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Education Software For The Modelling And Calibration Of Kinematic Mechanisms

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Abstract

This paper presents a new software for teaching the most important aspects of modelling, characterization and calibration of parallel mechanisms by means of the kinematic model, the kinematic parameter identification and the control of the system actuators and sensors. This application allows the student to develop competencies such as analysis and synthesis, to solve problems, research skills and to apply their knowledge.

The developed tool presents a special interest in areas such as education, industry and research, since the application interface allows the user to carry out the different steps of the calibration procedure in an easy way. Besides, only one application is necessary to perform all the procedure for data acquisition and kinematic parameter identification.

Moreover, thanks to the flexibility that the developed software offers in the programming, a senior undergraduate student can modify different algorithm variables and analyze the effects that take place with these changes. This application therefore presents an important utility as a teaching tool for the learning process and analysis of the different steps in the parallel mechanism optimization.

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Keywords: Education software; modelling; calibration; kinematic mechanism;

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1. Introduction

Parallel mechanisms have been widely used in different applications such as pick-and-place (Yamacli and Cambolat (2008)), medical applications (Maurin et al. (2004)), micropositioning (Yao et al. (2007)) or tool-machine (Hernández-Martinez et al. (2010)).

The Denavit-Hartenberg (D-H) method (Denavit and Hartenberg (1955)), is one of the most widely used methods in mechanism modelling (Cheng et al. (1995), Kim et al. (2001)) for obtaining the kinematic model. This technique models the joints with four parameters.

Once the kinematic model is obtained, the following step is the system optimization or calibration. Robot calibration consists of identifying the geometric parameters to improve the model accuracy. An accurate identification of the kinematic parameters considerably reduces the error of these systems. The objective of the calibration procedure is to minimize the error between the measured pose of the platform and the calculated pose in both open-loop and closed-loop mechanisms. However, special care must be taken in closed-loop mechanisms, since it is not possible to choose the model parameters arbitrarily, due mainly to the fact that some parameters are inter-related as they belong to a closed chain (Everett and Lin (1988)). This characteristic requires two kinds of equations in parallel mechanism calibration. Firstly, those transformations that relate the platform location with the reference system of the base by means of open-loop kinematic chains. Secondly, those closed-loop transformations which contain the constraints imposed by the closed-loop chains.

This procedure is usually carried out in four steps: determination of the kinematic model by means of non-linear equations, data acquisition, geometric parameter identification and model evaluation.

This paper presents an application -developed in Matlab- that allows us to perform all these steps for a parallel mechanism by means of a fast and easy interface.

The evaluation has been performed for a two DOF (degrees of freedom) parallel mechanism, obtaining a significant improvement in the system accuracy. Moreover, the developed software allows a specialized user to modify some algorithm variables. Thus, the user can analyze different mechanism designs, the workspace, the number and the pose of the computed positions in the data acquisition step and the influence of variables such as parameter initial values.

2. Methodology or Experimental Procedure

The developed tool has been programmed in Matlab. This application allows us to perform the modelling and calibration of the kinematic model.

To achieve this, four steps must be carried out: a) mechanism control; b) mechanism component characterization; c) mechanism behaviour evaluation; d) mechanism calibration.

2.1. Kinematic model

The non-contact measurement system developed consists of two positioning mechanisms with two vision cameras each one. Figure 1 shows a two-DOF positioning mechanism, azimuth and elevation, for the positioning of two vision cameras.

The parallel mechanism consists of four spherical ball joints, a universal joint and two prismatic joints.

The kinematic model establishes mathematical relations between the joint variables and the position and orientation of the moving platform.

The direct kinematic model (DKM) calculates the positioning and orientation of the platform, (x, y, z, α, β, γ), based on certain values of the joint variables, (q_1, .., q_n), according to Eq. (1).

$$[x, y, z, \alpha, \beta, \gamma]' = g(q_1, .., q_n) \tag{1}$$

The inverse kinematic model (IKM) obtains the joint variables (such as actuator elongation), given by (q_1, .., q_n), for a determined spatial positioning of the platform, (x, y, z, α, β, γ), according to Eq. (2).

$$q_k = f_k(x, y, z, \alpha, \beta, \gamma) \text{ with } k=1..n \tag{2}$$

The D-H method allows us to obtain the kinematic model.

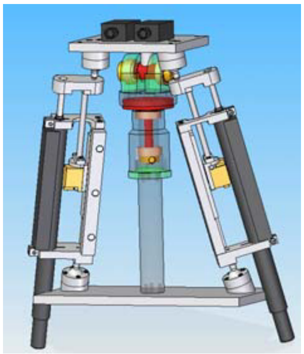

Fig. 1. Positioning mechanism.

The kinematic model development will allow us to calculate the necessary actuator elongations in order to the platform can describe rotations with azimuth angles of $\varphi_1 = \pm 45°$ and elevation angles of $\varphi_2 = \pm 30°$, with respect to the nominal configuration (Figure 1).

2.2. Calibration

The objective of the calibration is to obtain the kinematic parameter values that minimize the system error. This procedure mainly consists of four stages:

- Determination of the kinematic model by means of non-linear equations
- Data acquisition
- Optimization or geometric parameter identification
- Model evaluation.

Once the kinematic model is obtained, the following step is data acquisition. The method used in this work for the platform calibration is external calibration. Three standard spheres were fixed to the moving platform as shown in Figure 2, and measured by means of the CMM with respect to the system A, placed on the moving platform. This measurement will allow us to calculate the standard sphere centres with respect to the reference system A, thus obtaining the position and orientation of the moving platform with respect to the reference system A.

The optimization of geometric parameters to minimize the platform error, E_i, where the sub-index i denotes the platform position. The non-linear equations, obtained in the forward kinematic model development, must be solved for every geometric parameter combination in every platform position.

The objective function that minimizes the error, E_i, compares the nominal values obtained through the measurement of the standard spheres, $D_{ni}=[x, y, z, \alpha, \beta, \gamma]$, with the platform position and orientation values, given by the kinematic model, $D_{ti}=[x, y, z, \alpha, \beta, \gamma]$, as shown by Eq. (3).

$$E_i = \sum_{i=1}^{n} (D_{mi} - D_{pi})^2 \tag{3}$$

where the sub-index m_i denotes the externally measured values and the sub-index p_i indicates the values calculated by means of the kinematic model.

This procedure is usually performed through approximation methods based on least-square fitting. To achieve this, the objective function to minimize is defined as the quadratic difference of the error obtained between the value computed by the kinematic model and the measured value of the platform position. The increment value will depend on the optimization method chosen, and it is defined for each iteration. Numerical optimization techniques are usually used to minimize the platform error, and the Levenberg-Marquardt method is one of the most used methods to solve these algorithms.

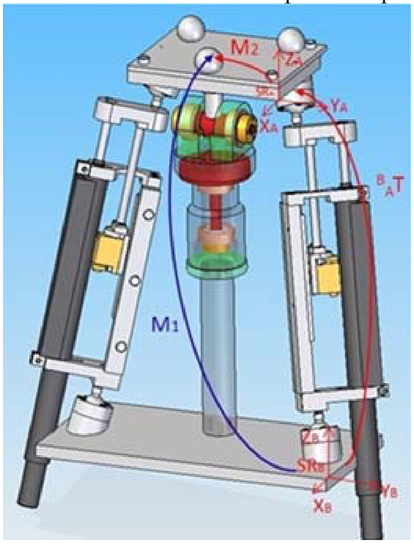

Fig. 2. Data acquisition.

3. Education software

The application developed was programmed in Matlab, and it allows us to perform the modelling and calibration of parallel mechanisms in an easy way.

The application consists of four mainly blocks (see Figure 3).

- The mechanism control
- The mechanism component characterization
- The mechanism behaviour evaluation
- The mechanism calibration

The control module allows us to control actuators and read encoder measurements.

The mechanism characterization performs three tests:

- Repeatability analysis in the actuator initialization
- Determination of the actuator backlash
- Repeatability analysis of the actuator in its entire work range

The repeatability analysis in the actuator initialization initializes the actuator to zero elongation. The actuator is then moved to the computed position and the measurement is captured by the linear optical sensor, thus obtaining the repeatability in the actuator initialization, as shown in Table 1.

The actuator backlash repeatability is then analysed. Linear optical sensors measure the actuator movement in the data acquisition process. To do this, the sensor scanning head is fixed to the rod actuator and the sensor glass scale is fixed to the actuator casing. The elongation of the actuator is increased to different computed positions.

To determine the actuator repeatability, the actuator backlash test should be performed at least five times, thus obtaining the deviation between the difference trajectories.

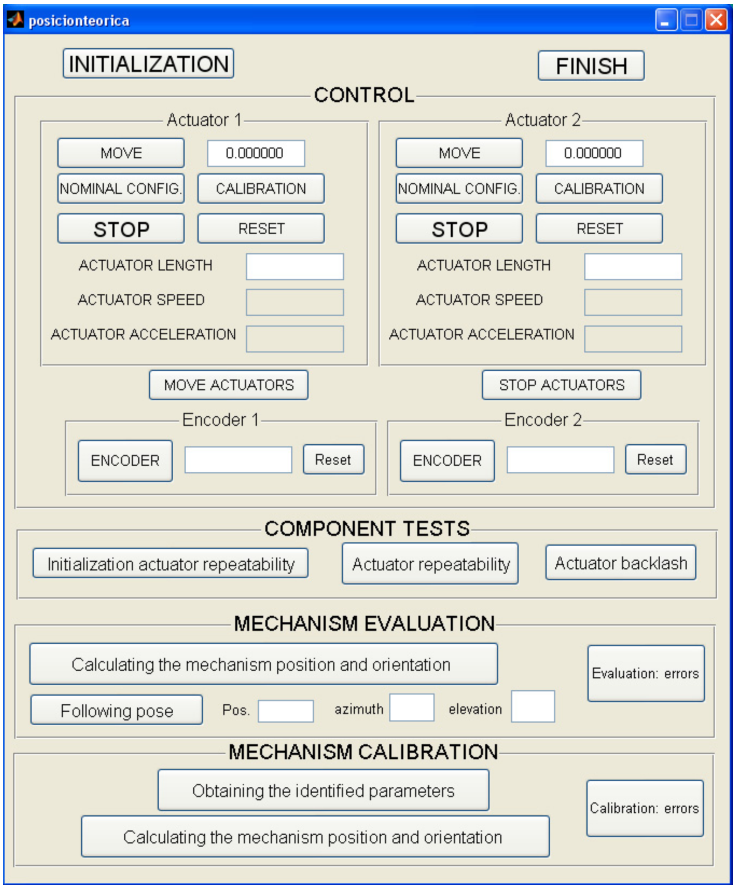

Fig. 3. Education software developed.

The following step evaluates the mechanism behaviour. This module calculates the position and orientation of the moving platform. The moving platform is placed in the nominal configuration, and the actuator elongation is obtained. The real position of the moving platform is then measured by means of a coordinate measuring machine and the algorithm compares the real and the calculated positions of the moving platform.

To do this, the algorithm must perform the following steps: firstly, positioning of the moving platform in the nominal configuration, secondly, defining the geometric parameter initial values. The following step is to calculate the moving platform position in the nominal configuration. In this step, the algorithm obtains the Euler parameter values (x, y, z, α, β, γ) from the values of the variables, φ_1 and φ_2. And, finally, calculating the actuator elongation to place the moving platform in the desired pose from the Euler parameters, the anchorage positions and the encoder actual readings.

One of the advantages of this application is its flexibility. The user can modify different algorithm variables and analyze the effects that take place with these changes. The application has been designed to allow the student to modify some characteristics in the design and modelling of the system. The values that can be modified in the kinematic model and in the mechanism evaluation are the following:

- Geometric parameter initial values
  This modification allows us to check the following statement: On one hand, if the geometric parameter initial values are near to the real values, the method used to solve the equation system ensures the algorithm convergence. On the other hand, if these values do not draw near to the real values, the algorithm cannot converge

Table 1. Repeatability in the actuator initialization.

Elongation	Error (mm)	Elongation	Error (mm)
5	0.045	40	0.045
10	0.044	45	0.044
15	0.044	50	0.045
20	0.043	55	0.044
25	0.045	60	0.044
30	0.045	65	0.045
35	0.045	70	0.042

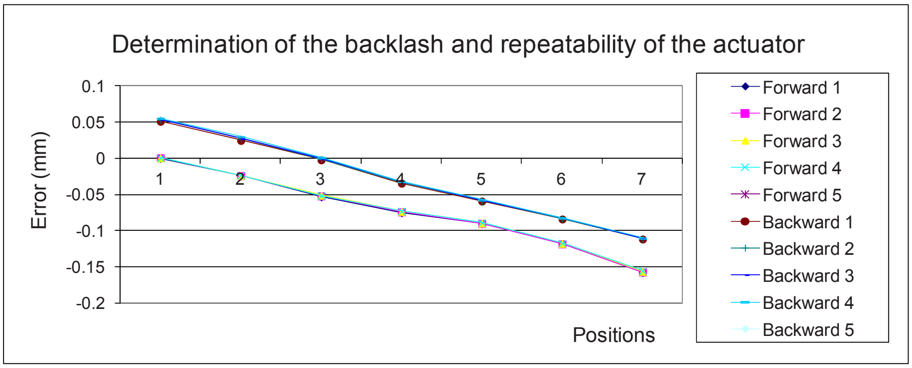

Fig. 4. Actuator backlash and repeatability.

- Computed positions
  Variable increments must be defined to go to the following position. These increments are established from the initial values of the joint variables, φ_1 and φ_2, covering the entire workspace. However, the user can modify these increments in order to change the analyzed poses inside the workspace. This option allows him to study the platform behaviour in different located areas.
- Joint anchorage positions
  The user can modify the position of the joint anchorages and study the effect that causes in the workspace.

Finally, module 4 performs the mechanism calibration. This module obtains the identified kinematic parameters and evaluates the mechanism error.

To achieve this, the algorithm developed performs the following steps:

- Calculation of the theoretical position and orientation of the moving platform by means of the kinematic model from the geometric parameter initial values (parameters without identifying).
- Objective function solution, by comparing the theoretical positions -obtained in point a)– with the measured positions (real position) captured in the mechanism evaluation stage. This step provides the identified parameter values that minimize the objective function.

Table 2. Mechanism error after calibration.

	Before calibration	After calibration
Mean error (mm)	3.324	0.285
Maximum error (mm)	5.361	0.485
Mean range (mm)	3.262	0.396
Standard deviation (mm)	0.913	0.139

- Calculation of the theoretical position and orientation of the moving platform by means of the kinematic model from the identified geometric parameter values.
- Mechanism error evaluation by comparing the theoretic positions –obtained in point c)– with the measured positions (real position) captured in the mechanism evaluation step.

The algorithm performs steps c) and d) iteratively until the objective function value is lower than the established tolerance.

4. Conclusions

The application has been programmed in a flexible way. The student can therefore modify different parameters and analyze the effect of these changes in the method convergence, in the mechanism behaviour and in the obtained workspace. The developed software allows the student to easily learn and understand the necessary steps in a mechanism calibration, allowing both an active and interactive learning and concept assimilation more efficient.

The procedure developed has been evaluated using a two DOF parallel mechanism, obtaining that the system precision improves more than one order of magnitude with the calibration procedure. The algorithm can be easily generalized to other parallel mechanisms containing rotary joints and actuators by modelling each kinematic chain.

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