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COBEM2019-1827 - ACCURACY EVALUATION OF INDUSTRIAL ROBOTS FOR MEDICAL APPLICATIONS: A CASE STUDY

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Abstract. *In recent years we have seen the undeniable advancement of robotics in the areas of medicine, due mainly to its accuracy of displacements and positioning. Researches show that robotics for medical applications have much to advance, presenting itself as a promising market in the coming years. However, the acquisition costs of this type of robots are high, when compared with classical industrial robots, in such way that, recognized medical centers around the world do not have perspectives in a short-term to access this technology. This work deals with a study of the potential of application of industrial robots, in medical and surgical procedures. Through the method developed in this work, it is possible to map inside the workspace of industrial robots, which regions are less influenced by constructive or manufacturing errors being therefore, more suitable for tasks that require precision, such as medical procedures. In order to develop this work, a mechanical part with a set of holes is used as a model simulating in a systematic way, the desired positions and orientations for the end-effector for a Kuka-Kr16 industrial robot used as a case study*

Keywords: *medical robotics; accuracy coefficients; accuracy of industrial robots; workspace analysis*

1. INTRODUCTION

Surgeries demand high precision and repeatability from the specialist physician, so the robotization of this procedure is interesting. Previous results show that the admissible errors in robotic surgeries are around 0.02mm (Omisore *et al.*, 2016; Taylor and Kazanzides, 2008), in order to guarantee the success of the procedure. Such an errors magnitudes are attended by robots typical of robotic surgeries such as Da Vinci and Zeus (Richter, 2013; Simaan *et al.*, 2018).

While the application of robots for medical procedures is a real prospect, the costs for designing, assembling and purchasing this class of robots limit in several ways the use of this technology as as in Brazil, where there are only 41 medical robots installed. In fact, the costs of acquiring a robot for medical procedures are high, reaching values between U$ 1.7 and U$ 2.0 millions (Michels *et al.*, 2018; Drake *et al.*, 1991), encouraging, on the other hand, the research and the development of alternatives based on low-cost solutions. Robots for medicine are of interest and have a wide needed, as a way to improve the quality of life and the quality of medical/surgical diagnoses and procedures.

In this work a case study is developed for a classical industrial robot - Kuka-Kr16 - where a mechanical specimen with a set of holes defined according to holes used in brain surgeries (Richter, 2013), is used in order to validate the proposition.

2. Robotization of surgerical procedures

Robotics application technology was already available in the 1980's, while in neurosurgery, robots start being used around the 1990's. In the course of the time, advances have been achieved and the use of robots has motivated the development of new applications (Simaan *et al.*, 2018).

In the context of robotics medical/surgery applications, the robot must assume some fundamental roles or operation modes and meet several requirements (Simaan *et al.*, 2018; Najarian and Afshari, 2012). To reach such requirements, it is important some additional capabilities associated with positioning accuracy and Interaction control. Interaction control is the problem of operating a robot in physical contact with the patient and is out of the scope of this paper. Thus, accuracy analysis is essential for robotic surgeries and the use of industrial robots has becoming common (Richter, 2013). The following sections present an accuracy study topic applied to an industrial robot.

3. Accuracy analysis for industrial robots

Accuracy analysis relates geometric tolerances belonging to the joints and robot's parts, to the end-effector's location precision requirements when constructive and /or manufacturing assembly errors (geometric errors) are present by Simas and Di Gregorio (2016). In general this analysis is used for lower-mobility manipulators (Liu *et al.*, 2011) or specific cases (He *et al.*, 2013) since their calibration procedures cannot compensate the effects of the geometric errors, that make the end-effector performs motions that do not belong to its designed displacement sub-group.

In (Simas and Di Gregorio, 2016) a general technique to perform the accuracy analysis is presented. Such technique has applicability for both robots with open or closed chains and consists in:

- the identification of the Independent Geometric Constants (IGCs) that define the geometry of the links;
- generation of an Extended Spatial Mechanism" (ESM) (Simas and Di Gregorio, 2016) in which contains only prismatic (P) and/or revolute (R) pairs obtained from the actual robot, by considering as additional passive-joints the IGCs's variables whose changes, making the end-effector moves out of its nominal displacement sub-group;
- the determination of the following form of the instantaneous input-output relationship of the ESM:

$$\vec{\omega} = \mathbf{D}_{f,P}\dot{\vec{q}}_{f,P} + \mathbf{D}_{f,R}\dot{\vec{q}}_{f,R} + \mathbf{D}_{g,P}\dot{\vec{q}}_{g,P} + \mathbf{D}_{g,R}\dot{\vec{q}}_{g,R} \tag{1a}$$

$$\dot{\vec{O}}_p = \mathbf{E}_{f,P}\dot{\vec{q}}_{f,P} + \mathbf{E}_{f,R}\dot{\vec{q}}_{f,R} + \mathbf{E}_{g,P}\dot{\vec{q}}_{g,P} + \mathbf{E}_{g,R}\dot{\vec{q}}_{g,R} \tag{1b}$$

  where $\dot{\vec{q}}_{j,P}$ and $\dot{\vec{q}}_{j,R}$ collect all the active ($j = f$) and additional passive variables P and R pairs, obtained from the IGCs's ($j = g$) and $\mathbf{D}_{f,i}$ ($\mathbf{E}_{f,i}$) and $\mathbf{D}_{g,i}$ ($\mathbf{E}_{g,i}$) are Jacobian matrices with 3 rows and respectively f and g columns, for i=R,P. The tuples $\vec{q}_{g,P}$ and $\vec{q}_{g,R}$ therefore represent the constructive or manufacturing errors between joints in length or angular terms respectively.
- the computation of the coefficients that appear in the following relationship, between the errors on the platform/end-effector pose and the geometric errors:

$$|\Delta\vec{\varphi}| \leq \delta_{f,P}\|\Delta\vec{q}_{f,P}\| + \delta_{f,R}\|\Delta\vec{q}_{f,R}\| + \delta_{g,P}\|\Delta\vec{q}_{g,P}\| + \delta_{g,R}\|\Delta\vec{q}_{g,R}\| \tag{2a}$$

$$\|\Delta\vec{O}_p\| \leq \epsilon_{f,P}\|\Delta\vec{q}_{f,P}\| + \epsilon_{f,R}\|\Delta\vec{q}_{f,R}\| + \epsilon_{g,P}\|\Delta\vec{q}_{g,P}\| + \epsilon_{g,R}\|\Delta\vec{q}_{g,R}\| \tag{2b}$$

  where $\delta_{j,P}$, $\delta_{j,R}$, $\epsilon_{j,P}$ and $\epsilon_{j,R}$ named "accuracy coefficients" are the largest singular values of the Jacobians matrices $\mathbf{D}_{j,P}$, $\mathbf{D}_{j,R}$, $\mathbf{E}_{j,P}$ and $\mathbf{E}_{j,R}$, respectively for $j = f$ and g. $\|\Delta\vec{O}_p\|$ and $|\Delta\vec{\varphi}|$ represent respectively the linear displacements and the rotation angle of a rotation matrix that lead the platform/end-effector from the nominal location to the actual one.

In this paper we study such a mapping, evaluating from a set of task specifications, in the form of coordinates of points and their respective desired orientations, under what limits an industrial robot has application for medical tasks, that involve the location of medical instruments or devices. Following a case study is performed in order to evaluate the proposition.

4. Case Study

The development of the case study to be presented in this paper, has application to any anthropomorphic industrial robot type $6R$ - Kuka-Kr16 [1] . It is interesting to note that with small adaptations, any industrial robot of similar conception can be analyzed by the following study to be performed.

From the direct kinematics model and using Eqs. (1, 2) the geometry of the Kuka-Kr16 is updated and presented in the Figure 1.

With respect to the Figure 1, we have generated ESM as a $RRPRRPRRPRPRPRR$ chain, where[2] $\vec{k}_b$, $\vec{k}_1$, $\vec{k}_2$, $\vec{k}_3$, $\vec{k}_4$ and $\vec{k}_5$ are the unit vectors of the active R pairs, obtained recursively.

The expressions presented $\vec{k}_i$, $\vec{u}_i$, $\vec{O}_i$, $\vec{d}_i$, for $i = 1, .., 6$ can be used in order to obtain the explicit geometric expressions of the ESM's Jacobians, presented in Eq. (1) by means of screw notation (Tsai, 1999)(Davidson and Hunt, 2004) used in the proposed accuracy coefficients method(Simas and Di Gregorio, 2016).

Considering the nominal geometry, when $O_1 = O_1'$, $O_2 = O_2'$, $O_4 = O_5' = O_5 = O_6$, $d_2 = d_3 = d_5 = n_4 = n_5 = 0$ and $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 0$ and, by the homogeneous matrices derived from the D-H method, the vectors and coordinates of the $\vec{k}_i$, $\vec{u}_i$, $\vec{O}_i$, $\vec{d}_i$, are obtained for composition of the Jacobians. With the differential model, the errors can be mapped according to the Equation 2. In the next section a study is performed in order to evaluate the proposed

[1]For more information visit: https://www.kuka.com/en-us/products/robotics-systems/industrial-robots/kr-cybertech

[2]The coordinate systems $O_b - x_b y_b z_b$, from accuracy coefficients analysis and $O_0 - x_0 y_0 z_0$, from D-H convention, are the same.

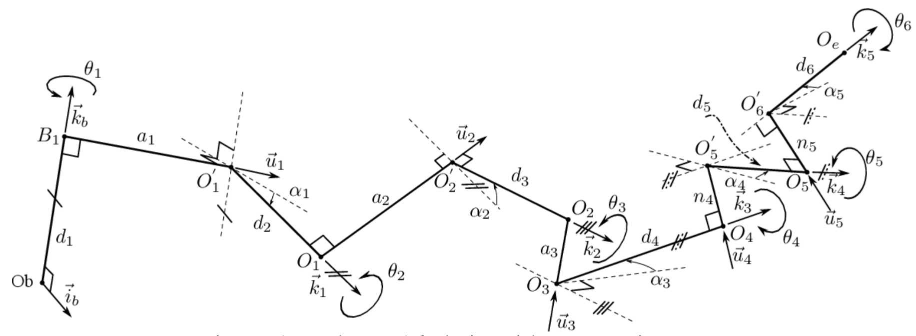


Figure 1: Kuka-Kr16 chain with geometric errors

analysis.

5. Experimentation and results

For the evaluation of the geometric performance of the Kuka-Kr16 industrial robot, a prototype of a mechanical specimen was adopted and used. This prototype was conceived by the authors in order to simulate a real task conditions, inspired in the classical peg-in-hole problem in robotics. Figure 2 depicts the used mechanical specimen.

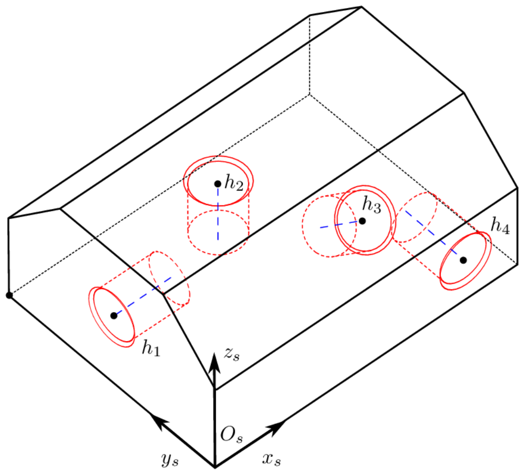


Figure 2: Prototype of the mechanical specimen, illustrating in red lines the used holes.

With respect to the Figure 2, it can be observe that there are four holes available on the faces of the specimen and they are oriented along the axes of the local coordinate system $O_s - x_s y_s z_s$.

The Kuka-Kr16's accuracy analysis consists of positioning the mechanical specimen inside a useful workspace (uW) (Lou *et al.*, 2005), defined inside the available workspace of the robot. Studying the Kuka-Kr16's reachable workspace, it was chosen a cube as uW. Such cube was centered on the coordinates $[780\ ,0\ ,345]^T$ mm with side length 500mm, having its edges parallel to the axes of the base coordinate system $O_b - x_b y_b z_b$.

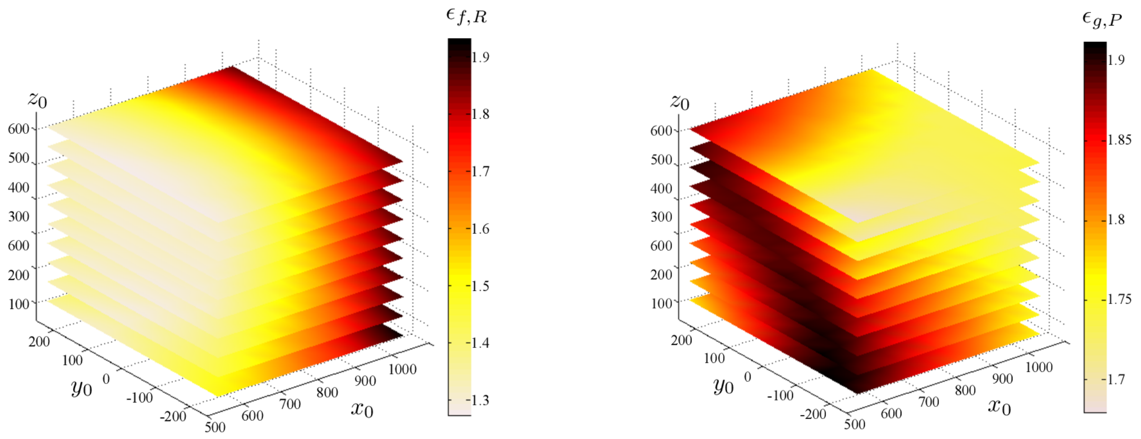
For each location of the mechanical specimen, the Kuka-Kr16's accuracy coefficients are computed in two points on the center axis of each hole. The first point consists in the coordinates of the hole on the surface of the mechanical specimen and second point is the respectively depth point of the hole

5.1 Results

In this case study, the task consists in making the robot access the 8 points belonging to the holes (2 points by hole) of the mechanical specimen for a fixed orientation and different positions inside its reachable workspace. At each point, the accuracy coefficients are computed and the "worst-case", or the highest values computed for each one is stored.

The higher values for the accuracy coefficients, and the respective variation of these values inside uW, show the regions where the possible (usually intrinsic) constructive and manufacturing errors, present in the robot, have major influence. Here we are not evaluating the dimensional quality of the robot, but rather which regions of the uW performs the best robot poses, indicated by the reached minimal positioning and orientation errors of the end-effector.

Evaluating the obtained numerical results, it was observed a constant value for $\delta_{f,R} = 1.7321$, and $\delta_{f,P} = 0$, once the robot has not active P pairs. The remaining accuracy coefficients, $\epsilon_{f,R}$, $\epsilon_{g,P}$, $\delta_{g,P}$ and $\epsilon_{g,R}$ range along the locations assumed by the mechanical specimen. Figures 3a, and 3b, present the partial graphical results depicting how the accuracy coefficients vary over each square surface of the uW cube.



(a) (b)

Figure 3: (a) Behavior of the range of $\epsilon_{f,R}$ and (b) behavior of range of $\epsilon_{g,P}$ inside uW.

6. CONCLUSIONS

This paper presented a case study in which the possibility of using a classic industrial robot for applications in robotic medicine was analyzed.

The study here developed used the Kuka Kr16 industrial robot as a reference, which together with the accuracy coefficients method, it was possible to identify inside an useful workspace, which region suffers less influences of constructive or manufacturing errors defined in terms of the orientation of joint's axes and distances between common normals.

As a way of evaluating the capacity of the proposed method it was used a mechanical specimen that represents some common medical activities as the brain surgeries. The proposed method here developed is a useful tool for the study of the feasibility of applying robots in tasks, where is required limited errors of positioning and orientation to the end-effector.

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8. RESPONSIBILITY NOTICE

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