

Simulation of a parallel mechanical elbow with 3 DOF

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ABSTRACT

The kinematics simulation and modeling of a mechanical elbow of 3 degrees of freedom, is introduced by highlighting the main features of the mechanism related to the design criteria. The mechanical elbow is used as a transhumeral prosthetic part, and it has been built as a parallel topology consisting of electric linear actuators and universal joints. The parallel mechanism has 4 legs. 3 are electric linear actuators, and the fourth leg provides mechanical support for the whole structure and holds a DC Motor that performs the action of gripping objects. Furthermore, this paper shows the inverse kinematics for the elbow by geometric methods, and the MatLab-simulation results show the workspace of the movement and the ability of the mechanical elbow to replicate the movements of a biological one.

Keywords: Kinematics, Modeling, Simulation, Robot kinematics.

RESUMEN

El propósito de este documento es mostrar el modelado y simulación de un codo mecánico de 3 grados de libertad empleado como prótesis de codo transhumeral. El mecanismo paralelo tiene 4 piernas de las cuales 3 son actuadores eléctricos lineales y la cuarta pierna proporciona soporte mecánico para toda la estructura y aloja un motor que realiza la prensión de objetos. En el trabajo se resumen las principales características del mecanismo acorde con los criterios de diseño empleados. Se desarrolla la cinemática inversa para el codo por métodos geométricos y los resultados son usados con propósitos de simulación para mostrar el espacio de trabajo y su capacidad de movimiento para replicar los movimientos de un codo biológico. Las simulaciones son desarrolladas bajo el ambiente de MatLAB.

Palabras clave: cinemática, simulación, modelado, cinemática de robot.

1. Introduction

Current research in prosthetics has been focused on the development of prosthetic hands and prosthetic legs [1]. However, the research and development of elbows is very poor and current research has only been focused on prosthetic elbows with one degree of freedom (DOF). In the same manner, both mechanical and myoelectric prosthetic elbows [2] are serial and with a single DOF, such as Utah Arm [3], and the Edinburgh Arm [4]. An improved development is a serial mechanism with 3 DOF [5], but with the disadvantage that it is not suitable for high weights and its electronic devices are not portable so it cannot be used in prosthetic elbows. Similar developments with pneumatic muscles present this problem [6]. In contrast, a complete and

functional prosthetic elbow must have 3 motorized axes in order to provide 3 DOF [7][8], namely: flexion-extension, pronation-supination and humeral rotation, as shown in Fig. 1. These movements can be defined with major axes according to [9][10], and this capacity lets us evaluate the movements required for a prosthetic elbow, which should perform the movements of a biological one.

In [11]-[12], a new motorized design of a prosthetic elbow performing flexion-extension, pronation-supination, and humeral rotation, with the characteristic of having electrical drives actuators in a parallel topology is introduced, as shown in Fig. 2. Its main advantage is that it provides an improved workspace higher than typical parallel robots, due to the mechanical

configuration and universal joints. Most importantly it is that the link of the mechanical elbow supports high loads and allows a workspace fitness for a prosthetic hand with 3 DOF. Henceforth, in this paper a general description on the modeling and simulation of the prosthesis and its ability to emulate human elbow movements is introduced.

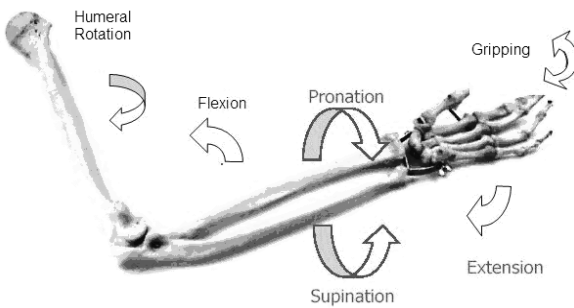


Figure 1. Movements of a human elbow: flexion-extension, pronation-supination, and humeral rotation.

2. Elbow prosthesis mechanism

2.1. Design basics

There are different types of actuators [13]-[14], but we have found that the best electrical actuators are those that have the following characteristics: small size, low weight, low power consumption, high torque, the best power/volume ratio silent operation, minimal heat generation, fast response and simple control. The important part in the selection of an actuator is related to giving the prosthesis enough space to contain the electrical and electronic components. In this work, we used a DC brushless motor to have better power/volume and power/weight ratio than with brushed or induction motors. The mechanical design of the elbow was developed in Solid Edge, exploiting its ability to make kinematic and dynamic simulation

For instance, the basic concepts involved in the modeling and simulation of the parallel mechanical elbow of 3 DOF are modularity, self-contained and anthropometric relations.

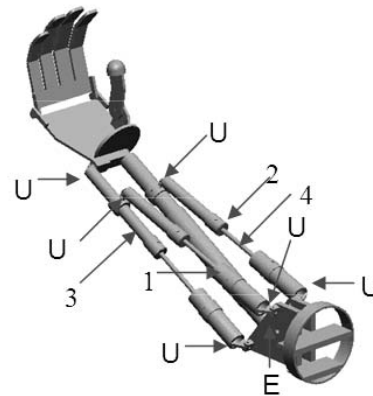


Figure 2. Elements of the mechanism/prosthesis proposed in [13]-[14]. It is a parallel topology with 3 linear actuators (1, 2, 3), and a fourth leg which supports the mechanical structure.

2.2. Overview of the mechanism

As shown in Fig. 2, the mechanism has four legs (links), one is fixed and enables the mechanism to have structural rigidity, and it contains the servo-motor allowing the movement of the hand gripping. Equally important, the other three legs are in parallel configuration consisting of linear actuators.

The elbow has a mechanical structure less than 1 Kg of weight. Its dimensions are approximately 30 cm long, 8 cm in diameter. The placement of the actuators is based on the biological structure of the upper limb, where each joint is driven by at least two muscles. Therefore, each movement is performed by activating at least two actuators in parallel. Basically, the parallel configuration of actuators allows the adding of their forces. This configuration allows the system to perform a

major number of forces on the same point, and it reflects the best employment of the components.

As a result, this system provides better characteristics of strength and lightness. Robustness, which has several links that give greater stability and lightness than the ratio of load-force capacity, is much higher compared with serial prosthesis, because the structure is lighter and the force is divided between the numbers of parallel actuators.

3. Modeling

The construction of the kinematic model for a parallel-robot does not have the same characteristics as for a serial robot. In the majority of serial robots, the Denavit-Hartenberg methodology is applied [15], where one can obtain a direct kinematic model in a systematic manner, and it is independent of its physical configuration.

To obtain the inverse kinematic model of a parallel mechanism, the use of geometric considerations for each configuration and numerical methods for solving the system of equations is required. However, in parallel robots, the direct kinematic model is quite complex to derive, and in many cases it cannot have a single analytical solution [16]. Besides, there are pioneering studies on kinematic models such as the interval analysis [17], [18], topological synthesis [19], quadratic form [20], complex linear approximation [21], theory screws [22], kinetostatic model [23], and Lie algebra [24], among others. Furthermore, in the case of the parallel mechanical elbow described herein, we use the methods proposed in [25]-[28].

3.1. Kinematic model

For the kinematic modeling, it can be assumed that the mechanism behaves as a single block [29], due to the configuration of the legs. In Fig. 2, the cylinders work as follows: the movement of

humeral rotation is labeled by angle θ , the bending of the elbow is labeled by γ , and pronation and supination by β . The dimensions of the cylinders labeled by γ and θ are infinity small, since their joint is spherical. These considerations are necessary because the joint is considered spherical.

According to a kind of Euler angle, the parallel mechanism has the rotation matrix described by (1). The mechanism allows the workspace shown in Fig. 3, based on the ranges of movement for a biological elbow. As can be seen, the space is semi-spherical and includes ranges of motion involving the operation of the electric linear actuators (parallel mechanism for the elbow).

$${}^A R_B = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} = \begin{bmatrix} c\theta c\beta - c\gamma s\theta s\beta & -c\gamma c\theta c\beta - c\theta s\beta & -s\gamma s\theta \\ c\gamma c\theta s\beta + s\theta c\beta & c\gamma c\theta c\beta - s\theta s\beta & s\gamma c\theta \\ -s\gamma s\beta & -s\gamma c\beta & c\gamma \end{bmatrix} \quad (1)$$

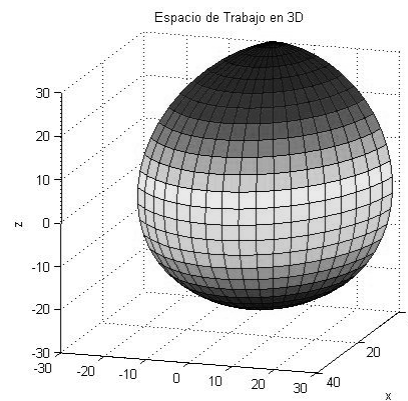


Figure 3. Workspace of the parallel mechanism.

3.2. Kinematic modeling of an artificial muscle

Figure 4 shows a linear electric actuator diagram. This kind of actuators has the capacity of emulating the movement of a biological muscle. This device could be considered an artificial muscle with characteristics like those of human muscles for elbow prosthesis.

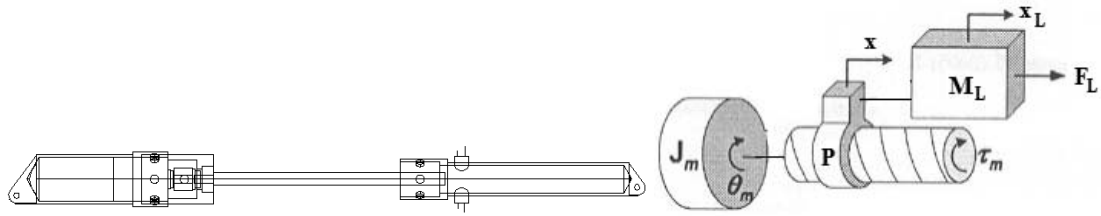


Figure 4. a) Scheme of linear electric actuator mechanism b) Free body diagram for the linear electrical actuator.

Figure 5 shows the relationship between the angular advance caused by the motor and the linear advance after the ball screw; in this case, β represents the angle of the ball-screw lead; l represents the step of the lead and $x(t)$ the linear advance [30][31]. In this way,

$$x(t) = \frac{l}{2\pi} \theta_m(t) \quad (2)$$

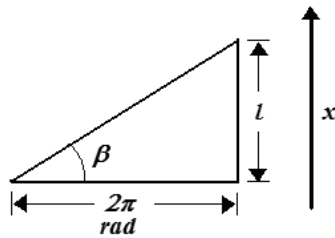


Figure 5. Workspace of the parallel mechanism.

Where $\theta_m(t)$ is given in radians and represents the angular advance generated by the motor.

From (2) we have:

$$\theta_m(t) = \frac{2\pi}{l} x(t) \quad (3)$$

With (3), the relation between angle position and linear position is found and lets us evaluate the movements required for a linear electric actuator in a prosthetic elbow.

3.2. Spatial kinematic model

In Fig. 6, the parallel mechanism of 3DOF to emulate the model by geometric methods is shown. For this mechanism. Let us consider the homogeneous transformation matrix given by (1), with the orthogonal-considerations. Considering that the positions of the linear actuators regarding the platform and the foundation are known in advanced by their coordinates.

The evaluation of q_i , which is the vector from the origin to each point placed at the end of the actuator on the platform, is determined by (4), which generates three equations (q_1, q_2, q_3) related with the base-points to the platform-points.

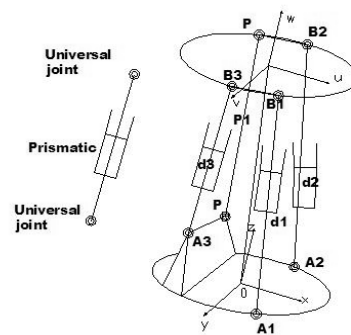


Figure 6. Simplified parallel mechanism.

$$q_i = p + {}^A R_B {}^B b_i \quad (4)$$

The distance of each linear actuator is obtained through (5), to derive the spatial kinematic model of the parallel mechanism to be used in the prosthetic elbow with 3 DOF. Finally, the inverse kinematic model for this parallel mechanism for prosthesis applications is (6):

$$d_i^2 = [q_i - a_i]^T [q_i - a_i] \quad (5)$$

$$\|d_i\| = \sqrt{[q_i - a_i]^T [q_i - a_i]} \quad (6)$$

With (6), the flexion-extension, pronation-supination and humeral rotation angles are found and let us evaluate the movements required for a prosthetic elbow, which should perform the movements of a biological one.

4. Simulation

From (1) to (6), implemented in MatLab, a simulator and graphics of the behavior are obtained, which facilitates the study on inverse

kinematics. In this manner, one can simulate the evolution of the DOFs from and to the desired position of the mechanism.

The simulator displays kinematic behaviors of the parallel mechanism in 3 dimensions to view and make the movements required for the prosthetic elbow (see Fig. 9). It also assesses the behavior of the actuators and their extensions or contractions as an entire body, to verify that the structure is hold in a single block. The simulator allows us to get insight on aspects for a redesign, which is by changing geometric parameters, angles, lengths and others to explore alternatives and mechanism of the elbow.

4.1. Simulations results

4.1.1. Linear electric actuator

Fig. 7 shows the linear electric actuator in extending and contracting modes. Figure 8 shows the behaviors of the linear electric actuators in the linear electric actuator for a parallel mechanical elbow, in this case the displacement is linear both of angular and linear position.

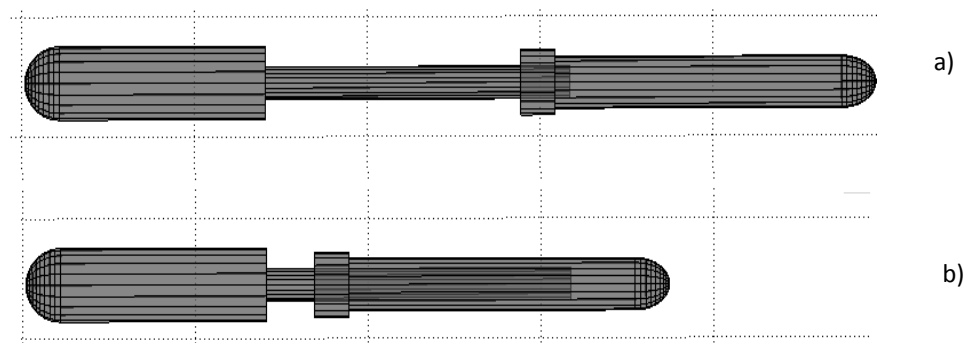


Figure 7. a) Linear actuator extended b) linear actuator contracted.

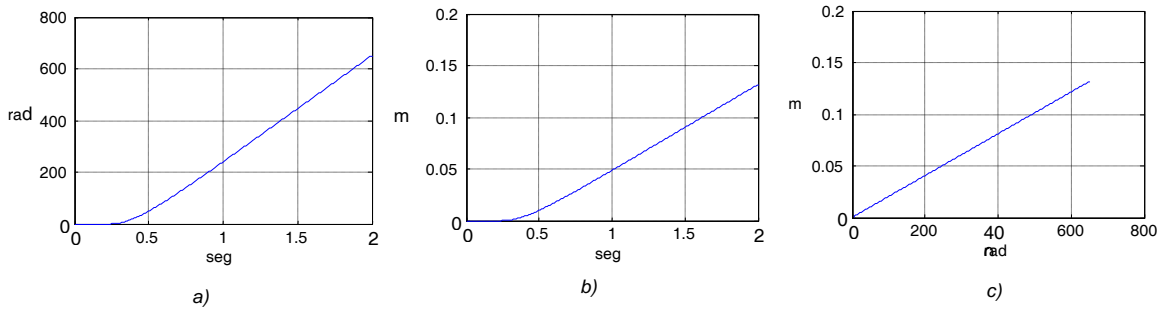


Figure 8. a) Angular position b) Linear Position c) Angular position vs. linear position.

In Fig. 9 to Fig. 10, the behaviors of the linear electric actuators in the parallel mechanical elbow are shown. For flexion-extension, only two

actuators (1 and 2) perform movement. Similarly, for the humeral rotation, only actuators 2 and 3 perform movement.

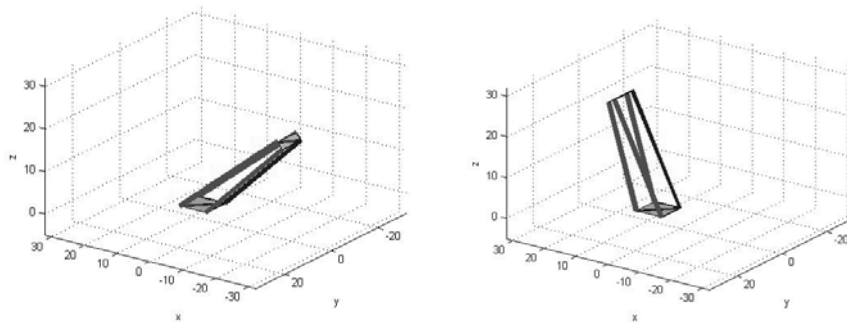


Figure 9. Simulation of the parallel mechanism in flexion-extension movement.

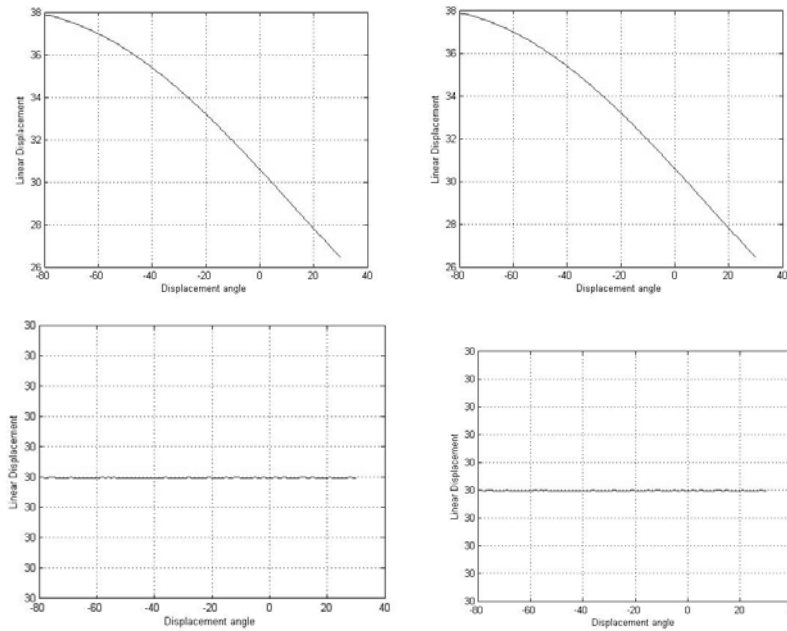


Figure 10. Behavior of the linear electric actuator 1,2,3,4 in flexion-extension movement.

Finally, the movement of pronation-supination is shown in Fig. 11 to Fig. 12; in this case, the linear actuator 3 performs movement in order to reach the desired movement. One can see that actuators 1 and 3 perform the same movement behaviors.

In humeral rotation, similar results are obtained and actuators 2 and 3 develop movement while actuator 3 does not. Graphics in the previous sections show that is possible for this mechanism to develop the same movements like a biological arm as flexion-extension, pronation-supination and humeral rotation. Thanks to this, a patient can use this mechanism and perform many tasks in his life.

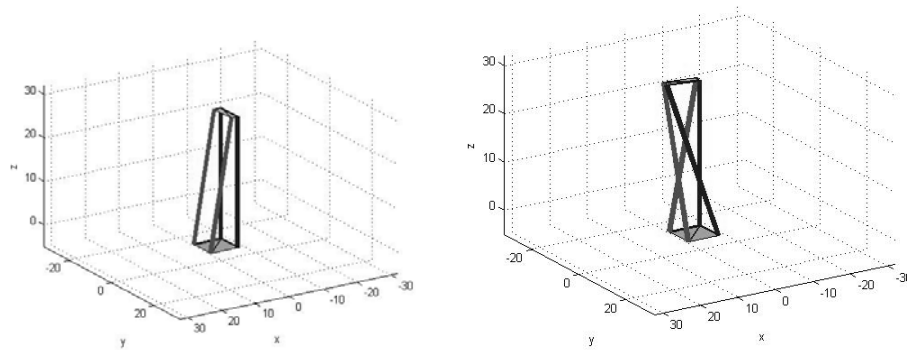


Figure 11. Simulation for a parallel mechanism in pronation-supination movement.

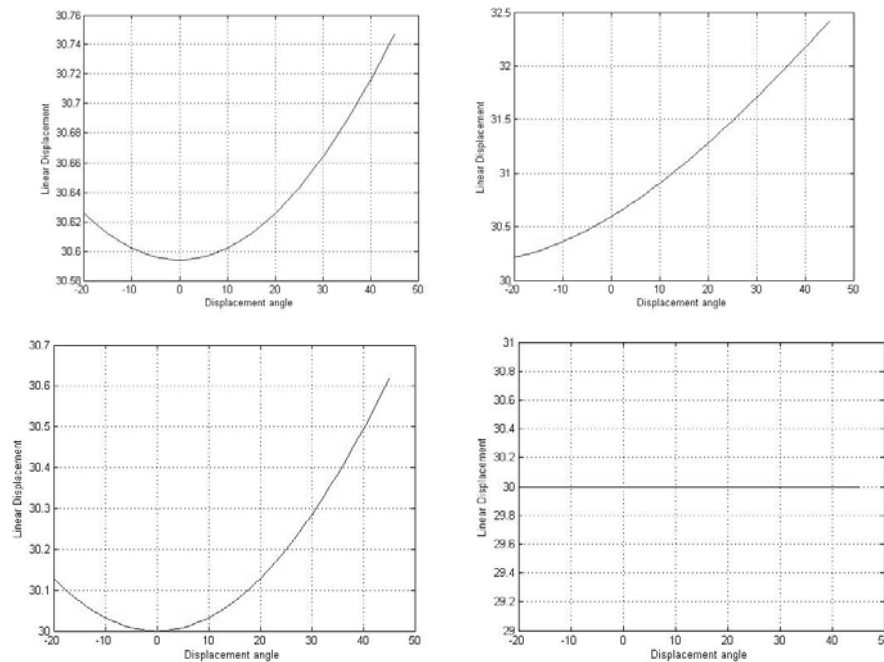


Figure 12. Behavior of the linear electric actuator 1,2,3,4 in pronation-supination movement.

5. Conclusion

It was shown that the kinematic model of a parallel robot does not have the same characteristics as for a series robot. Furthermore, the kinematic analysis for a parallel mechanic elbow has been introduced. Some design aspects and the most relevant details of their physical structure, the mechanics and kinematics, have been described. As main features, it includes: anthropomorphic, 3 DOF as a mechanism; mechanically self-contained, to be tailored to the patient; modularity of hardware and software to facilitate the addition, modification, expansion or replacement of parts.

The characteristics of the prosthetic functions such as large number of DOFs, control and easy of movement, light, and anthropomorphic high performance characteristics, depend directly from the actuators and mechanisms that are used in prosthetics.

The parallel prototype has been inspired by the human biological elbow operation and it was intended to be a medium to seek for functional restoration in patients with transhumeral amputation.

Finally, a simulator to view graphics on the scene in a realistic, simple and visual sense has been developed, and it shows its usefulness for the analysis of a three-dimensional kinematic mechanism, which is a test-bed for the elbow designed as a parallel mechanism.

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