Mechanisms and Machine Science

Georg Rauter · Philippe C. Cattin · Azhar Zam · Robert Riener · Giuseppe Carbone · Doina Pisla *Editors*

New Trends in Medical and Service Robotics

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Mechanisms and Machine Science

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Preface

Medical and service robots face growing demands on their functionality and performance in a broad range of applications. Therefore, strengthening our community through interdisciplinary work is beneficial for all parties involved: researchers, technology providers, medical healthcare personnel, and most importantly patients. This year, methods from laser physics and virtual/augmented reality-based surgical planning have found their way to augment the functionality, possibilities, and safety of medical and service robots.

This year, we had to face difficult circumstances due to the worldwide pandemic situation with COVID-19 that prevented us from realizing MESROB 2020, the 7th International Workshop on New Trends in Medical and Service Robotics, Basel, Switzerland. Nevertheless, our faithful community keeps supporting our successful story of MESROB workshops, which led to this book. The oral presentations of the accepted papers in these proceedings are planned for MESROB 2020, which should be finally held at the University Hospital Basel, Basel, Switzerland.

The entire story of MESROB conference events started with the first of its kind in 2012 in Cluj-Napoca, Romania. Following events were MESROB 2013 at Institute “Mihailo Pupin” in Belgrade, Serbia; MESROB 2014 at EPFL in Lausanne, Switzerland; MESROB 2015 at IRCCyN in Nantes, France; MESROB 2016 co-organized by the University of Innsbruck and Joanneum Research in Graz, Austria, and MESROB 2018 at the School of Engineering of the University of Cassino and South Latium in Cassino, Italy.

This workshop series is also sponsored by IFToMM, the “International Federation for the Promotion of Mechanism and Machine Science” and is one of the main conferences for the IFToMM Technical Committees on Biomechanical Engineering, Robotics and Mechatronics, and Computational Kinematics. The content of the MESROB 2020 book covers a wide range of aspects and topics such as 1) assistive devices, 2) surgical robotics, 3) lasers, planning, and navigation in surgery, 4) performance evaluation, 5) mobile and service robots, and 6) tissue modeling. These contributions are provided as a collection of 37 papers that were selected among the 49 submitted contributions on the basis of a blind peer-review process.

We wish to express our gratitude to the authors, the reviewers, and the scientific committee for their valuable contribution to ensure the scientific quality of MESROB 2020.

July 2020

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Contents

Assistive Devices

Trajectory Planning and Fuzzy Control of a Hand Exoskeleton for Assisted Rehabilitation

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Abstract. One of the current trends within service robotics is the development of exoskeletons for rehabilitation. It has been reported in literature that the use of exoskeletons can help to solve some problems relating to repetitive tasks that involve rehabilitation therapies. The present paper deals with dynamic modeling and the development of a controller based on fuzzy logic for the trajectory tracking that describes basic movements used in rehabilitation therapy. The ranges of movement are obtained by video analysis software and the paths are designed using Bézier curves. The proposed controller is evaluated numerically with simulations using the obtained dynamic equations.

Keywords: Exoskeleton · Fuzzy logic · Trajectory planning.

1 Introduction

In recent years, the development of robotic systems to support rehabilitation has increased considerably. It is possible to find options for these type of devices for different parts of the body in the market. The importance of improving the function of the hand after suffering an injury has stimulated the increase in the development of exoskeletal devices at a commercial and research level. Reports of the control of these devices are scarce in literature. An example of an alternative technique that works for controlling these devices is the fuzzy logic controller reported in [1,2]. The application of fuzzy logic in the design and implementation of control systems is one of the main areas of advancements. The main advantage in the use of fuzzy logic systems is the approximation of its behavior where there are no analytical functions or numerical relationships as well as having the capacity to understand biological, medical, social, economic or political systems [3]. The use of artificial intelligence (AI) in the area of rehabilitation robotics has increased substantially

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in recent years. An example of this is the development of algorithms for fuzzy logic which allow the control of devices and classify signals from the body, thus providing information and robustness. The control of the devices developed at a research level has a tendency to focus on the mechanism position. The implementation of its basics control systems does not consider safety, comfort, or the correct accomplishment of the patient's rehabilitation tasks. These data are not reported in literature [4]. The selection and application of a control technique must depend on the focus and type of routine for the rehabilitation that will be implemented in the device. It must be carried out in conjunction with the implementation of an instrumentation system that acquires the necessary variables to develop precise control and functionality for the device [5].

This work presents the dynamic model and the control based on fuzzy logic of a hand exoskeleton for assisted rehabilitation. The proposed trajectories take into account the basic movements used in rehabilitation therapies. The ranges of movement are obtained by video analysis software. The paths are designed using Bézier polynomials in order to obtain smooth profiles for position, velocity and acceleration of the mechanism.

2 Exoskeleton Design

The exoskeleton is designed for independent movement of each of the fingers. The transmission of power for the movement of each phalanx is carried out through a pinion-rack mechanism while the prismatic and angular movements are performed through gear-rack kits. These two movements give the mechanism the ability to follow instant finger velocity centers, which minimizes the error that exists between the instantaneous center of velocity of the mechanism with regard to the center of rotation of the phalanges. This allows coverage of the movement ranges of a healthy hand and avoid the mechanical interference between the exoskeleton and the user's finger.

Each finger of the exoskeleton was divided into three blocks. The first block is located on the metacarpal bone and secured to the base of the exoskeleton. This block is responsible for the movement of the proximal phalanx. The second block is located on the proximal phalanx and is responsible for the movement of the middle phalanx. The last block operates as a receptor of the movement and is located on the distal phalanx. The exoskeleton has 2 active and 2 passive Degrees of Freedom (DOF) for the index, middle and annular fingers, while the thumb and the little finger have 1 active and 1 passive DOF. The movement of each finger is controlled independently and the weight of the mechanical prototype is 750 g. Figure 1 shows a partial view of the exoskeleton. Details about design and kinematic analysis of the proposed hand exoskeleton are presented in [6].

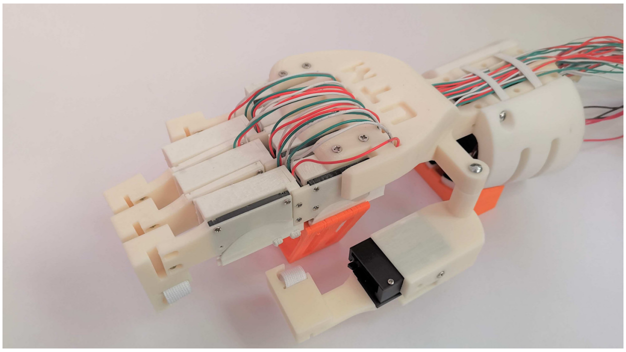

Fig. 1. Final prototype assembly

2.1 Dynamic Model

For each degree of freedom there is an actuator. For each phalanx, a motor is responsible for the movement that allows the finger to be modelled as a planar manipulator with 2 DOF. The exoskeleton finger model is shown in Fig. 2.

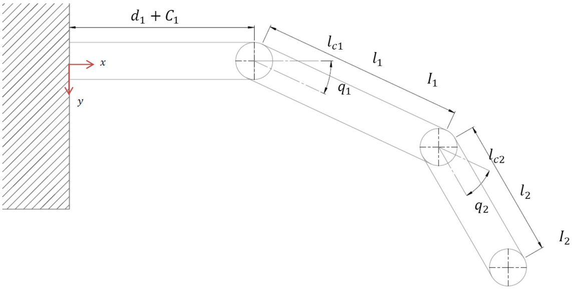

Fig. 2. Arm model of 2 degrees of freedom.

Using the Euler-Lagrange method [7], the dynamic model is obtained and it can be written in the general form as:

$$\tau = M(q)\ddot{q} + C(q)\dot{q} + g(q) \tag{1}$$

where: q is the angular displacement of the joint; $M(q)$ is the inertia matrix of the manipulator; $C(q)$ is the centrifugal force and the Coriolis force; $G(q)$ is the gravity term. q_1 and q_2 represent the angular displacement of the proximal and middle phalanx.

3 Modeling of Trajectories

The basic hand movements considered during the development of the project and found during rehabilitation therapies are: fist, cylindrical grip and tip pinch

[8]. For the cylindrical grip exercises the user takes a plastic cylinder with a diameter of 8 cm and a length of 12 cm. For the development of the tip pinch the user takes a marker of trade with the tips of the thumb and index finger.

The reference for the system's tracking problem is obtained using Bézier curves and with the help of a Vicon motion capture system. This determines the starting and ending positions for the phalanges in each movement to be performed. In each phalanx a mark was placed to follow its trajectory in cartesian coordinates; a reference mark is positioned on the wrist. The tests performed are available in [9] as a free download. Rotation matrices were applied to the data to analyze them in an XZ plane, and this data was processed in Matlab. The results of different tests for the angles for each phalanx in the three movements are shown in Table 1. The data values are in degrees (°).

Table 1. Phalange movement ranges for three movements.

Movement	Phalanx	Thumb	Index finger	Middle finger	Ring finger	Little finger
Fist	Proximal	54.1086	38.6238	60.2354	33.1456	54.1086
	Middle	–	82.7016	79.8522	87.4303	62.9804
	Distal	62.9804	81.3978	76.847	81.3978	83.4123
Tip pinch	Proximal	54.8130	54.8130	61.4474	61.5974	54.8130
	Middle	–	45.1992	45.5139	49.8300	45.1992
	Distal	50.3636	50.3836	52.9135	50.0200	50.3636
Cylindrical	Proximal	35.2300	17.8251	2.0200	1.9800	1.9500
Grasp	Middle	–	49.1760	3.0200	3.4500	3.3800
	Distal	44.9800	37.2291	2.9801	2.9800	3.0200

With the data obtained from the final angle for each of the phalanges, it is possible to determine the trajectories that the exoskeleton should follow. In order to accomplish this, the use of Bézier curves is proposed. A soft path will prevent injury to the user and comply with the desired position of a safe way for the patient and the device [10]. The Bézier curve can be obtained through equation (2), [11].

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} P_i (i-t)^{n-i} t^i \tag{2}$$

where: P_0, P_n are the starting and ending points of the Bézier curve; $P_1 ... P_{n-1}$ are the control points of the Bézier curve and t is the parameter that influences the distribution of the interpolation of the points. To obtain the trajectory, the Bézier polynomial was implemented in Simulink, where the parameters to be introduced are given by Table 1. These desired displacement values for the proximal and middle phalanx are represented in the system as the variables q_{1d} and q_{2d}.

4 Fuzzy PD Controller

Fuzzy logic control was based on the patterns in [12], where it is part of a classic PD that combines the error and change in error which results in a fuzzy version of PD controller. A closed loop is needed in the PD controller to perform the comparison of the reference input with the output produced by the controller. In addition, a controller can be MIMO or SISO. The typical SISO controller regulates a control signal according to an error signal. The exoskeleton system contains a motor for the movement of each phalanx which results in the ability to have a decentralized SISO control type for the movement of each of the motors. For the implementation of the fuzzy control, the inputs of the system are the reference values in degrees that each of the phalanges has to reach during movement. The angular position of the control systems output is subtracted from the angular position of reference in the input, thus obtaining an error from which it is possible to determine its variation in time.

4.1 Fuzzification

The fuzzy type controllers have linguistic variables as input. For this controller, the variables are error and change ratio. At this point in the driver development, the input variables remain membership functions. The output of the controller is a value corresponding to the high cycle of the pulse width modulator (PWM), which controls the speed of the actuator. The functions that model linguistic terms are trapezoidal, and the error is defined betwen $[-1, 1]$. Each encoder reads the error that is updated and normalized. The PWM signal will be generated by an Arduino board, which works on 8-bit resolution [0–255] equivalent to 0–100% of the duty cycle. For the undertaking of the tests the maximum duty cycle is 21%, which is equivalent to 8 bits in range of $[-53, 53]$. Similarly, the same linguistic terms of Table 2 are applied.

Table 2. Linguistic terms and Fuzzy rules.

Linguistic variable	Abbreviation	Linguistic term	Rules
Error	NE	Negative error	If (NE) and (NC) Then (NV)
	ZE	Zero error	If (NE) and (ZC) Then (NV)
	PE	Positive error	If (NE) and (PC) Then (NV)
Change	NC	Negative change	If (ZE) and (NC) Then (NV)
	ZC	Zero change	If (ZE) and (ZC) Then (ZV)
	PC	Positive change	If (ZE) and (PC) Then (PV)
Voltaje	NV	Negative voltaje	If (PE) and (NC) Then (PV)
	ZV	Zero voltaje	If (PE) and (ZC) Then (PV)
	PV	Positive voltaje	If (PE) and (PC) Then (PV)

4.2 Fuzzy Rules

To relate entries with the outputs it is necessary to establish input groups of fuzzy rule combinations. Since the system has two entries with three linguistic terms each, a total of 9 rules are obtained. The rules can be seen in Table 2.

4.3 Inference System

The Mandani method was used as the inference method for the fuzzy intersection. The Matlab Fuzzy Logic Toolbox was used for this phase because it is a practical tool for the calibration of a diffuse system due its graphical interface and the possibility of evaluating the results with the sliding surface. The sliding surface obtained from this diffuse system is shown in Fig. 3. The location of the parameters of the membership functions becomes a less complicated task, otherwise the adjustment of these parameters must be tested with an error of the real system.

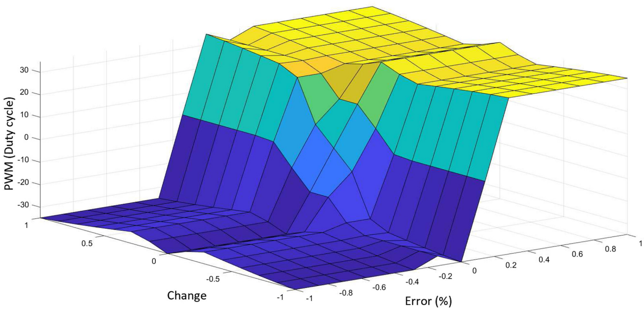

Fig. 3. Sliding surface obtained for the linguistic variables of the system.

5 Results

The simulation of the fuzzy controller was carried out using the Simulink software, taking into account that the dynamic equation (1) was used for simulation purposes. It is worth noting that at this point in the simulation, the dynamics of the motor were not taken into account as the controller's output is obtained through the torque corresponding to the motor. Figure 4 shows the Simulink block diagram for the control test of the system. The generation of the trajectory in the physical system will be determined by the recognition of electromyographic signals for the detection of the movements. It is later reproduced by the mechanism, wich takes the form of a type of bilateral assisted therapy.

The advantage of having DC motors for each of the phalanx movements is the use of separate fuzzy controllers for each of the motors. The movement of a grip cylinder and fist that the proximal and middle phalanx of the index finger performs are shown in Figs. 5 and 6.

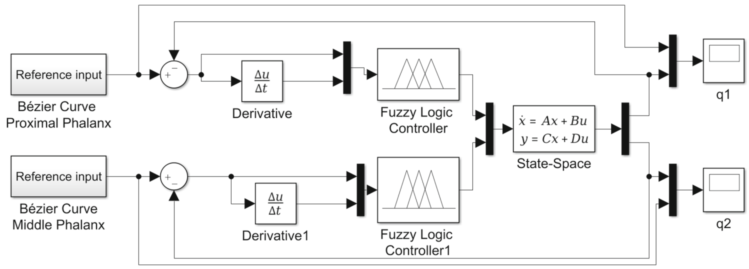

Fig. 4. Control implementation block diagram in Simulink.

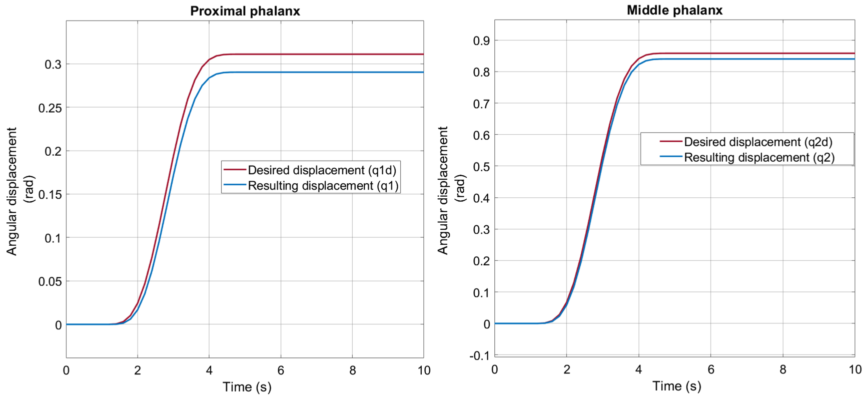

Fig. 5. System response for cylindrical grip.

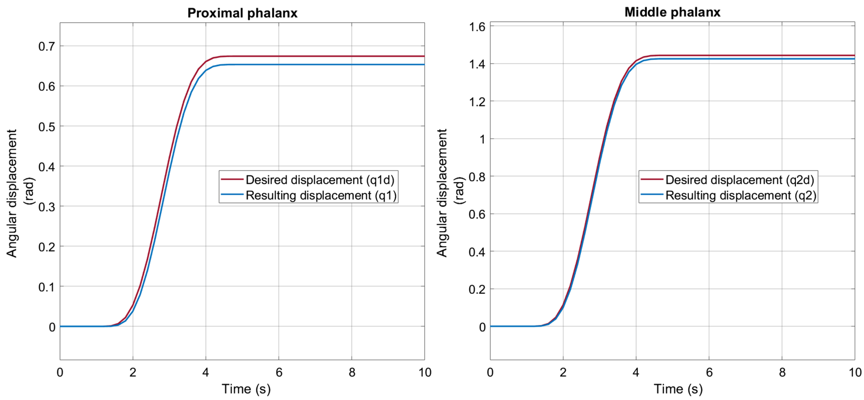

Fig. 6. System response for fist.

The fuzzy controller allowed the tracking of the trajectory that has been introduced to the model of the exoskeleton. The response of the system with the controller has been successful. The results obtained were applied to the model of a finger of the exoskeleton. The replication of this control is applied to each one of the fingers because they move independently. For the tests performed, the average error generated by the five fingers corresponds to 2.1% for the proximal phalanx and 2.4% for the middle phalanx, its equivalent in degrees is 1.19° and 1.04° correspondingly. With some previous tests carried out with different classic controllers like the PD, approximate variations in the response of 0.2° were obtained compared to the results of a fuzzy controller. This technique was implemented because the gains are adaptable without the need to re-synchronize them in their future physical implementation, unlike other control techniques where the gain tuning becomes a complicated task.

6 Conclusions

The implementation of fuzzy controllers represents an advantage for systems in which obtaining the model is tedious or in which it fails to accurately represent the system. Obtaining the dynamic model of the exoskeleton is an approximation which can make a big difference to the real system, as there are components that have been generalized. Contrary to other control techniques based on a model whose parameters vary in a real implementation, the technique chosen for this paper shows the guidelines for the development of a decentralized fuzzy controller that allows the control of both motors in order to obtain more natural movements.

References

1. Irastorza-Landa, N., et al.: Design of continuous EMG classification approaches towards the control of a robotic exoskeleton in reaching movements. In: Proceedings of 2017 International Conference on Rehabilitation Robotics (ICORR), IEEE, pp. 128–133 (2017)
2. Silva, A.F., et al.: Fuzzy control of a robotic finger actuated by shape memory alloy wires. J. Dyn. Syst. Meas. Control **140**(6), 064502 (2018)
3. De Silva, C.W.: Intelligent Control: Fuzzy Logic Applications. CRC Press, New York (2018)
4. Basteris, A., Nijenhuis, S.M., et al.: Training modalities in robot-mediated upper rehabilitation in stroke: a framework for classification based on a systematic review. J. Neuroeng. Rehabil. **11**(1), 1–15 (2014)
5. Leonardis, D., Barsotti, M., Loconsole, C., et al.: An EMG-controlled robotic hand exoskeleton for bilateral rehabilitation. IEEE Trans. Haptics **8**(2), 140–151 (2015)
6. De la Cruz Sánchez, B., Arias Montiel, M., Lugo-González, E.: Development of hand exoskeleton prototype for assisted rehabilitation. In: Gasparetto, A., Ceccarelli, M. (eds.) Mechanism Design for Robotics. Mechanisms and Machine Science, vol. 66, pp. 378–385. Springer, Cham (2019)
7. Jazar, R.N.: Theory of Applied Robotics: Kinematics, Dynamics, and Control, 2nd edn., p. XXIII, 883. Springer, USA (2010)

8. Cailliet, R.: Hand Pain and Impairment, vol. 3. FA Davis Company (1971)
9. De la Cruz Sánchez, B., Arias Montiel, M., Lugo González, E.: MOCAP data base for three hand movements. Mendeley Data (2020)
10. Xu, Z., Wei, S., Wang, N., Zhang, X.: Trajectory planning with Bezier curve in cartesian space for industrial gluing robot. In: Zhang, X., Liu, H., Chen, Z., Wang, N. (eds.) Intelligent Robotics and Applications. ICIRA 2014. Lecture Notes in Computer Science, vol. 8918, pp. 146–154. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-13963-0_15
11. Ju Mei, Z., and Hong Lun,W.: Inserting control points for Bezier curve approximation. In: Proceedings of the 31st Chinese Control Conference, IEEE, pp. 2416–2420 (2012)
12. Jantzen, J.: Foundations of Fuzzy Control: A Practical Approach. Wiley, Chichester (2013)

Design of a Novel Robot for Upper Limb Rehabilitation

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Abstract. This paper addresses the design of a novel robotic device for upper limb rehabilitation tasks. The main goals of the design process have been to achieve a design of a rehabilitation device, which can be easily portable also for home use. Specific attention has been devoted to design of the main mechatronic components by developing specific kinematics and dynamics models. The design process includes the implementation of a specific control hardware and software. Preliminary experimental tests are reported to show the effectiveness and feasibility of the proposed design solution.

Keywords: Design · Simulations · Parallel robots · Upper limb rehabilitation

1 Introduction

Robotic assisted rehabilitation is a relatively young and rapidly growing field with increasing applications in clinical care, as reported for example in [1–10]. The development of robots for the rehabilitation of the upper limbs are characterized by a complexity that is increasing with the movement to be simulated, [1].

Most famous commercial upper limb rehabilitation robots are the MIT-MANUS, [2], now sold as InMotion ARM (Interactive Motion Technologies, USA) and ARMin (now sold as ArmeoPower by Hocoma AG, Switzerland), [3], but also two other models used today in clinics: ArmeoSpring [4] and ReoGo [5]. The MANUS is a five-bar SCARA robot with only two translational degrees of freedom (DOFs) for the movement of the elbow and forearm. Motorska's ReoGo is a robotic system for upper limb therapy with up to 3 DOFs. ArmeoSpring is a passive orthosis for upper limb. It offers a large 3D workspace, where one can detect the 3D position and gripping force of the arm. ArmeoPower is a motorized version of ArmeoSpring, with 6 DOFs, capable of supporting the weight of a patient's arm and assisting the patient during specific exercises, adapting to the patient's capabilities, in a large 3D workspace, [4]. Several researchers are still researching and developing novel design solutions for limb rehabilitation, including exoskeletons, or new kinematic architectures or cable driven parallel architectures as for example in [6–12].

This paper, addresses this open problem by proposing a new design solution that can be easily portable also for home use and at same time have performances similar to

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existing design solutions. Accordingly, a specific design process is herewith outlined by focusing at main mechanical components. Preliminary experimental tests are reported to show the effectiveness and feasibility of the proposed design solution.

2 Requirements of the Proposed Device

A preliminary analysis was conducted on the characteristics of existing commercial devices for upper limb rehabilitation. A comparison has been made on basis of costs, workspace and payload. Results are summarized in Table 1. Given the high costs, none of the existing devices can be considered suitable for home use. Among the existing devices ReoGo is the cheapest solution with 3 active DOFs and a payload of 5 kg. Accordingly, further studies and clinical tests have been made with a ReoGo device, which authors tested as courtesy of ANMIC rehabilitation clinic in Crotone, Italy, Fig. 1. Although the most promising commercial product, ReoGo is too bulky and expansive for a home use. This gives the motivation for designing a novel robotic device to be much more compact, lightweight and cheap while keeping a workspace and payload comparable with the ReoGo device.

Table 1. Comparison from different robotic solution

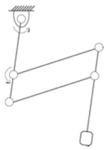
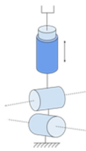
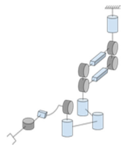
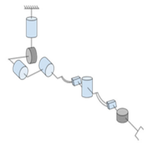
		InMotion 	ReoGo 	ArmeoSpring 	ArmeoPower 
price		$ 100.000	$ 85.000	$62.500	$198.000
weight		83 Kg	79 Kg	82 Kg	205 Kg
Work-space	X	400 mm	400 mm	600 mm	600 mm
	Y	400 mm	400 mm	400 mm	400 mm
	Z	Not allowed	200 mm	600 mm	600 mm
payload		~5 Kg	~5 Kg	~2.5 Kg (forearm) ~3.8 Kg (arm)	~6 Kg (forearm) ~8 Kg (arm)
Risolution		Not available	Not available	<0.2°	<0.2°
DOFs		2DOF	3 DOF	6 DOF	6 DOF
Arm motions		Planar movements	3D movements	3D complex move-ments with passive joints	3D complex movements with active joints

Fig. 1. First author testing ReoGo at ANMIC rehabilitation clinic in Crotone, Italy.

3 The Selected Kinematic Model

A topology search has been carried out as topic of a master thesis by considering workspace shapes and (dimensionless) sizes. This has allowed to identify a delta-like parallel architecture as promising for obtaining a compact solution with a potential high payload to own weight ratio, [13]. Accordingly, Fig. 2 reports the kinematic model of the proposed delta-like parallel architecture. Kinematic equations have been established and numerically solved in Matlab environment in order to perform a size synthesis. Result of the synthesis process have been the main sizes of the proposed Delta-like architecture to fulfil a workspace comparable with ReoGo. Plots of the finally achieved workspace are shown in Fig. 3. Further investigations will address also other performance indices such as stiffness and dexterity.

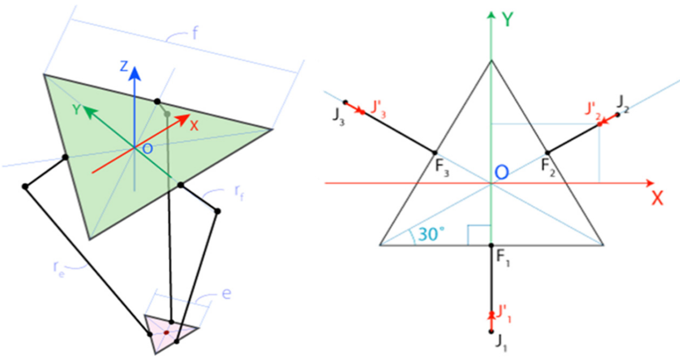


Fig. 2. Kinematic scheme of the proposed delta-like architecture.

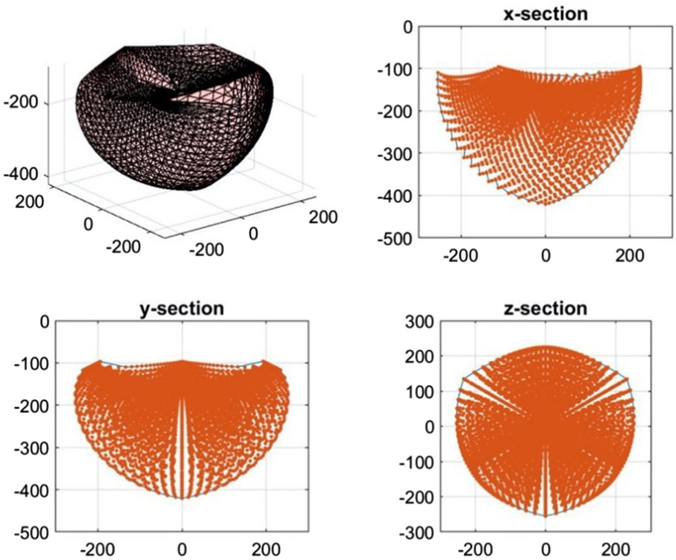


Fig. 3. Plots of the workspace of the proposed device.

4 Mechanical Design

Following the kinematic synthesis, the design process has been focusing at the mechanical design of each component. In particular, FEM analyses and dynamic simulations have been carried out to size main links and actuators, as outlined in the 3D CAD model reported in Fig. 4. Further attention has been devoted at design a specific gearbox for obtaining the desired motion ranges and payloads.

Dynamic simulations have been carried out with two approaches. A first approach consists of establishing a simplified analytical dynamic model, which has been developed as based on the principle of virtual powers. The related solving algorithm has been developed in a symbolic solver environment (Mathematica software). This analytical model requires as input the position of the centers of mass versus time. For the purpose, a law of motion has been imposed for the joints to fulfil a specific vertical motion of the end-effector along the Z axis. The motion laws have been obtained starting from the analytical formulation of direct kinematics as reported for example in [13]. Figure 5 shows the calculated paths performed by the centers of masses when the manipulator performs a prescribed motion of the end-effector along the Z axis. Paths of the center of masses can be computed for any desired motion of the manipulator.

The main output of the solution of the analytical dynamic model consists of the required input motor torques. For example, Fig. 6 shows the motor torque versus time for the prescribed vertical motion of the end-effector along the Z axis. Given the symmetry of the prescribed motion all motors require the same torque. the maximum torque during this movement is about 2.7 Nm.

Further simulations have been carried out by developing a specific model within MSC.Adams environment. This allowed a more accurate modelling of the proposed

Fig. 4. 3D CAD model of the proposed robotic device.

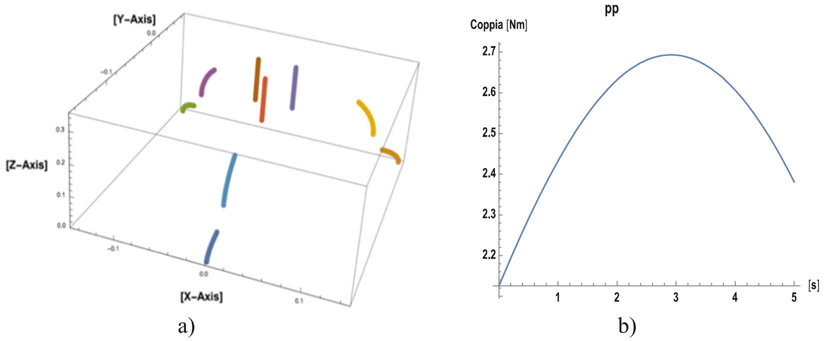


Fig. 5. Simulation results for a prescribed vertical motion of the end-effector along the Z axis: a) Calculated path trajectories of centers of mass; b) required motor torque.

device as well as simulation of several operation conditions. Some examples of the obtained results are reported in Fig. 6. All the simulations confirmed the results of the theoretical model in terms of maximum required torque of 2.7 Nm when a maximum payload of 5 kg is applied to the end effector.

To obtain a compact and cheap model, it was decided to use Nema-17 stepper motors. However, these motors require a gearbox for fulfilling the required speed and torque. For the purpose, given the compactness requirements, it has been decide to design a specific epicyclical gearbox. After a careful design process, the adopted solution has three gears with 10, 17 and 44 teeth, respectively. The module of all gears has been defined as equal to 0.9.

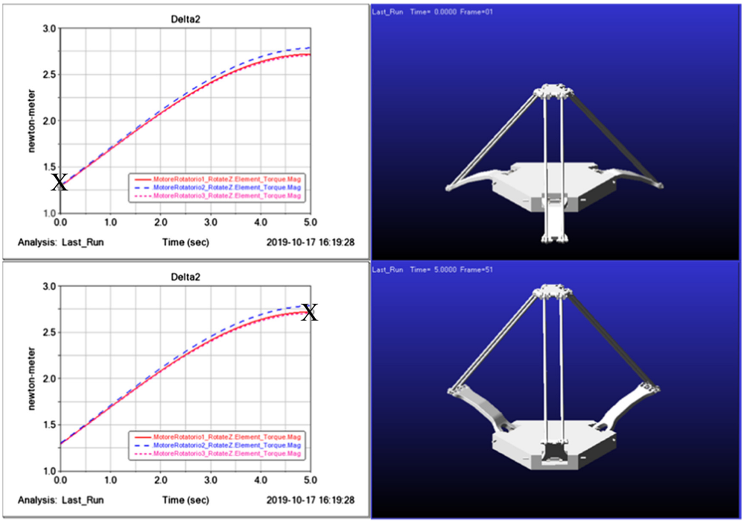


Fig. 6. Simulation output of motor's torques in MSC.Adams (in the plots the X indicates the value corresponding to the robot configuration that is shown on the right side).

5 Control Architecture and Wiring

The control architecture is based on Arduino UNO controller as outlined in Fig. 7. Other main components are: three stepper motors with related drivers, an AC/DC stabilized IO 110/220 V OU 12 V - 10A power supply, limit range safety switches and LCS screen. Communication with a PC is achieved through a serial port, exchanging I/O data on the same channel. Arduino's digital PINs are used to control the stepper motors and to navigate into menu using three buttons, while an Arduino's analog PIN is used for sensors, by using a mapping method on the analog PIN. In this way it is possible to register the motion interaction with the patient's hand. A specific low-cost force sensing has been developed (under patenting):

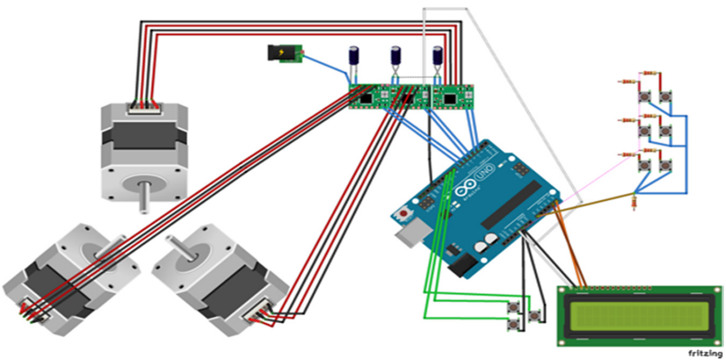


Fig. 7. A scheme of the proposed control architecture.

6 Preliminary Tests

This section presents some preliminary experimental tests that have carried out to validate the main features of the prototype. For example Fig. 8 shows the built prototype while performing the prescribed vertical motion of the end-effector along the Z axis, which has been described in Fig. 5.

Fig. 8. Preliminary tests during elevation movement

Further, experimental tests have been carried out with objects of different weights until reaching the prescribed payload of 5 kg. Several trajectories have been tested. For example, Fig. 9 shows a test for a prescribed X, Y, Z motion of the end-effector while lifting a smartphone. This experiment has been carried out at three different input velocities. The IMU sensor on the end-effector measured the acceleration data, which are reported in Fig. 10. It is worth noting that high vibrations can be identified at slow speed. This is mostly due to working principle of the stepper motors as well as by the characteristics of the gearboxes. A proper smooth motion is achieved at nominal operation speed.

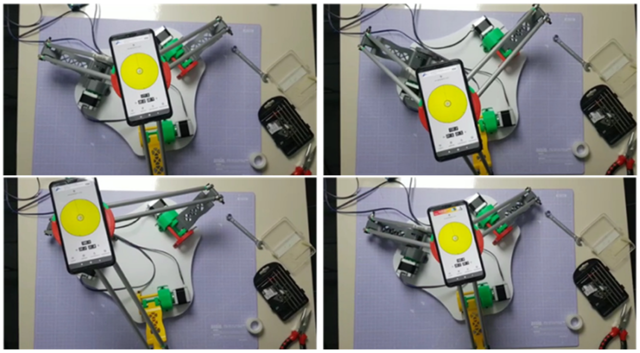


Fig. 9. A robot testing with a smartphone on its end-effector.

The experiments confirm that the device perform the same movements, motion ranges and payload of a commercial device while it can be conveniently placed on a common desk at home. Although just referring to a 3D printed prototype, the overall costs are promising to be below a total of 1000 Euros.