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Optimal design and application of a low-cost wire-sensor system for the kinematic calibration of industrial manipulators

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ABSTRACT

The paper presents the results of a research project whose aim is investigating, from both a theoretical and an experimental point of view, all the aspects connected to the optimal design and use of a 6 DoF draw-wire sensors based measuring system in the kinematic calibration of industrial robots context. One essential operation in calibration is the measurement of the pose of the robotic gripper in a predefined set of points inside the working space. For this purpose optical devices, like laser trackers, are usually employed due to their precision, although they are very expensive. Therefore, the study of a low-cost measuring system and the investigation of the reachable performances could represent a relevant outcome in the evolution of the calibration task. With this aim the design of a wire-sensors based measuring system was developed and applied to a six revolute degrees of freedom anthropomorphic robot. In a preliminary phase, with the aid of simulations tools, the measuring system was optimized to obtain isotropic accuracy and high sensitivity, while in the following experimental phase the same system was employed for the kinematic calibration of the robot, achieving an accuracy lower than the robot repeatability, which practically represents a physical limit.

1. Introduction

Industrial robots may be limited in their position accuracy. The inaccuracy is due mainly to geometrical factors; whenever close constructive tolerances are used in the robot manufacturing, there is always a deviance between nominal and actual dimensions of the robot mechanical links. Other factors like thermal and load deformation, backlash, etc., …, contribute to increase gripper position errors. The precision of manipulators' position can be expressed in terms of many parameters, the most common of them being accuracy and repeatability [1]. Some of the mentioned factors produce constant effects and influence accuracy, while others produce variable effects and influence repeatability.

Industrial robots are generally highly repetitive, while their accuracy is sometime insufficient. For not calibrated industrial robots the accuracy is often up to some millimeters. Therefore, in many applications a calibration process becomes necessary. Accuracy depends on repetitive errors, the effect of which can be foreseen and compensated. This activity is called "calibration".

Very often a proper calibration can improve the robot accuracy up to a value close to the robot repeatability [2–7].

The kinematic calibration of a robot consists of two main parts:

1. the measurement of the gripper position and orientation error (pose error) for a set of poses in the workspace;
2. the development of a mathematical technique to determine the actuators' stroke able to compensate the measured error.

Several different tools are available for the measurement of the pose error [8,9]; the most common in industrial settings are the optical devices (e.g. laser trackers), which are very expensive equipments.

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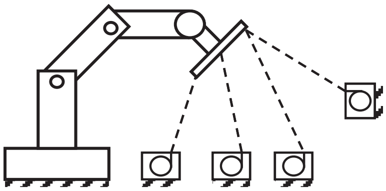

Fig. 1. Robot calibration with wire-sensor based measuring system.

The aim of this study is to investigate, from both a theoretical and an experimental point of view, the optimal design and use of a measuring system based on wire-sensors able to measure pose errors for the kinematic calibration of a robotic manipulator (Fig. 1).

In some applications cable-based sensors appear to be interesting, since they offer a good balance of accuracy, resolution, cost, portability and measuring range. They are much cheaper than optical sensors and can have a sufficiently large workspace for measuring moving objects (up to some meters), with an average accuracy from 0.1% to 0.01% of the range of motion.

Literature refers to the use of a cable-based tracking system (called *CaTraSys*) developed at Laboratory of Robotics and Mechatronics in Cassino: the experimental evaluation of robot kinematic performances, the measurement of the gripper pose and the working space by trilateration [10,11] and an experimental identification of human walking characteristics for rehabilitative issues [12,13].

Draw-wire sensors are commonly used for many other applications: position measurement on X-ray machines and in Computer Tomography, lift height measurements on wheel gripper and lifting systems, measurements of the separation movement in the realizing phase of satellites into space, vertical measurements of the aircraft wings deflections in structural tests, monitoring of the thermal expansion of pipelines in power stations, etc. [14].

A measuring system based on wire-sensors may be a good choice for applications that require limited accuracy and low-cost.

None of the mentioned papers describe optimization criteria to improve the precision of the measuring system.

The accuracy of the kinematic calibration depends on both the measuring system and the selection of measurement poses [15,16]. In [17] and [18] an innovative approach for the optimal selection of measurement poses is presented.

The focus of the present work is the optimization of the measuring system. The poses for the experiments were chosen in order to optimize the observability of the parameters.

This paper describes the optimal design principle of a new low-cost optimized 6-wire instrument conceived to calibrate industrial manipulators. The optimal configuration of the transducer was determined by applying an approach, developed by the authors, based on the study of the properties of appropriate matrices, in order to achieve high sensibility and an isotropic accuracy within a certain working space and to maximize the pose measurement precision.

Practical application of the low-cost 6-wire instrument to the calibration of an industrial robot is described.

The robot considered is a 6-DoF (degrees of freedom) anthropomorphic robot called DOGHI.

The measuring system is physically connected to the robot and without external measuring systems able to calibrate it. For this reason it is necessary to calibrate the complete system and develop a parametrical model of the system composed of the robot and the 6-wire instrument.

The carried out work can be summarized into three phases: the system design (preliminary phase), the simulation phase for the optimization of the configuration and the experimentation phase.

In the preliminary phase the structure of the measurement system architecture was developed, identifying two different configurations for the positioning of the measurement transducers, with the aim of optimizing their actual location this improved the quality of the measurement system.

In the simulation phase the influence of the number and the locations of the sensors on the calibration performances was investigated and the observability and redundancy of the parameters were studied.

In the experimentation phase the performances of the sensors (accuracy, repeatability and linearity) were evaluated by connecting the wire sensors to the linear axes of a parallel–serial robot equipped with linear optical encoders. Finally, the calibration of the DOGHI robot was performed by experimental measurements of its positioning error and by using the Newton–Raphson algorithm and an extended Kalman filter for the identification of the model parameters.

All these steps are critically described in the next sections.

2. The measurement system

The measurement system must measure the 3D position and orientation of the robot gripper.

2.1. Wire sensors

The choice of wire sensors has been considered as they are much cheaper than optical devices. They would, however, guarantee an adequate precision in measurement. According to the standards for the certification of robot performance EN ISO 9283 [1], the measurement procedure must have an uncertainty value not exceeding the 25% of the one to be verified. In our case,