0.00320 0.00000] | |

Table 1
Intrinsic parameters of left camera

| ***Intrinsic parameters of right camera*** | |
|---|---|
| | |
| *Focal Length* | |
| [1143.87472 1223.25521] ± [6.05871 6.62174 ] | |
| *Principal point* | |
| [369.00391 318.22975] ± [14.36227 11.10687 ] | |
| *Skew* | |
| 90.00000 ± 0.00000 degrees | |
| *Distortion coefficients* | |
| [-0.24641 -0.75423 -0.00017 0.00070 0.00000] ± [0.05955 1.02850 0.00155 0.00145 0.00000] | |

Table 2
Intrinsic parameters of right camera

Stereo calibration concurs to characterize also vision system extrinsic parameters by computing position of right camera versus left camera. Results are two vector: rotation vector and translation vector.

| ***Position of right camera vs left camera*** |
|---|
| |
| *Rotation vector(rodrigues notation)* |
| [0.07195 0.35935 0.02153] ± [0.01258 0.01765 0.00405 ] |
| |
| *Translation vector* |
| [-550.91623 -41.33307 142.00317 ] ± [ 2.52165 1.35156 7.91933 ] |

Table 3
Position of right camera vs left camera

## III IMAGES ANALYSIS

The acknowledgment in the image plan of a workspace point, is obtained by means of a luminous mark. Exalting the luminous contrast, it is possible to characterize the barycentre of the small portion of image area relative to luminous mark. This mark is placed on the extremity of revolute robot third link, so it represents end-effector reference point.

The developed vision algorithm can be reassumed in four steps:

1 reading frame, Fig. 5;
2 frame brightness modification, Fig.6;
3 search of luminous mark in image, Fig. 7;
4 acknowledgment of mark coordinates in pixel, Fig. 8;

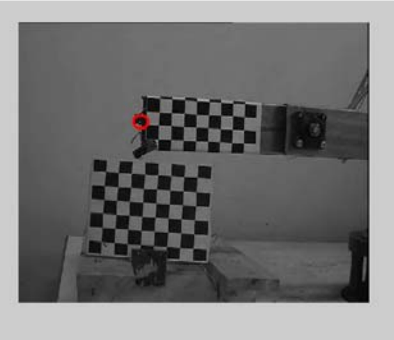


Figure 5
Vision algorithm- step 1

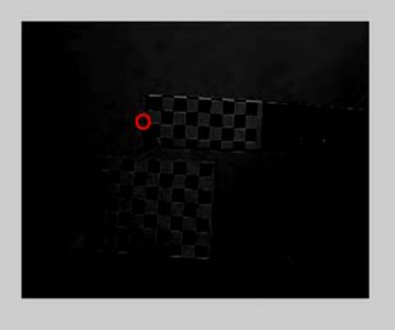


Figure 6
Vision algorithm- step 2

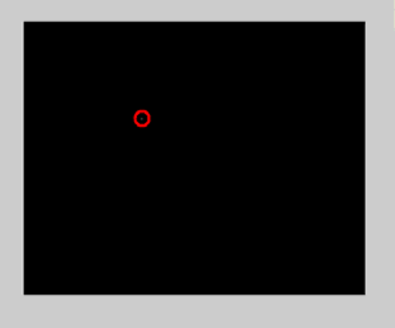


Figure 7
Vision algorithm- step 3

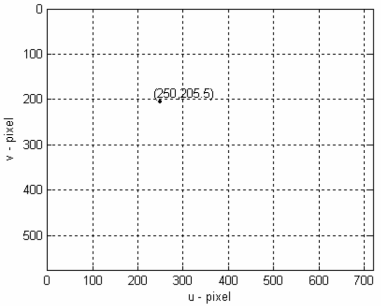


Figure 8
Vision algorithm- step 4

## IV CAMERA MODEL VALIDATION

To validate camera model, it is possible to calculate end-effector position in image plane, by means of equation (1).

The procedure consists in following steps:

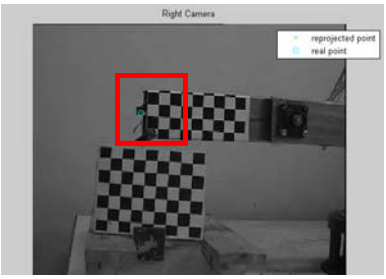
- robot placement by assigning joint coordinates;
- photos acquisition;
- substitution of robot joint coordinates in equation (1);
- comparison between calculated position in image plane and real robot mark coordinates in photos.

Results can be visualized directly on the acquired images.

Vision system consists of two cameras, each camera 'observes' robot movements from different position.

After calibration, all intrisic and extrinsic camera parameters are known, so assigning the robot joints coordinates it is possible to calculate its end-effector projection in image plane.

In Figures 9 and 10, calculate positions are shown (green X), for right and left camera.



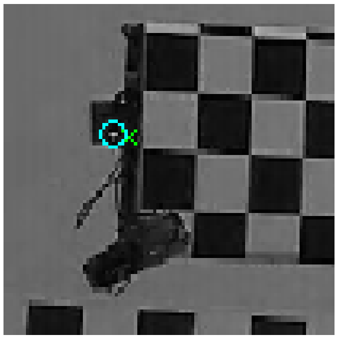


Figure 9
Right camera

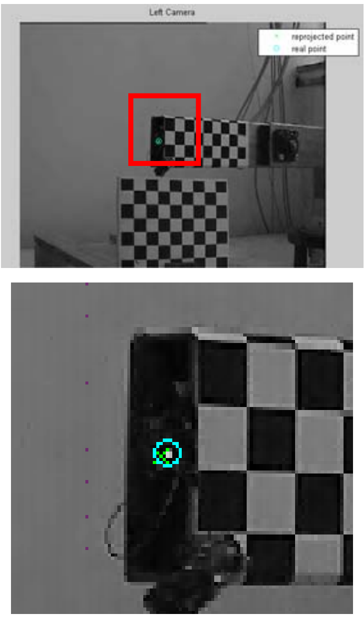


Figure 10
Left camera

Some little differences are visible between real mark position (blue O) and its calculate position (green X), these are due to the camera calibration precision. In the following tables, coordinates in pixel are reported for each camera, it is possible to observe that error percentage for both cameras (right: 2,7% horizontal and 0,78% vertical; left: 1,18% horizontal and 0,75% vertical) is greater in the image horizontal direction. Also this aspect depends by vision system calibration, infact a not specify optimization of this procedure is obvious in the uncertainty of calculated focal length for both cameras.

| ***Right camera*** | |
|---|---|
| *Real point* | |
| horizontal | 250 |
| vertical | 205.5 |
| | |
| *Calculated point* | |
| horizontal | 256.8104 |
| vertical | 207.1015 |

Table 4
Real and calculated point coordinates for right camera

| ***Left camera*** | |
|---|---|
| *Real point* | |
| horizontal | 327.8 |
| vertical | 278.7 |
| | |
| *Calculated point* | |
| horizontal | 323.9329 |
| vertical | 280.7962 |

Table 5
Real and calculated point coordinates for left camera

## IV KINEMATIC CALIBRATION

The calibration technique [6] essentially consists in the following steps:

I The end-effector is located in an even position in the work space;

II A vision system acquires and records the robot's image and gives the coordinates of an assigned point of the end-effector, expressed in pixels in the image plane.

III By means of a suitable camera model, it is possible to find a relation between these coordinates expressed in pixels, and the coordinates of the assigned point of the end-effector in the world (Cartesian) frame.

IV By means of the servomotor position transducers, the values of the joint position parameters are recorded for that end-effector position in the work space.

In this way, for each of the camera images, the following arrays are obtained:

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix}, \quad \begin{pmatrix} \theta_{1,i} \\ \theta_{2,i} \\ \theta_{3,i} \end{pmatrix} \qquad (2)$$

where: $i = 1,\ldots,N$, and $N$ is the number of acquired camera images (frames).

If the coordinates in the working space and the joint parameters are known, it's possible to write the direct kinematics equations in which the unknown are those Denavit-Hartenberg parameters that differ from the joint parameters; thus these Denavit-Hartenberg parameters represent the unknown of the kinematic calibration problem.

Experimental tests have been executed on a revolute robot prototype with 3 d.o.f., in order to verify the effectiveness of the algorithm.

Twenty images of the robot in twenty different positions of its workspace, with two cameras, have been acquired. After a vision system calibration, by means of an optimization algorithm that uses minimum square technique, it is possible to solve the system of equations (1) and to obtain a numerical solution. Using two cameras we have 2*20=40 equations (1), to find nine D-H parameters that characterize the kinematics structure of a three axis revolute robot.

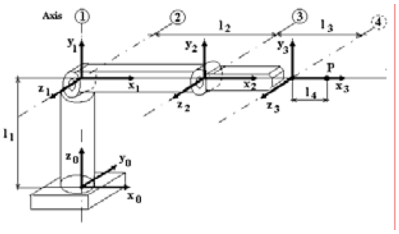


Figure 11
Revolute robot scheme

In the Tables 6 and 7, real parameters and calculated parameters are shown.

| Joint | ai | αi | θi | di |
|---|---|---|---|---|
| 1 | 0 | 90° | -180°÷ 180° | $l_1$= 449 mm |
| 2 | $l_2$= 400 mm | 0° | -90°÷ 45° | 0 |
| 3 | $l_3$= 400 mm | 0° | -90°÷ 90° | 0 |

Table 6
Real prototype D-H parameters

| Joint | ai | αi | θi | di |
|---|---|---|---|---|
| 1 | 7.04 mm | 86.28° | -180°÷ 180° | $l_1$= 447.15 mm |
| 2 | $l_2$= 396.16 mm | 0.94° | -90°÷ 45° | 10.85 mm |
| 3 | $l_3$= 413.65 mm | 0° | -90°÷ 90° | 13.75 mm |

Table 7
Calculated prototype D-H parameters

## Conclusion

This early results show that by the proposed calibration technique it seems to be possible to obtain a good evaluations of the Denavit-Hartenberg parameters.

The errors at this moment, are generally lower than 1% and it seems to be possible to decrease them significantly.

Probably the errors are mainly due to the following aspects:

- poor resolving power due to the little number of pixels of the adopted telecameras.
- Errors in the cameras calibration.
- Need of tuning of the test rig.

Anyway these early results seem to be encouraging, so experimental investigations are in progress mainly to increase the precision of the cameras calibration and the tuning of the test rig.

## Acknowledgement

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