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Artificial neural networks for feedback control of a human elbow hydraulic prosthesis

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ABSTRACT

The paper addresses feedback control of actuated prostheses based on the Stewart platform parallel mechanism. In such a problem it is essential to apply a feasible numerical method to determine in real time the solution of the forward kinematics, which is highly nonlinear and characterized by analytical indetermination. In this paper, the forward kinematics problem for a human elbow hydraulic prosthesis developed by the research group of Polytechnic of Bari is solved using artificial neural networks as an effective and simple method to obtain in real time the solution of the problem while limiting the computational effort. We show the effectiveness of the technique by designing a PID controller that governs the arm motion thanks to the provided neural computation of the forward kinematics.

1. Introduction

The topic of actuated prostheses for human use is nowadays one of the most important branches of bio-robotics. The goal of giving back to amputees the possibility to carry out daily activities on their own represents a fascinating challenge for both medical and engineering researchers. The first studies about this topic started with the so-called "Utah Arm" (Late 70's, University of Utah), that was the first artificial limb able to decode myoelectric signals coming from nerves and still represents, in its latest version, one of the most diffused and commercially available architectures [27].

Nowadays, several solutions are available in the related literature to model and simulate the work of articulations in limb prostheses: the choices of research groups from all over the world concern both the mechanisms typology and energy supply. Two useful examples are the serial gas-actuated arm by Fite et al. [5] and the parallel architecture by Mendoza-Vázquez et al. [26], equipped with linear electrical actuators. The research group of the Polytechnic of Bari (Italy) developed a parallel simplified "Stewart platform like" mechanism [6], with a wire transmission that links the floating platform to three hydraulic cylinders. The device uses two cylindrical elementary hinges to connect forearm and arm, and three hydraulic actuators placed on the upper arm to reduce moving masses. These actuators are classified into two main ones (frontally placed) and a secondary one (placed in the rear of the prosthesis). Each frontal actuator is linked with two wires, one towards the front forearm and the other towards the rear part of the forearm. These two actuators are in charge of the positioning of the floating platform, connected to the forearm. The rear piston brings a pulley that forces another wire connected with the forearm.

This particular parallel geometry is characterized by the analytical indetermination of the forward kinematics problem, in spite of the solution of the inverse one. Indeed, the configuration required to the linear actuators for each position of the floating platform, and consequently their law of motion, is easily obtained analytically using rotation matrices with the required orientation angles. However, it is not possible to univocally determine the configuration of the mobile platform starting from the actuators' elongations. In fact, the forward kinematics problem of the Stewart platform consists in finding the position of the moving platform for a given set of limbs (connecting wires) lengths. The problem is to find the angular coordinates of the elbow prosthesis knowing the elongations of the rods of the hydraulic cylinders. The formulation of closure relations generates highly non-linear

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equations with multiple solutions [17]. Hence, in the literature different numerical methods have been studied to determine in real time the solution of the forward kinematics problem for parallel mechanisms such as the Stewart platform. Many contributions provide a solution to the forward kinematics problem based on numerical iterative schemes, such as the Newton–Raphson method, closed-form solutions, or approaches based on predictors. Innocenti and Parenti Castelli [21] proposed the formulation of a "closure equation" to solve the problem iteratively. This approach was further employed in [8,20,22,28,24,25,29,18,30] with different approximations and iterations. Moreover, Wen and Liang [31] provided the closed-form solutions for the general planar Stewart platform. Further contributions in this direction may be found in [4,19]. However, these methods are numerical, not strict closed-form methods.

In this paper, the problem is solved using artificial neural networks as an effective and simple method to obtain in real time the solution of the forward kinematics problem while limiting the computational effort. The proposed approach is applied to the hydraulic prosthesis developed by the research group of the Polytechnic of Bari [6] and we show the effectiveness of the method by designing a PID closed loop controller that effectively governs the arm motion thanks to the provided neural computation of the forward kinematics.

In the context of neural approaches, the first contribution was proposed by Lee and Han [23] who developed a technique based on linear predictors, where gains of each predictor are calculated by a neural network. Moreover, Geng and Haynes [7] used an innovative approach with neural networks with a relative error of few percents. In this paper we improve this result, achieving a better performance. More specifically, dealing with a particular Stewart-like parallel platform, we take a general way to solve the problem that can be extended to more general cases of multi-input–multi-output systems. In particular, the specificity of our system, featuring a joint in the center that is the prosthesis elbow, leads us to search for a suitable method to solve the forward kinematics problem. In fact, the system topology specificity lies in the fact that two hydraulic linear actuators govern, by some connecting rods, both the elbow motion (that is obtained by imposing suitable identical elongations to the pistons) and the wrist motion (that is obtained by imposing opposite motions to the pistons). Thus, the system features a complexity due to the simultaneous motion of elbow and wrist. Hence, we adopted a parallel mechanical structure that leads to equally partitioning the actuator effort between the two pistons, which operate concurrently. Such an energetic optimization, obtained by means of the Stewart platform, leads to a complex kinematics of the component. Using a modified platform also led to a simple determination of the component inverse kinematics, thus leading to a straightforward neural networks training. In fact, a neural approach was also proposed by Dehghani et al. [3] using a three layers network, while we employ a single layer one, with optimal performance and without unnecessary complications.

Summing up, the proposed solution leads to several advantages, namely:

1. the use of identical actuators working in parallel and not in series (which would lead to different actuators because of the different ranges of the kinematics variables);
2. a prosthesis behavior that is similar to that of the human limbs thanks to the double effect pistons, which can be assimilated to the bicep-quadricep group;
3. a suitable system robustness in the employment of oleo dynamics pistons (thus theoretically immovable after being elongated);
4. a limited computational complexity thanks to the artificial neural network use;
5. a more rapid response in simulation with respect to a numerical algorithm for determining the inverse kinematics, at the cost of a longer network training phase, which may however be carried out offline, disregarding time constraints; and
6. the ability to reconfigure the system according to the changes in its structure with a low computational effort (namely, by simply re-training the neural network on a new example set).

The remainder of the paper is organized as follows. Section 2 positions the paper in the related literature, discussing its contribution. In addition, Section 3 describes in detail the innovative elbow prosthetic device. Hence, the subsequent section describes the model of such a device and Section 4 addresses the solution of the forward kinematics problem by artificial neural networks. In addition, Section 4 develops a closed loop controller of the device. The paper ends with a concluding section and an up to date reference list.

2. The elbow prosthetic device

The architecture of the hydraulic prosthesis developed by the research group of Polytechnic of Bari is schematized in Fig. 1. The prosthesis concept is based on the replica of human articulations: the mechanism implements a cable transmission in order to mimic human body tendons and is based on a parallel mechanism, with the aim of maintaining coupled movements of flexion/extension and pronation/supination, so as to optimize the actuators' power consumption. In Fig. 1 a 3D kinematics scheme of the mechanism is shown: the upper and lower hinges allow respectively the flexion/extension and the pronation/supination movements. The two wished forearm Degrees Of Freedom (DOFs) are directly actuated by the coordinated motion of two hydraulic double effect cylinders. One more (rear) cylinder is equipped, as shown in Fig. 1, with a collaborative function during flexion movements. In this paper the device is considered actuated just by the two principal cylinders. A tendon-based transmission is set, to transmit the motion to the platform, to give stiffness to the mechanism in all directions during motion, and to take advantage of the third cylinder, as described in [6] in more detail.

The device is based on a parallel mechanism, in which the motion along the required DOF is obtained acting on the lengths of the links L_1 and L_2, that connect points B_1–P_1 and B_2–P_2 (see Fig. 2).

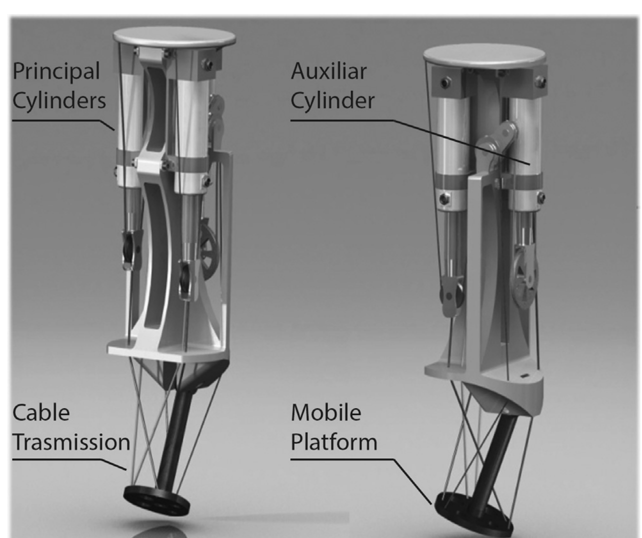

Fig. 1. 3D Scheme of the elbow prosthesis developed by the research group of Polytechnic of Bari (front and rear view).