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The unified orthogonal architecture of industrial serial manipulators

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ABSTRACT

The well-known inverse kinematics problem of six-degree-of-freedom serial manipulators has been solved with several approaches, but no attention has been given to provide an explicit solution involving the generality of industrial manipulators architecture. With the aim of embracing a large spectrum of industrial manipulators in a unified platform, an anthropomorphic classification is introduced. This classification considers sixteen different architectures, whose inverse kinematics is solved with a single approach, due to the geometric derivation introduced here as well. It is remarked that with this derivation, the user has the control of the eight possible solutions for a given pose, as they are identified by three Boolean variables defined in the pseudo-code presented. To emphasize this feature, an example is given to show the advantage of being able to visualize alternative configurations. A complementary formulation is introduced to solve the inverse kinematics of five-degree-of-freedom manipulators. Furthermore, it is presented a case study in which a survey of industrial manipulators is tagged according to the classification defined here.

1. Introduction

Algorithms that solve the inverse kinematics problem of all six-degree-of-freedom (6 DOF) serial manipulators have been presented in the past. For instance [1] used dialytic elimination to derive a 16 degree polynomial in the tangent of the half-angle of a joint variable. Whereas in [2,3], the authors presented designed rules for finding manipulators with simple inverse kinematics. They also studied the influence of structural parameters on the reduction of degree of characteristic polynomial. Furthermore, for the solution of the inverse kinematics with the use of symbolic computation, the authors in [4] included the solution of the GMF Arc Mate industrial manipulator. For serial manipulators containing a spherical or planar sub-chain, [5] developed an explicit algebraic solution of 6R serial manipulators. Other studies regarding kinematic transformations for the PUMA 560 manipulator have been reported [6], where some parameters are introduced to characterize configurations and they are used to find the inverse kinematic solution. Algorithms for the inverse kinematics solution for general 6R manipulators have been presented [7,8], where the solution must be obtained with numerical methods.

For decoupled serial manipulators, the inverse kinematic problem is solved in two parts, first the position and then the orientation [9], where the formulation is provided for all types of decoupled manipulators, however, in some cases, the solution for the position problem should be obtained numerically. For the case of orthogonal decoupled manipulators [10], the closed-form solution is presented for simple cases, i.e., those in which most of DH parameters [11], are zero. Other studies on orthogonal manipulators with less than 6 DOF have been reported [12]. In this case, although the inverse kinematic solution is provided analytically, it is not general since most of the DH parameters are zero as well. Studies on workspace topologies of commercial manipulators [13,14], present a classification as function of workspace kinematics properties, but it is not related to the anthropomorphic architecture of the manipulators.

The main objective of this paper is to provide a framework for the architecture design and simulation of industrial serial manipulators grouped into a classification based in their orthogonal and/or anthropomorphic architecture with spherical wrist and 6 DOF or less.

In order to understand the study made for the industrial serial manipulators, a section describing the software package applied to test the manipulators architecture, is presented in the first place, then, a classification based on the twist angles of the first three axes of the manipulator is introduced. Then, a section is dedicated to introduce the pseudo-code regarding the formulation of the closed- form solution to the inverse kinematics problem on serial orthogonal and decoupled manipulators. Topics of the last two sections are the design of a manipulator's skeleton to explore possible alternative configurations for a given task, and the discussion of a case study where a survey of industrial manipulators is presented.

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2. A brief description of the graphical tool

A software package named ADRS (Architecture Design and Robot Simulation), dedicated to the architecture design and simulation of serial manipulators is being developed under the ADEFID platform [15]. ADEFID is basically a software development kit written in MS Visual Studio® C++ with the aid of OpenGL libraries.

Besides its attributes in training robotics, ADRS applications have been extended to assist research issues, as they are shown in further sections. Such is the case where the skeleton models are generated to clearly illustrate the classification introduced here for industrial manipulators, or the case where for a given manipulator pose, all possible solutions can be displayed in-line to find alternative configurations.

Moreover, ADRS is being created under object oriented programming concept and it is an open source software, what makes possible to test different algorithms related to manipulator problems, by defining custom classes without changing all the graphical tools required to handle the manipulator's architecture, in other words, if a researcher develops a novel algorithm for the inverse kinematic solution of a redundant manipulator per say, he can create a sub-class of the CRobot class (which is an ADEFID's library component), and override the virtual function SetFullInverse() to test its own algorithm. Then, after compiling the code, the skeleton of the manipulator to be tested can be designed interactively with the desired DH parameters and the simulation can be performed to visualize the test results. In Section 4, SetFullInverse() and other functions are overridden to test the approach introduced in this paper.

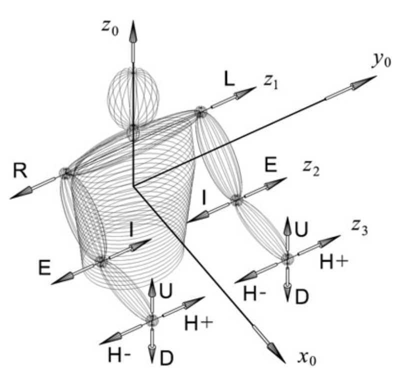

Fig. 1. Nomenclature definition on the anthropomorphic classification.

3. Notation and manipulators' architecture

The Denavit–Hartenberg notation [11], which defines four parameters, namely, angle (θ), offset (b), distance (a) and twist angle (α), is applied on the study presented here, which is focused on the orthogonal architecture of serial decoupled manipulators.

The main feature of the results of this study is that most of industrial manipulators can be considered within the resulting classification, which is based upon the value of the twist angles regarding the first three joints. In theory, the twist angle of these joints can be set arbitrarily, however, the closed-form inverse kinematics solution derived here for 6 DOF decoupled manipulators is achieved if these angles hold given values. Thus, α_1 can be either 90° or 270°, if the manipulator is right shoulder (R) or left shoulder (L), respectively, whereas the elbow is considered external (E) or internal (I) if α_2 is either 0° or 180°, respectively. Furthermore, the forearm can be facing down (D), up (U), or horizontally (H), depending on the value of α_3, which in turn, can hold 0°, 90°, 180°, or 270°. A graphical representation of the nomenclature adopted along this work is presented in Fig. 1. It is important to note that this classification is made from the anthropomorphic point of view, and each combination of shoulder, elbow and forearm, provides a different solution of the inverse kinematics problem. The approach presented here is valid for all combinations.

The convention on the description defined above is based on the *zero configuration* of the manipulator, i.e., all joint variables are set to zero. Furthermore, once the distance and offset of each link of a given manipulator are defined, there are up to sixteen possible manipulator architectures depending on the combination of the twist angles. In all cases, for simplicity and because they do not intervene in the classification, the last three joints defining the wrist are omitted.

The architecture of most common frequently encountered industrial serial manipulators lies in this classification. Table 1 shows these combinations as sixteen possible assemblies associating the twist angles to the shoulder, elbow and forearm of the manipulator. Furthermore, the rightmost column of Table 1 indicates which of the DH parameters are required to define the forearm.

Thus, manipulators with right shoulder and external elbow are shown in Fig. 2 whereas, those with left shoulder and internal

Table 1
Anthropomorphic classification according to the twist angles.

Arch.	Description				α_1	α_2	α_3	Parameter defining the forearm
RED	Right shoulder		Forearm down		90	0	90	a_3 and/or b_4
REU		External elbow	Forearm up				270	
REH+			Horizontalforearm	Ext. wrist			0	a_3
REH-				Int. wrist			180	
RID		Internal elbow	Forearm down			180	270	a_3 and/or b_4
RIU			Forearm up				90	
RIH+			Horizontalforearm	Ext. wrist			180	a_3
RIH-				Int. wrist			0	
LED	Left shoulder		Forearm down		270	0	270	a_3 and/or b_4
LEU		External elbow	Forearm up				90	
LEH+			Horizontal forearm	Ext. wrist			0	a_3
LEH-				Int. wrist			180	
LID		Internal elbow	Forearm down			180	90	a_3 and/or b_4
LIU			Forearm up				270	
LIH+			Horizontal forearm	Ext. wrist			180	a_3
LIH-				Int. wrist			0	

Note: Manipulators with symmetrical architecture on the shoulder ($b_2=0$) use "*S*" instead of "*R*" or "*L*", for example, a manipulator that can be considered either RID or LID, is named as SID manipulator.