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Kinematic analysis of the finger exoskeleton using MATLAB/Simulink

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A paralyzed and not fully functional part of human body can be supported by the properly designed exoskeleton system with motoric abilities. It can help in rehabilitation, or movement of a disabled/paralyzed limb. Both suitably selected geometry and specialized software are studied applying the MATLAB environment. A finger exoskeleton was the base for MATLAB/Simulink model.

Specialized software, such as MATLAB/Simulink give us an opportunity to optimize calculation reaching precise results, which help in next steps of design process. The calculations carried out yield information regarding movement relation between three functionally connected actuators and showed distance and velocity changes during the whole simulation time.

Key words: *kinematic, finger exoskeleton, MATLAB/Simulink*

1. Introduction

In the literal sense by the word exoskeleton we mean an external skeleton that secures and supports animal body. This is opposite to internal skeleton, which is supporting body. Some animals (i.e., a turtle) have both types of skeletons, internal and external (shell). Shells protect animals from environmental threats such as predator attack.

Exoskeletons can also be found in human history. One of the exoskeleton types used by humans is an armor. Armors have been used for ages, for protection against injuries. Contrary to an animal shell, which is a result of a natural process, armor is an artificial exoskeleton.

Exoskeletons can also be divi ded into active and passive.

The aforementioned typical, historical armor is a passive design. Its movement is based on human musculoskeletal system. It protects human, but at the same time it decreases their movement abilities.

We can also imagine a design of an active exoskeleton. This kind of system can increase movement abilities, such as velocity or forces generated by limbs. In Hybrid Assistive Limb [1] design we can observe this kind of construction in the real life. It supports lower and upper part of human body during daily activities such as standing, walking, climbing stairs or lifting heavy loads up to 40 kg.

As said before, an active exoskeleton can be used in daily activities, but it is not the only purpose of this kind of design. It can be used by army for military applications (Sarcos/Raytheon company project), as industrial design or for medical purposes, such as help in movement of disabled/paralyzed limbs or rehabilitation.

Articles describing medical purpose exoskeleton devices designed for rehabilitation are [2]–[4], and for movement of disabled/paralyzed part of the human body [5].

Properly designed exoskeleton can also help by limiting fatigue of supported part of the body during professional activities. This kind of device was described in work [6].

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Active exoskeletons may cover the needs of movement of full human body or only the selected part. In this paper we have taken into consideration a finger exoskeleton. Suitably selected geometry is studied applying specialized software – MATLAB/Simulink environment.

2. Materials and methods

The model used in MATLAB/Simulink environment is the base of the finger exoskeleton. It will support movement of a disabled, or paralyzed finger, and its design is based on information regarding human finger skeleton [7].

The main design assumption is to provide finger movement abilities close to natural, by applying the lowest possible forces on a finger joint. This approach gives an opportunity to use the system not only for support of disabled/paralyzed fingers, but also for an increase of forces generated by the finger above natural model. All internal joint forces are transmitted by the exoskeleton. This is achieved by a four link system mounted on a human palm.

The composition of the design is shown in Fig. 1. The basic system is composed of three link subsystem (*d*, *c*, *e*) and one link (*k*) supporting finger. It is being driven by two actuators. S_1 is responsible for a movement of subsystem, S_2 position is related to S_1 movement and adjusts position of *k*-link. The *k*-link is connected with a finger and moves around a finger joint center of rotation.

S_2 actuator adjustment is realized in such a way that in every position a straight line between *A*, *R*, and *S* points is obtained.

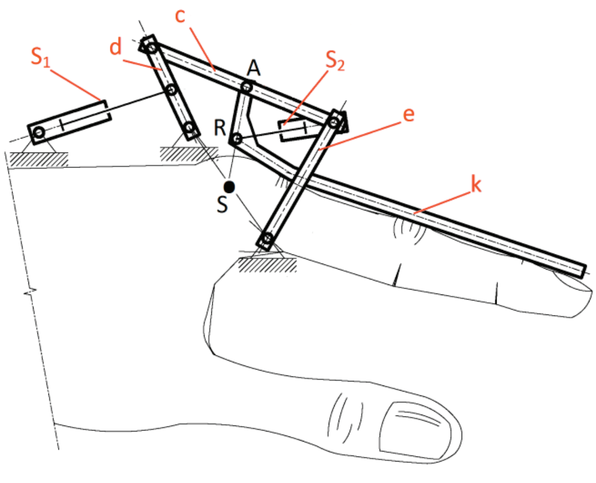

Fig. 1. Physical model

The geometrical model of the system is shown in Fig. 2. *d*, *c*, *e*, and *k* are the lengths of basic system links. x_1, and x_2, are the lengths of S_1 and S_2 actuators. α_1, α_2, α_3 and α_k are respectively *e*-, *d*-, *c*-, and *k*-link angles. α_7 is the S_1 actuator angle. a_1, b_1, *a* and *b* are the system mount dimensions. Point *A* is placed in the geometrical center of *c*-link. Between points *E* and *R* S_2 actuator is placed. As mentioned before point *S* is the finger joint center of rotation.

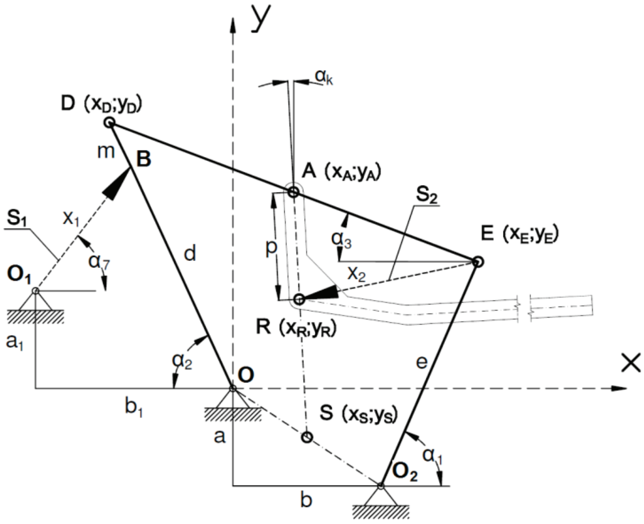

Fig. 2. Geometrical model

System calculations are based on reference [8]. α_2, and α_7 angles can be calculated from the following system of equations

$$\alpha_7 = \arccos\left(\frac{b_1 - (d-m)\cos\alpha_2}{x_1}\right),$$
$$\alpha_2 = \arcsin\left(\frac{\alpha_1 + x_1 \sin\alpha_7}{d-m}\right). \tag{1}$$

α_3 and α_1 angles are found from the formulas

$$\alpha_3 = \mathrm{arctg}\left(\frac{d\sin\alpha_2 + a}{d\cos\alpha_2 + b}\right)$$
$$-arc\cos\left[\frac{((d\sin\alpha_2 + a)^2 + (d\cos\alpha_2 + b)^2)^2 + c^2 - e^2}{2((d\sin\alpha_2 + a)^2 + (d\cos\alpha_2 + b)^2)c}\right]; \tag{2}$$

$$\alpha_1 = arc\sin\left(\frac{a + s\sin\alpha_2 - c\sin\alpha_3}{e}\right); \tag{3}$$

and remembering that y_A and y_R are the *y*-axis coordinates of points *A* and *R*, respectively, and α_k can be calculated by the following formula

$$\alpha_k = \arccos\left(\frac{y_A - y_R}{p}\right). \qquad (4)$$

Angular velocities ω_1, ω_2, ω_3 and ω_k are calculated as time derivatives of α_1, α_2, α_3 and α_k angles. x_2 position is estimated by the equation

$$x_2 = \sqrt{(x_E - x_R)^2 + (y_E - y_R)^2}\,, \qquad (5)$$

where x_E, y_E, and x_R, y_R are respectively point E and R coordinates.

Distance between points A and S is given by the following formula

$$AS = \sqrt{(y_A - y_S)^2 + (x_S - x_A)^2}\,, \qquad (6)$$

where x_A, y_A, and x_S, y_S are respectively point A and S coordinates.

3. Results

Solutions of the governing equations are found using the MATLAB/Simulink scheme. The program yields detailed information regarding specified values, such as actuator length (x_1, x_2), actuator velocity

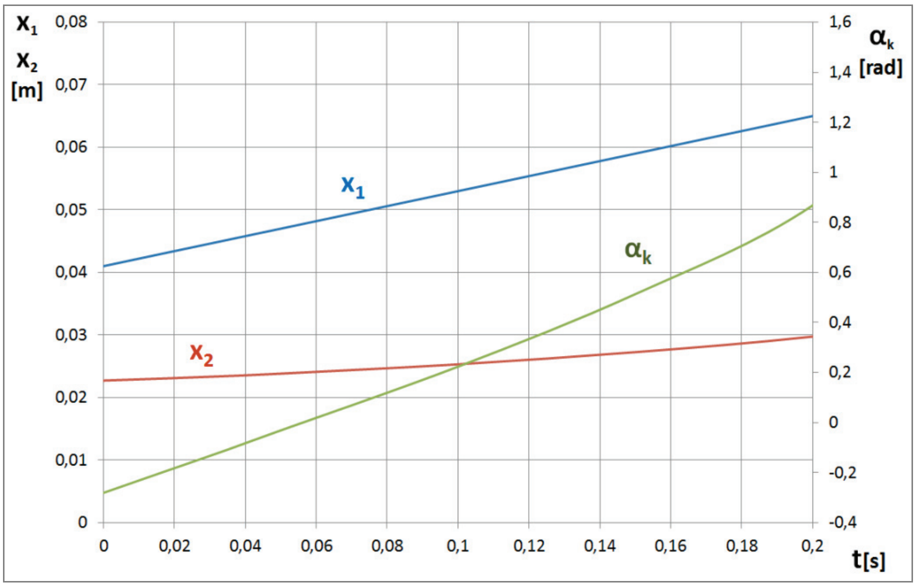

Fig. 3. x_1, x_2 and α_k vs. time

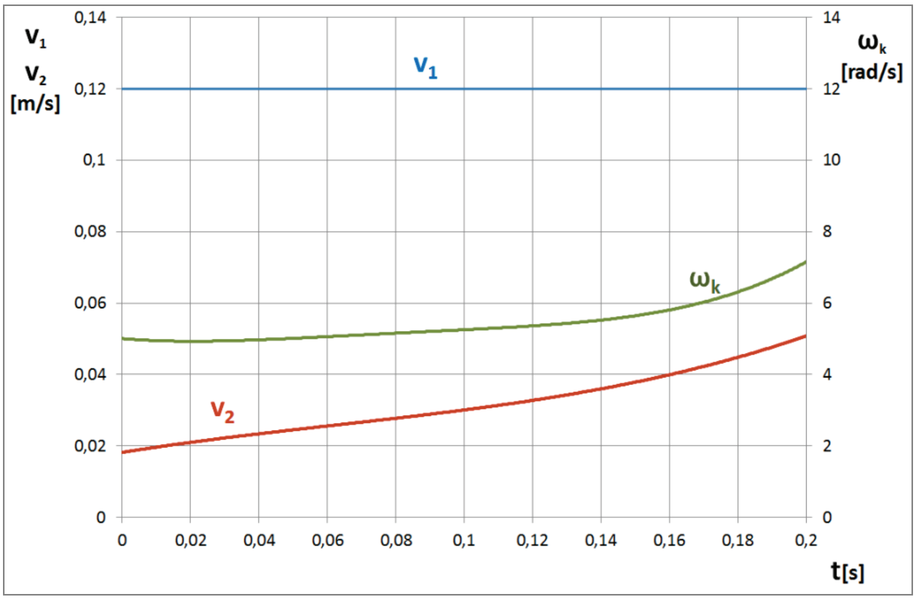

Fig. 4. v_1, v_2 and ω_k vs. time

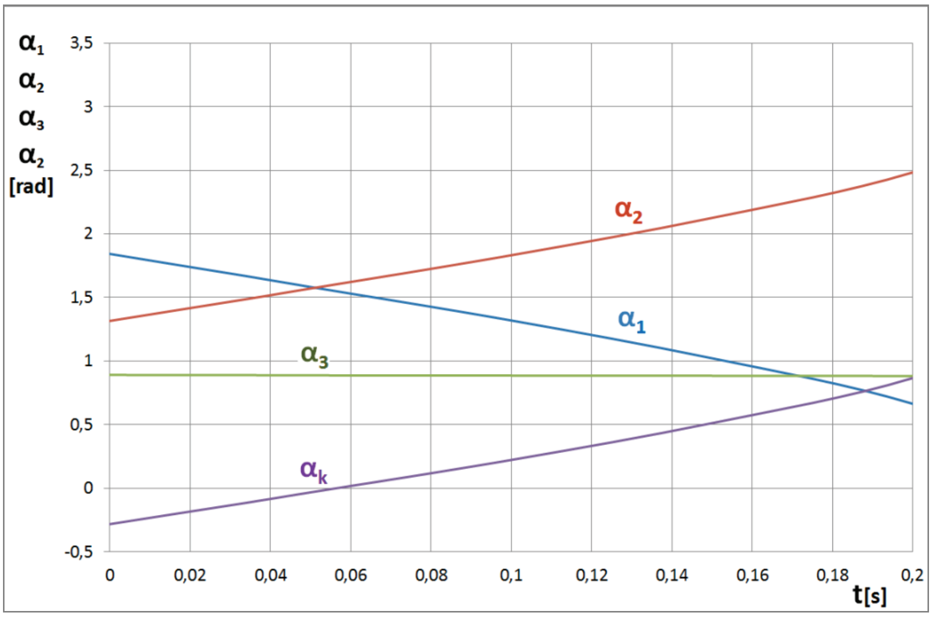

Fig. 5. α_1, α_2, α_3 and α_k vs. time

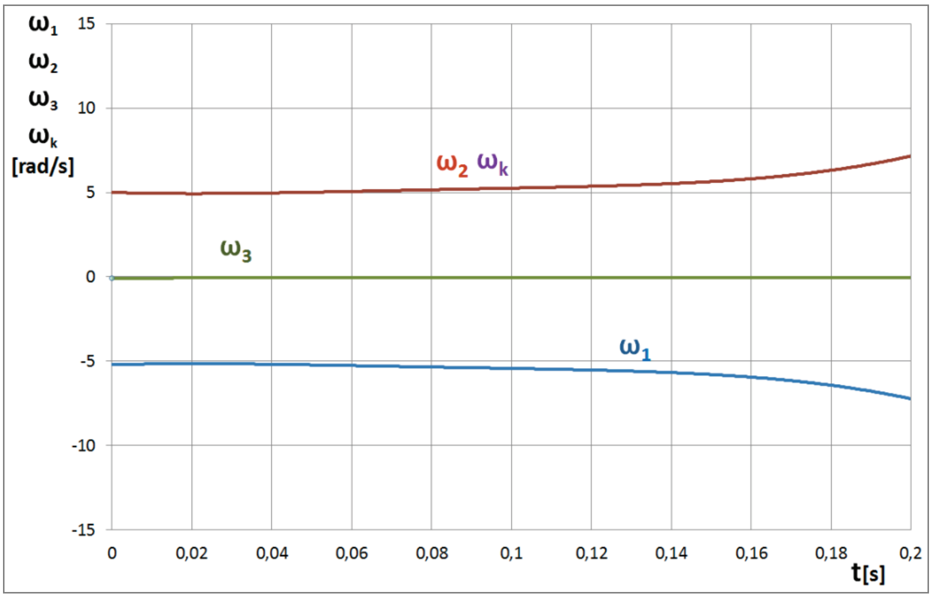

Fig. 6. ω_1, ω_2, ω_3 and ω_k vs. time

(v_1, v_2), angles (α_1, α_2, α_3, α_k), and angular velocities (ω_1, ω_2, ω_3, ω_k), which gives an opportunity to understand systems behavior.

MATLAB/Simulink software was used to check system behavior for specific parameter configuration:

$v_1 = 0.12$ [m/s]; $a_1 = 0.014$ [m];
$b_1 = 0.046$ [m]; $a = 0.045$ [m];
$b = 0.037$ [m]; $d = 0.035$ [m];
$m = 0.011$ [m]; $c = 0.058$ [m];
$e = 0.035$ [m]; $p = 0.007$ [m];
Total simulation time 0.20 [s];
Full range $\alpha_k \sim 1{,}745$ [rad] (100°).

These parameters are used in real life system model adapted for left palm of a 33-year-old man 180 cm tall.

Time based diagrams show the length of S_1 and S_2 actuators compared with the α_k angle (Fig. 3), v_1, v_2 velocities compared with ω_k angular velocity (Fig. 4), α_1, α_2, α_3, α_k angles (Fig. 5), ω_1, ω_2, ω_3, ω_k angular velocities (Fig. 6).

Main results of the simulation are reported in Table 1.

Numerical results of geometric data given by MATLAB/Simulink model have been checked on the

Table 1. Values of selected lengths, velocities, angles and angular velocities for specified time steps

t (s)	x_1 [m]	V_1 [m/s]	x_2 [m]	V_2 [m/s]	α_1 [rad]	α_1 [°]	ω_1 [rad/s]	α_2 rad]	α_2 [°]	ω_2 [rad/s]	α_3 [rad]	α_3 [°]	ω_3 [rad/s]	α_k [rad]	α_k [°]	ω_k [rad/s]
0.00	0.041	0.12	0.022	0.019	1.84	105.6	–5.20	1.31	75.4	5.09	0.89	51.1	–0.07	–0.28	–16.1	4.99
0.05	0.047	0.12	0.024	0.025	1.58	90.7	–5.32	1.57	90.0	5.22	0.89	50.9	–0.10	–0.03	–1.8	5.12
0.10	0.053	0.12	0.025	0.029	1.31	75.6	–5.27	1.83	105.0	5.23	0.89	50.8	–0.03	0.22	12.8	5.09
0.15	0.059	0.12	0.027	0.038	1.02	58.6	–5.93	2.12	121.8	5.86	0.88	50.7	–0.03	0.51	29.4	5.79
0.20	0.065	0.12	0.029	0.049	0.66	38.1	–7.15	2.48	142.3	7.15	0.88	50.6	–0.03	0.87	49.7	7.08
0.25	0.071	0.12	0.033	0.072	0.08	4.7	–11.65	3.06	175.8	11.69	0.88	50.4	–0.07	1.46	83.6	11.83

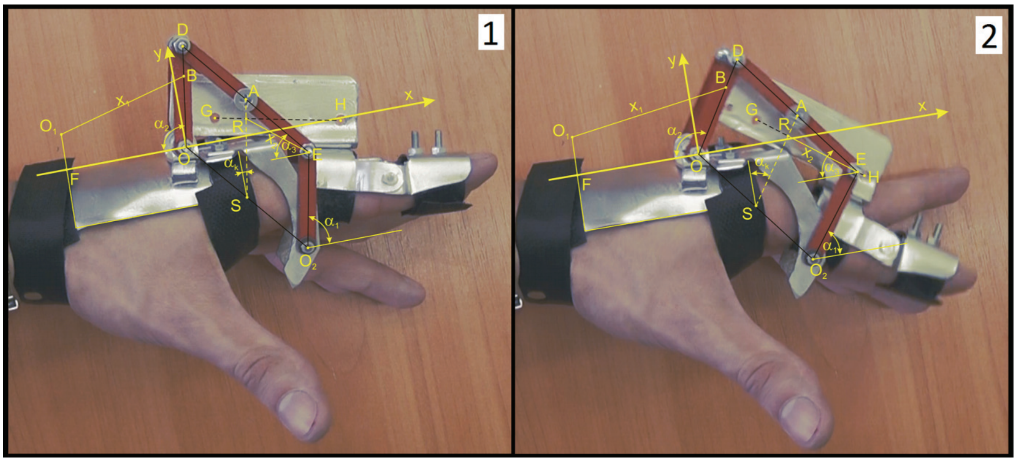

Fig. 7. Position 1 and Position 2 of the real model

Table 2. Values of selected lengths and angles for two positions of real and numerical model of finger exoskeleton

	x_1 [m]	x_2 [m]	α_1 [rad]	α_1 [°]	α_2 [rad]	α_2 [°]	α_3 [rad]	α_3 [°]	α_k [rad]	α_k [°]
Position 1 real model	0.051	0.026	1.38	79	1.73	99	0.89	51	0.17	10
Position 1 simulation	0.051	0.024	1.40	80	1.75	100	0.89	51	0.14	8
Position 2 real model	0.060	0.029	0.94	54	2.11	121	0.91	52	0.61	35
Position 2 simulation	0.060	0.028	0.93	53	2.24	128	0.89	51	0.61	35

basis of a real life model. For this check a video capturing method has been used. Because the system described in MATLAB/Simulink has the same basic dimensions, it is possible to check program output data by measuring geometric data on registered image. Two pictures showing random model position were selected from the captured image material.

Comparison between real measurement and the simulation is reported in Table 2.

4. Discussion

The proposed physical and mathematical models allow the control of a human finger movement. Specialized software, such as MATLAB/Simulink gives us an opportunity to optimize calculation reaching precise results, which helps in the next steps of design process.

A different mechanical approach, but the same purpose of exoskeleton design is presented in [9]. In this paper, MATLAB software application enables us to read information regarding angles, forces and torques in the device designed.

The calculations carried out yield information regarding movement relation between two functionally connected actuators S_1 and S_2. Calculation performed in MATLAB/Simulink environment have given information regarding S_1 and S_2 actuator length change (x_1 and x_2 values) during the full movement phase on the basis of constant S_1 actuator velocity (v_1). In Fig. 3, we can also observe the influence of x_1 distance on α_k angle change. This is important information because as α_k is the *k*-link angle, so it is also the total finger angle.

Other values that can be found after analyzing the model are velocity of the second S_2 actuator (v_2), system angles (α_1, α_2, α_3, and α_k) and angular velocities (ω_1, ω_2, ω_3, and ω_k). Important information is the *AS* distance. This is additional parameter which has to be taken into consideration during the calculation process. It is crucial for the selection of a_1, b_1, a, b, c, d, e, p lengths because it determines the position of *k*-link with respect to the finger joint center of rotation point. *AS* distance change in required movement range has to be possibly the lowest because it influences finger leading precision. For that purpose all system dimensions have to be carefully selected. In the system presented in this paper the distance between point O_2 and O is the same as the length of *c*-link. That is why the *AS* distance is constant and its value is 0.035 m. Constant *AS* distance is the best possible solution in this kind of system.

A brief check of the MATLAB/Simulink model has been conducted using preliminary real model and the video capturing method. As shown in Table 2 for the same x_1 distance for real life and numerical model, the differences in parameters such as S_2 actuator length, α_1, α_2, α_3 and α_k angles, are small considering the required accuracy of full system, limited by the not rigid connection between human body and exoskeleton itself. The differences between the numbers are also caused by positioning the hand in front of camera during image capturing, as the camera capturing plane has to be parallel to the finger exoskeleton movement plane.

The MATLAB/Simulink model presented is a step in the finger exoskeleton design phase. It shows relation between x_1 and x_2 co-ordinates and actually it is being complemented with dynamics calculations which will give information regarding acting forces and torques. It was used for calculation of preliminary real model (shown briefly in Fig. 7), and will be used in design process of finger exoskeleton prototype. Its optimization will also be conducted on the basis of MATLAB/Simulink model.

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