LINarm++
Affordable and Advanced LINear device for ARM rehabilitation

Deliverable D3.2
Mechatronic device

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Executive summary

This document summarizes the conception, design, manufacturing and assessment phases of LINarm2, the mechatronic device integrated in the LINarm++ platform.
Section 1 reports the main functional and technical concepts behind the LINarm2 device, i.e. the effectiveness of approximating functional movements by linear trajectories and the embedding of a variable stiffness actuator (VSA) within the device. Section 2 reports the highlights of the new VSA embedded in LINarm2. Section 3 reports details about the design phase. Section 4 e 5 describes the electronic components embedded in LINarm2 and the peculiar aspects of the control system. Section 6 includes the description of the manufactured and assembled prototype.

1 Introduction

The upper limb is an incredible adaptive organ that allows performing high-level interactive movements and is capable of accomplishing numerous functional tasks in an infinitive number of kinematic solutions. It is a sophisticated multi-joint system designed for multitasking functioning and capable of performing from heavy jobs to tasks requiring fine movements, not to mention exploration and manipulation of objects [1]. Certainly, not all movements may be trained and this variability makes the selection of a reduced number of them necessary, a selection that, preferably, should be done on the basis of key determinants of the movement control.

In this framework of reasoning, an analysis of which are the main functions of the different joints/organs of the upper limb is helpful for finding a solution to the problem. Making a strong simplification, the shoulder may be seen as the joint that enables the orienteering in the space of the entire upper limb, the elbow as the elongation-shortening element that allows reaching objects (and taking them towards the body) and, finally, the hand as the end effector, the organ that enables direct interaction with the environment [2]. Within this schematic model, shoulder and elbow movements are propaedeutic for hand positioning in space and, therefore, the motor recovery of specific functional movements of these two joints becomes a primary issue in rehabilitation.

Given all this above, two functional gestures only are sufficient to study the shoulder and elbow compound movements that are frequently used in Activities of Daily Living (ADLs): 1) the Reaching Movement (RM, Fig. 1) against gravity and 2) the Hand-to-Mouth Movement (HtMM, Fig. 2) [3]. In fact, these particular gestures allow us to perform tasks like eating, reaching for objects and, taking them towards the body/face. Similarly, passing from assessment to rehabilitation, by training these two gestures only, motor recovery can be obtained of important compound movements like shoulder flexion (against gravity) and elbow extension, and, elbow flexion (against gravity) and shoulder flexion [4].

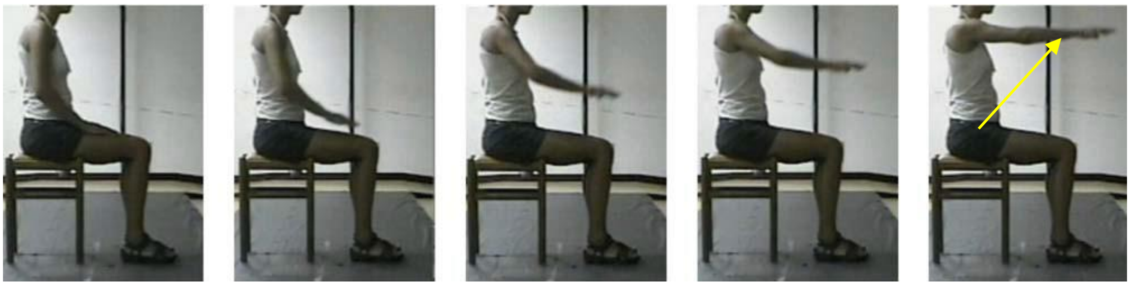


Fig. 1: Frame sequence of the Reaching Movement (RM) performed by a healthy subject. The trajectory of the RM may be approximated to a straight one.

Fig. 2: Frame sequence of the Hand to Mouth Movement (HtMM) performed by a healthy subject. The trajectory of the HtMM may be approximated to a straight one if special articulated handles are used.

Considering the relevance of RM and HtMM and promising results obtained so far, a solution to enable patients to be trained by a robotic device with one these two movements is considered beneficial and constituted the origin of the LINarm device development [5].

With regard to the RM, the solution to the problem may be easily found in a simple support able to fix a linear axis to a table and enabling the possibility to incline it vertically (and horizontally) (Fig. 1). More complicated is the solution for the HtMM since the hand trajectory is not properly straight and, further considering that the movement is towards the face, the orientation of LINarm has to be accurately studied and the solution should be thought considering the also the use of properly customized handle (Fig. 2). Anyway, in both cases a linear movement represents a good approximation and, for this reason, the concept behind the LINarm device is considered promising.

For these reasons, the development of a modular solution enabling differently oriented movements, approximating them as linear, is considered a good compromise and strategy to be included in a low-cost device for home rehabilitation. Therefore, during the (re)design phase of LINarm this requirement was effectively taken into account.

Focusing on the mechatronic actuation schemes of rehabilitation devices, rigid mechanical actuations coupled with force sensors or backdrivable transmissions are typically employed to infer the interaction force between the device and the patient. However, in the last years, the effectiveness of adding mechanical compliance to the actuation system is being explored. The use of Variable Stiffness Actuators (VSAs) [6][7][8] can represent a promising technology, thanks to their inherent adjustment of the mechanical stiffness, force estimation and robustness to external perturbations in physical human-robot interacting scenarios. Referring to devices for rehabilitation, examples of VSA-based devices are exoskeletons for the upper limb [9][10], a bipedal robot exploiting VSA to control the knee stiffness [11], a Variable Stiffness Treadmill (VST) for the investigation of gait [12] and a 1-DOF end-effector device for upper-limb reaching rehabilitation [13]. For these reasons and state-of-the-art solutions the realization of a new rehabilitation device based on a VSA has been realized, namely LINarm [5], and refined within LINarm++.

2 A new Cam-based Variable Stiffness Actuation

Variable Stiffness Actuators (VSA) allow the adjustment, in a controlled manner, of their own mechanical stiffness. A VSA is typically made up of two Series Elastic Actuators (SEA) arranged in parallel w.r.t. a mobile mass (Fig. 3). A SEA is, in general terms, made up of a rigid actuator and an elastic element (e.g. a spring) arranged serially. Two SEA featuring non-linear stiffness, arranged in parallel and exerting opposite forces, characterize a typical VSA. SEA stiffness nonlinearity is required to make the VSA stiffness adjustable [14].

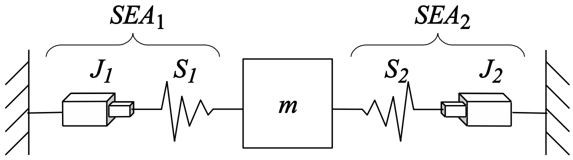


Fig. 3: The *antagonist configuration* of the *LWWCVSA* enabling a linear actuator to feature a variable stiffness behaviour: two non-linear SEA arranged in parallel allows to control the position and the stiffness of a mobile mass *m*.

Currently existing VSAs allow to feature a rotational actuator with a variable stiffness characteristic. In order to realize a linear axis featuring a variable stiffness actuator may be possible, therefore, to transmit the rotational motion of a rotational VSA to a carriage, by a belt-based or a wire-based transmission mechanism. The main limitation of this approach is that the vast majority of the so-far developed VSA allows to perform a limited rotational stroke, typically less than a round angle, preventing the realization of a long-stroke, theoretically unlimited, linear motion. On the other side, to author's knowledge, no VSA have been so far specifically developed for linear motions, required to realize the variable-stiffness motion of LINarm. The LWWC-VSA (i.e. Linear Wire-Wrapped Cam VSA) (Fig. 4) has been specifically conceived and developed and integrated in LINarm2. Its layout has been conceived with the specific objectives of realizing a system characterized by a limited number of components, a relatively compact, clean and customizable design, characterized by a stress distribution which allows it to be realized by a common desktop 3d-printer, featuring also low-cost applications with a variable stiffness.

Fig. 4: Concept design of the Linear Wire-Wrapped Cam VSA (LWWC-VSA).

The LWWC-VSA features two antagonist LWWC-SEA (Linear Wire-Wrapped Cam – Series Elastic Actuator) configured in parallel, enabling to control both the eqilibrium position and the stiffness of a linear axis. In the following sections the actuator is presented, starting from the elements and the layout of a single LWWC-SEA, up to the configuration of the LWWC-VSA.

Neglecting analytical details within this report (reported in details in D3.1), the mechanical system can be schematized as reported in Fig. 5.

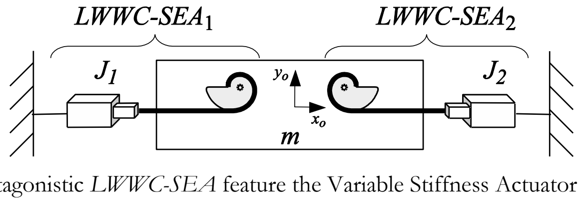


Fig. 5: The antagonistic *LWWC-SEA* feature the Variable Stiffness Actuator *LWWC-VSA*.

Referring to Fig. 6 let us denote by
$\delta = x_2 - x_1$ the distance between two reference points of wires
$\xi = x_m - x_h$ the displacement of the mobile part from the reference position,
where $x_h = (x_2 - x_1)/2$ is the equilibrium position of the mobile part.

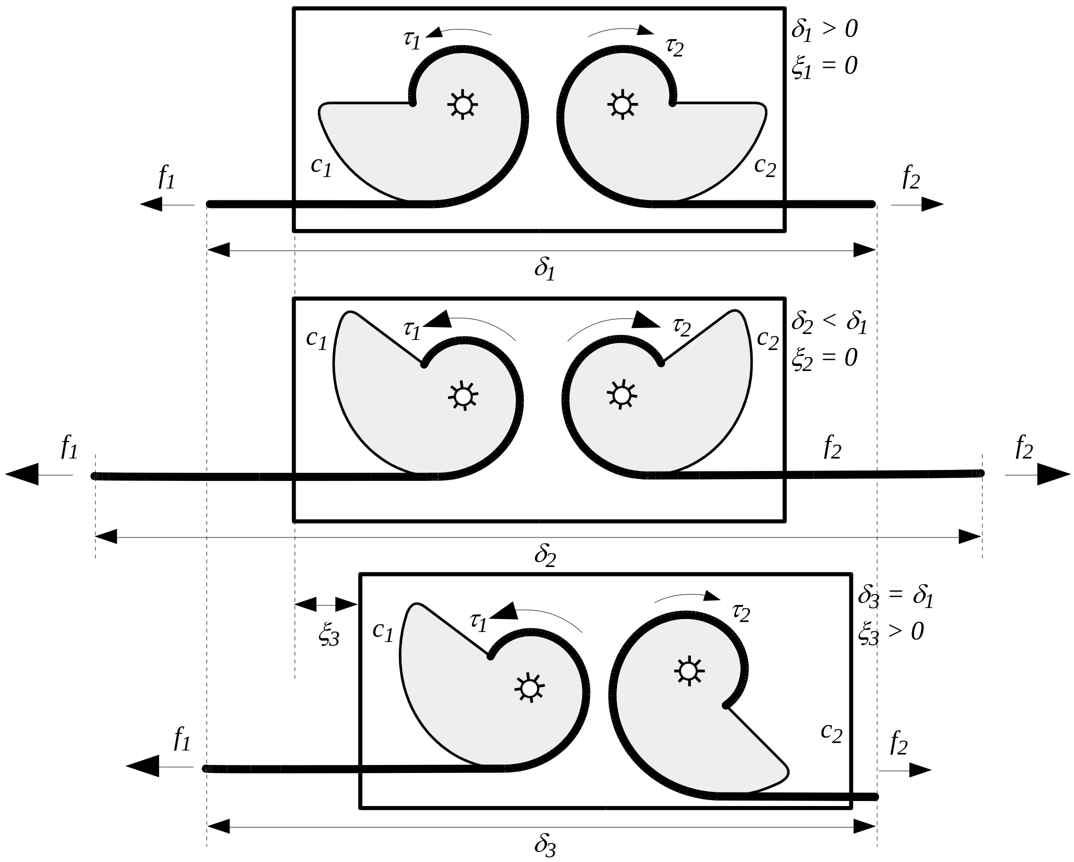


Fig. 6: Effect of modifying wire pretensioning and mobile body position.

The total force applied to the mobile part of the LWWC-VSA is

$$f_v = f_1 + f_2 \tag{7}$$

denoting by f_i the linear force applied to *i*-th LWWC-SEA.
Similarly, the resulting stiffness is

$$k_v = k_1 + k_2 \tag{8}$$

Both f_v and k_v are function of both δ and ξ.

3 Design

LINarm2 is an improved version of LINarm [5], a VSA robotic device for the rehabilitation of the upper limb (Fig. 7). It is characterized by a more compact and optimized design, and embeds a novel VSA architecture exploiting a wire-based mechanical transmission.

The peculiar novel VSA scheme, enabling a compact and light design, is illustrated in Fig. 8, embedding the principle of actuation described in Section 2. It has been dimensioned according to details reported in D3.1.

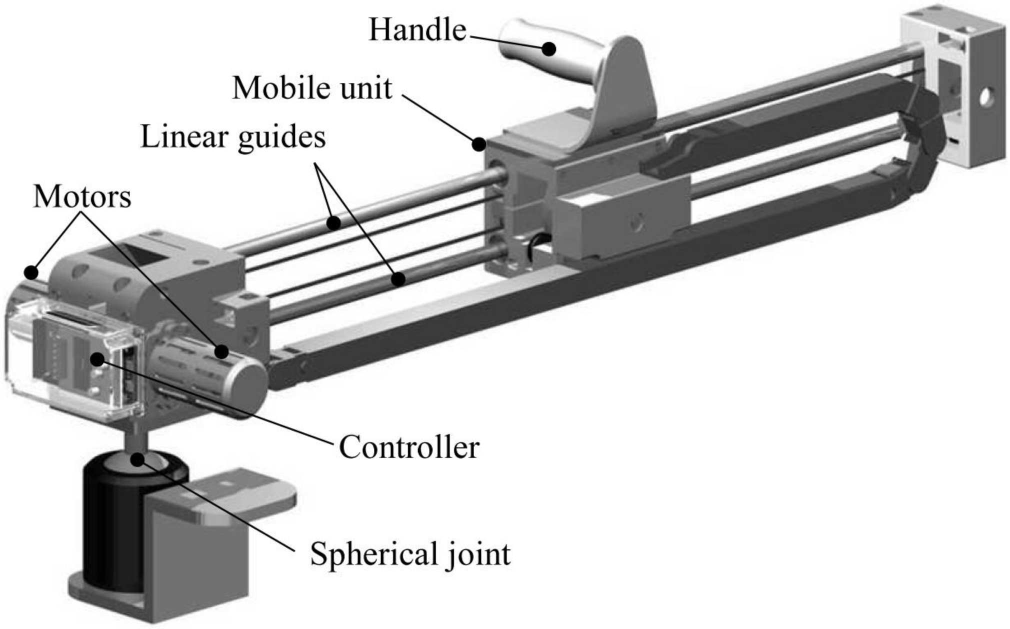


Fig. 7: Assembled view of the LINarm2 CAD model. The linear motion of the mobile unit is constrained linearly by two linear guides. Two motors, installed on the motorized unit, actuate two antagonist wires constrained to the VSA mechanism on the mobile unit. The position of the mobile unit is measured by an encoder synchronous belt. A spherical joint allows to orient the device along different directions as depicted in Fig. 5.

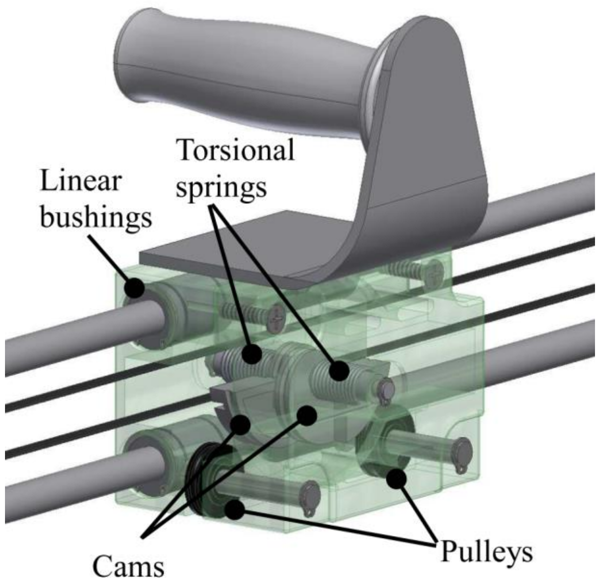


Fig. 8: Detailed view of the mobile unit of LINarm2. A single shaft supports the cams, constrained by torsional springs, of the VSA actuation architecture.

Particular attention has be given to the design of the system to wrap and unwrap the wires. In particular:

- The submodules of LINarm2 have been designed to optimize the cam shapes in order to guarantee a correct wrapping of the wire (Fig. 9). Moreover integrating the electronic board has been integrated in the main body of the system.
- The motor-driven drums which wrap the wire have been designed with deeper grooves to guarantee a correct wire wrapping and protection (Fig. 10).
- Shells have been added to drums to guarantee a correct wrapping/unwrapping of the wires (Fig. 11).

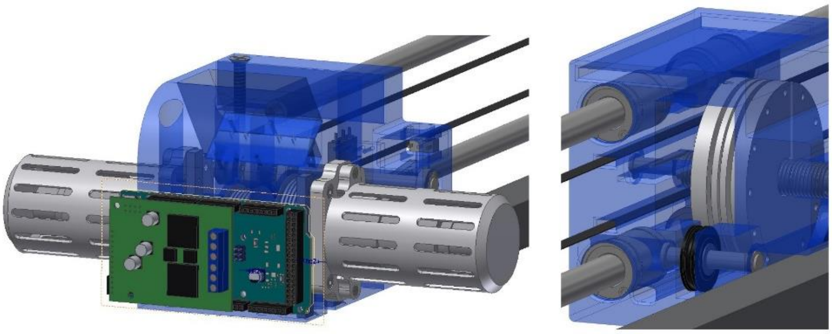


Fig. 9: Refined design of the actuation module and of the mobile part of the mechatronic device. It is worth to note the redesigned version of the cam embedded in the mobile platform, and a set of guiding elements to guarantee a correct wrapping of the wires.

Fig. 10: Drums.

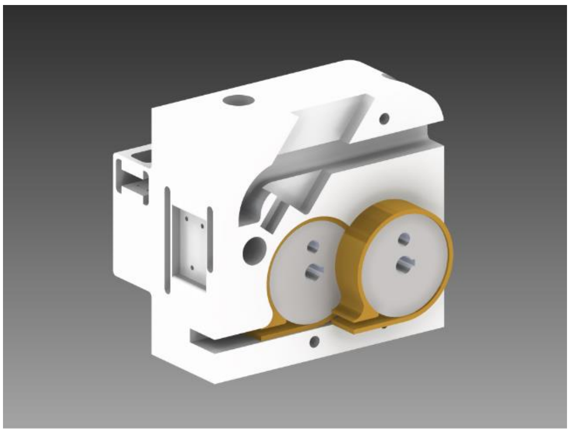


Fig. 11: Drum shells added to guarantee a correct wire wrapping and unwrapping.

4 Electronics

The final prototype (Fig. 17) is characterized by two rotational motors (Pololu Metal Gearmotor 37Dx57L mm) equipped by an internal incremental rotary encoder.
The electrical layout and connections are represented in Fig. 12. The control system is implemented in an Arduino-Due microcontroller board, in charge of closing control loops in real time and controlling motors through the Pololu Dual VNH5019 Motor Driver Shield.
Endstrokes Sx are used to reset the position of the incremental encoders.
Q1 and Q2 are two optical switches used to realize the incremental encoder which, through the connection to the mobile unit with a synchronous belt, allows to get the real-time position of the mobile unit.
Two units of the Motor Driver are connected to the two motors M.

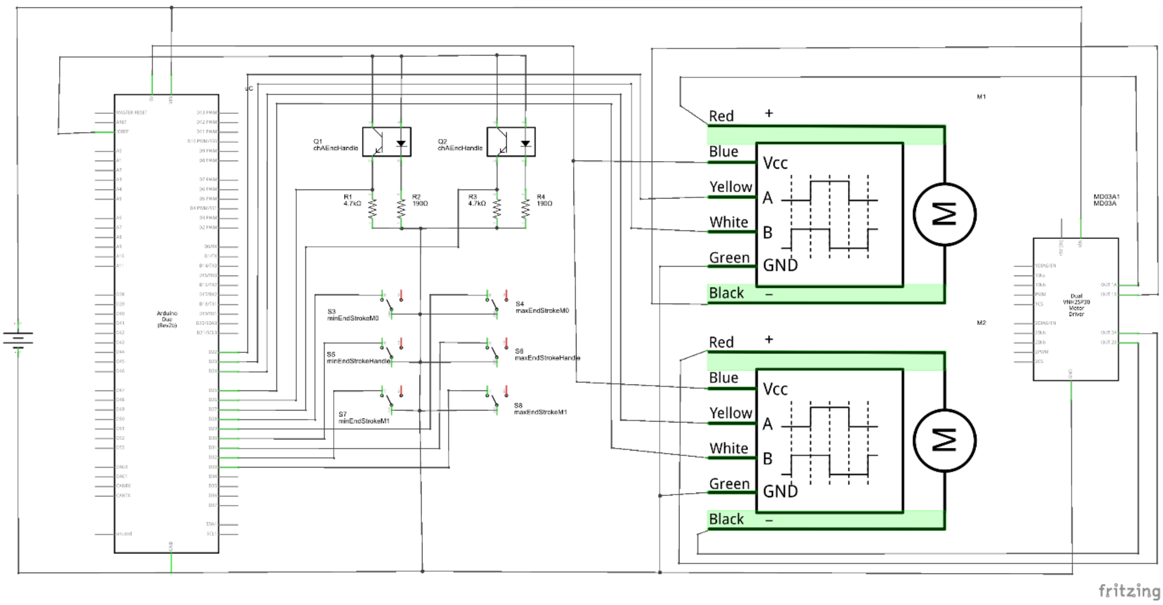


Fig. 12: Electrical components and connections.

5 Control

The control system is implemented exploiting the open-source ChibioOS/RT Real-Time Operating System, compiled for the ARM Cortex-M3 CPU. A A20-OLinuXino-MICRO, a low-cost and compact ARM-based computer, interfaced to the Arduino board through a serial connection, is in charge of high-level functionalities control, therapeutic exercises programming and rendering of an engaging virtual environment.

The real-time controller features passive and force-based control strategies, inferring the force applied by the user being known the force-displacement characteristic of the VSA embedded in the device.

Referring to the overall LINarm++ control architecture (Fig. 13), the Mechatronic control unit is denoted as *LINarm controller*. Refer to *Deliverable D2.2 - Control system* for further details about the overall control structure.

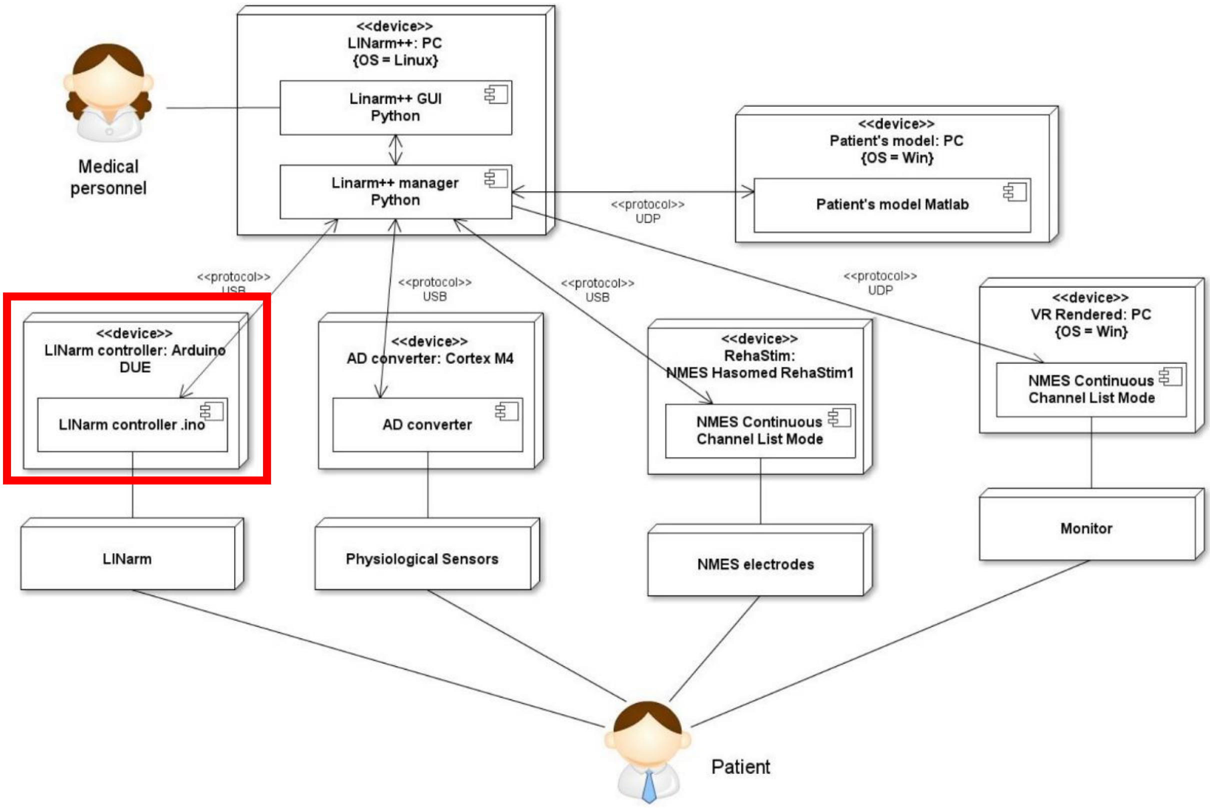


Fig. 13: The LINarm controller device, highlight in red, is the unit in charge of controlling the LINarm2 device within the LINarm++ architecture.

A simplified representation of the LINarm2 mechatronic system is represented in Fig. 14. The control system is in charge of controlling in real time both the equilibrium position x_e and the stiffness k_q of the device, controlling the actuators positions q_1 and q_2.

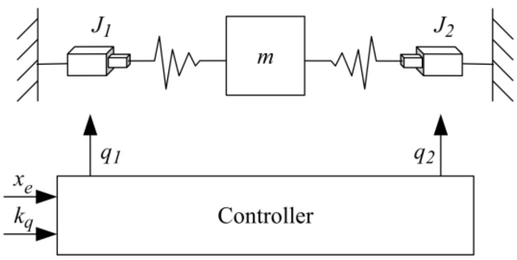


Fig. 14: The position of the end-effector equilibrium point and its stiffness are defined controlling in position the two actuators.

Considering a generic external force *fe* applied to the mobile body, given δ (being imposed by the controller) and measuring ξ (by a position sensor), i.e. the displacement of *m* from its equilibrium position, and therefore known *ka*, it is possible to infer *fe* exploiting the VSA as a force sensor and enabling closed-control-loop algorithms (Fig. 15).

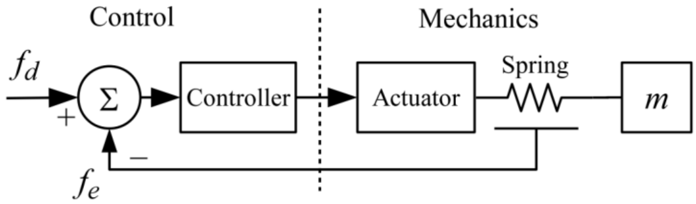


Fig. 15: An impedance control loop is feasible exploiting the value of the externally applied force, estimated on the basis ξ and δ.

Referring to Fig. 16, the control of the VSA stiffness (Fig. 16a) can be enhanced applying an admittance control algorithm which exploits the value of fe (Fig. 16b). This emulates a spring kc configured in series to *ka* (Fig. 16c). Instant by instant, given a target stiffness *kt*, it is therefore possible to properly tune both *ka* and *kc* through the relation

$k_t = (k_c^{-1} + k_a^{-1})^{-1}$.

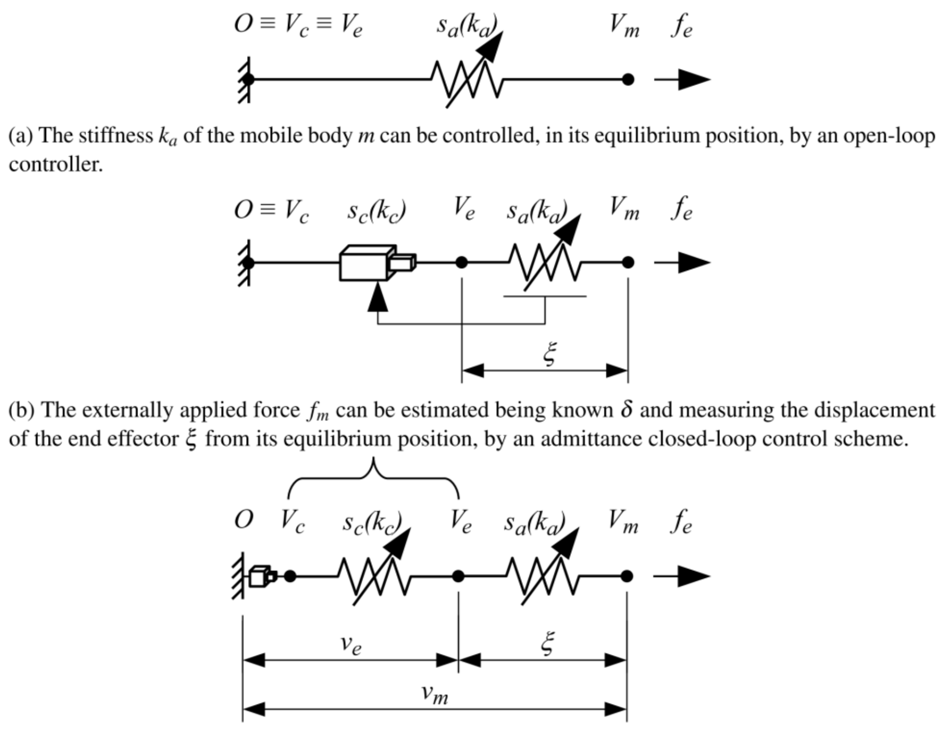


Fig. 16: Stiffness control of the mobile body *m* of a VSA.

To face specifically the rehabilitation requirements, an assistance mode has been added. In this mode the user is helped to reach a defined target.

The control is able to simulate a virtual spring between the handle and the target. In this mode the user experiences a force able to help the patient to reach the target. This control has been realized through a virtual force added to the user force in admittance control.

Considering k_a as the admittance coefficient, the assistance control can be espressed as:

$$v = k_a (F_u + F_a) = k_a *(F_u + (k_{ass} * \Delta))$$

where:

- F_u is the interaction force between patient and robot's handle
- F_a is the assistance force
- k_{ass} is the assistance coefficient
- Δ the diasplacement between handle of robot and the target

From the usability point of view, in order to avoid uncontrolled oscillations because of the inherent compliancy of the device, a force filter has been implemented in the controller. An exponential moving average has been used to obtain the force value for every time instant.

The exponential moving average applies weighting factors which decrease exponentially for increasing time instant. The exponential moving average for the position can be calculated recursively:

$$x_{ave}(t_i) = a*x(t_i) + (1-a)*x_{ave}(t_{i-1})$$

where α is a weighting factor, t_i is a time instant, x_{ave} is the average position, x is the postion reading.

Unvoidable delay, due to the presence of the filter, does particulary affect the dynamic response of the robot.

In admittance and assistance mode a *virtual admittance damping* has been used. This damping consists of a force, inverse to the velocity of the handle wrt the equilibrium position of the VSA actuator. Suitably choosing the value of damping permit to avoid annoying overshoot.

6 Manufacturing and assembly

Starting from the design of the device, the realization of the LINarm++ took place. A complete bill of materials was written up. All the commercial components were purchased. The complete bill of materials is moreover useful to evaluate the complete costs of materials included and assembled in the device, to better define and detail the Exploitation plan. The non-commercial components were realized in the shopfloor of CNR-ITIA. In order to meet different technical requirements, the laboratory took advantage of both traditional machining (milling machine, lathe machine) and additive manufacturing technologies. Precise mechanic components (e.g. shafts, drums) were realized by machine tools. Instead, parts that are not subjected to high physical strain (e.g. motor shell, carriage shell) were made by 3D printing techniques. Finally, the whole device assembly took place.

The employment of the additive manufacturing technologies was crucial to realize light components, made by a unique piece and characterized by complex geometries. In particular, the main components of the variable stiffness mechanism, cams, were realized in PLC. Although cams are subjected to moderate/high physical strain, printing layers orientation was optimized to realize an isotropic behaviour of the component to traction loads.

In order to reduce the impact of the friction on the carriage motion, the guide fixation housing and the bearing housing were machined (milled). Moreover, open linear ball bearing have been employed to reduce sliding frictions, maximizing mechanical transparency.

The complete assembled LINarm2 prototype is depicted in Fig. 17. The motorized unit embeds two motors. They actuate two antagonistic wires. The LinWWC-VSA is embedded in the mobile unit, whose motion is constrained linearly by two linear guides. A cable chain allows two installation of the sensorized handle developed in LINarm++ on the mobile unit.

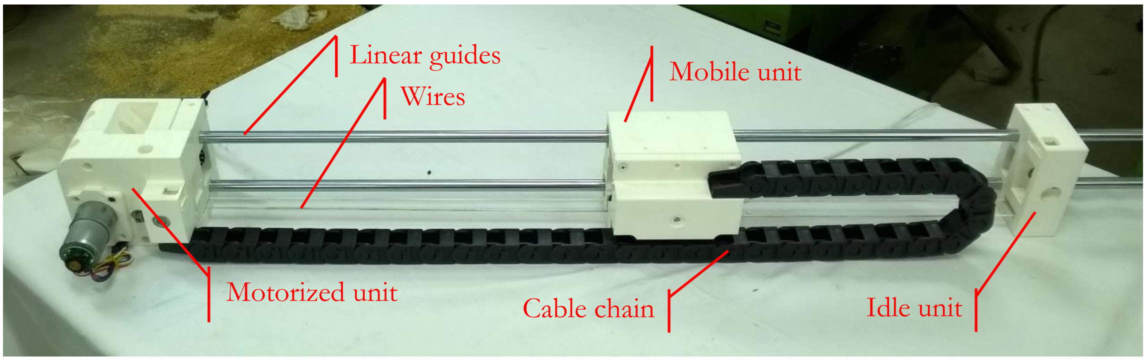


Fig. 17: Assembly view of the LINarm2 prototype.

The assembled mobile unit is depicted in Fig. 18. The cams are embedded in the unit and wrapped by the actuated wires. A synchronous belt is used to measure in real-time the displacement of the unit. The LinWWC-VSA mechanism embedded in the mobile unit is depicted In Fig. 19.
The motorized and the idle unit are depicted in Fig. 20 and Fig. 21.

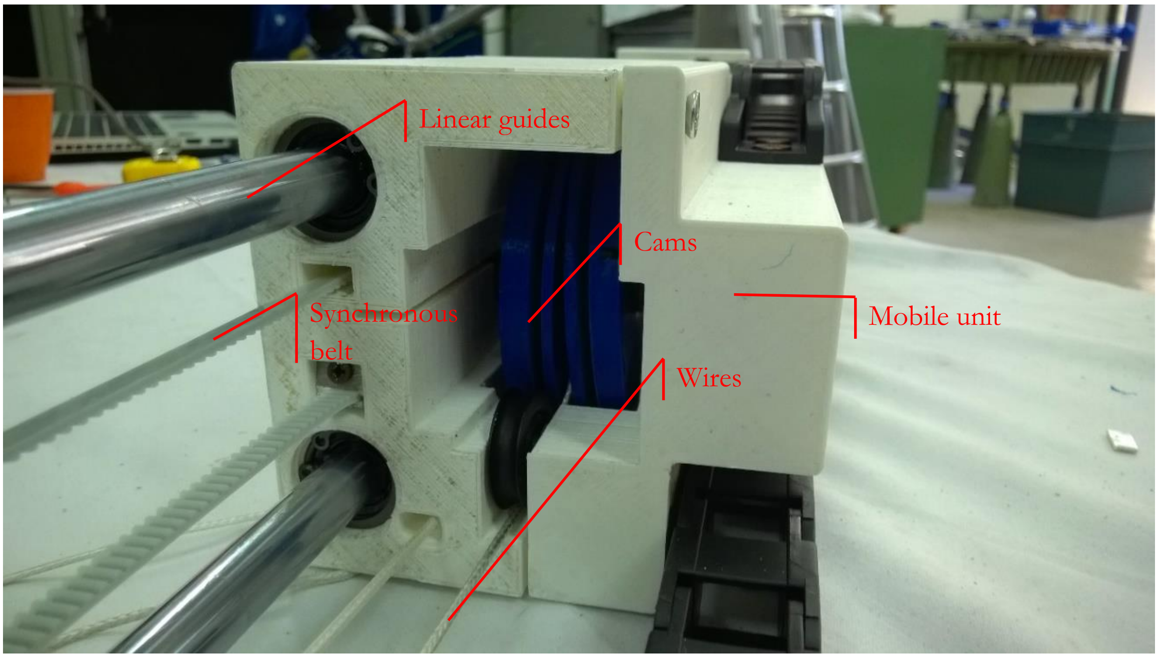


Fig. 18: Side view of the assembled carriage.

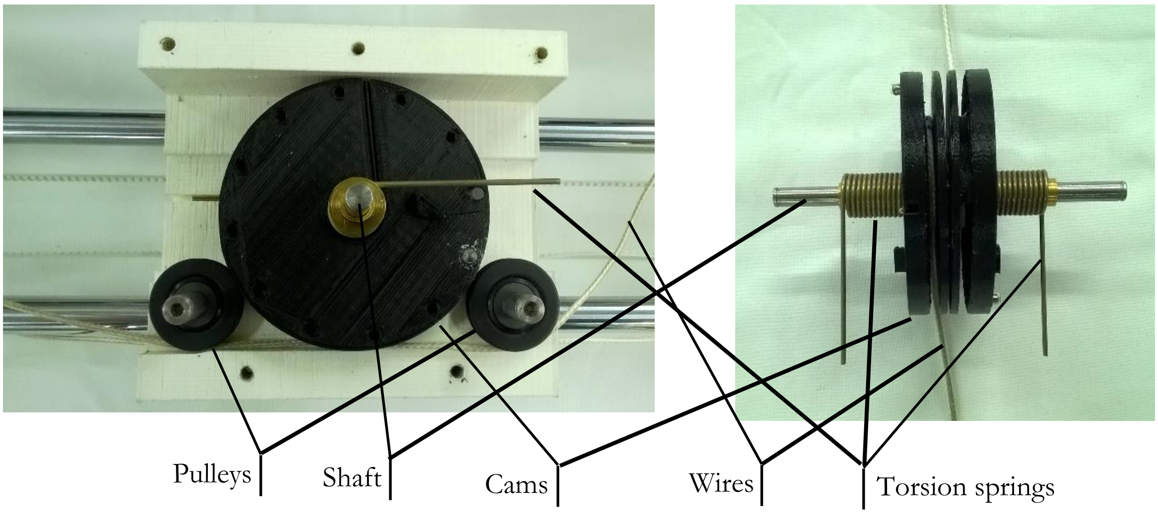
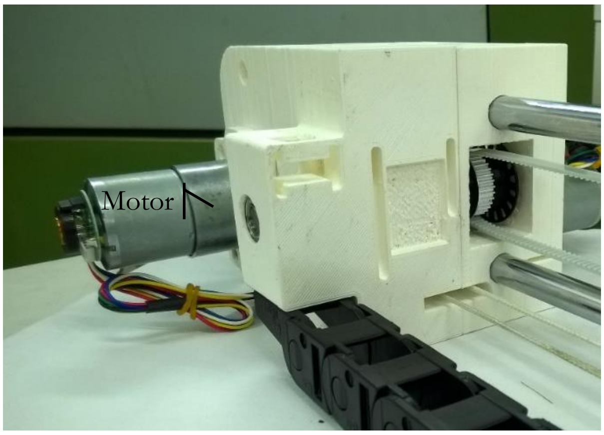


Fig. 19: Views of the LinWWC-VSA mechanism (see Section 2).



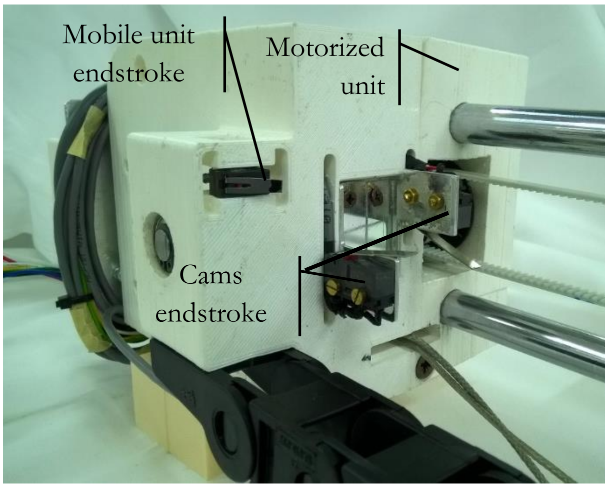


Fig. 20: Views of the assembled motorized unit. Since installed encoders are incremental, the endstrokes are used to reset the position of the mobile unit and of the cams.

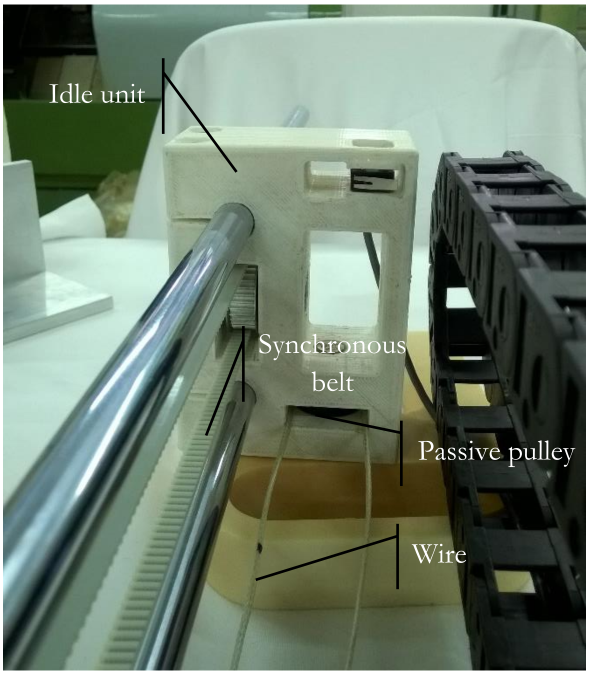


Fig. 21: View of the idle unit.

A picture taken during one of the first experimental trials is reported in Fig. 22.

Fig. 22: The Idrogenet responsible, Carlo Seneci, tested the prototype in an internal meting.

A picture the sensorized handle integrated to LINarm2 is reported in Fig. 23.

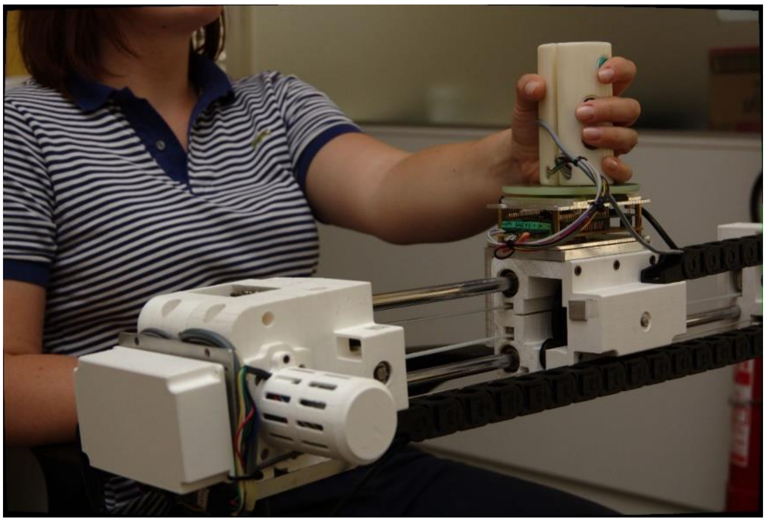


Fig. 23: The sensorized handle developed by UL is integrated in LINarm2.

LINarm2 can be fixed on a table or a tripod supported by a commercial spherical joint (Manfrotto MH057M0) installed at one of its extremities (Fig. 24), enabling it to be oriented along different directions allowing the execution of Reaching movements along different inclinations, Hand-to-Mouth movements and also movements along other directions as lateral movements normal to the sagittal plane.

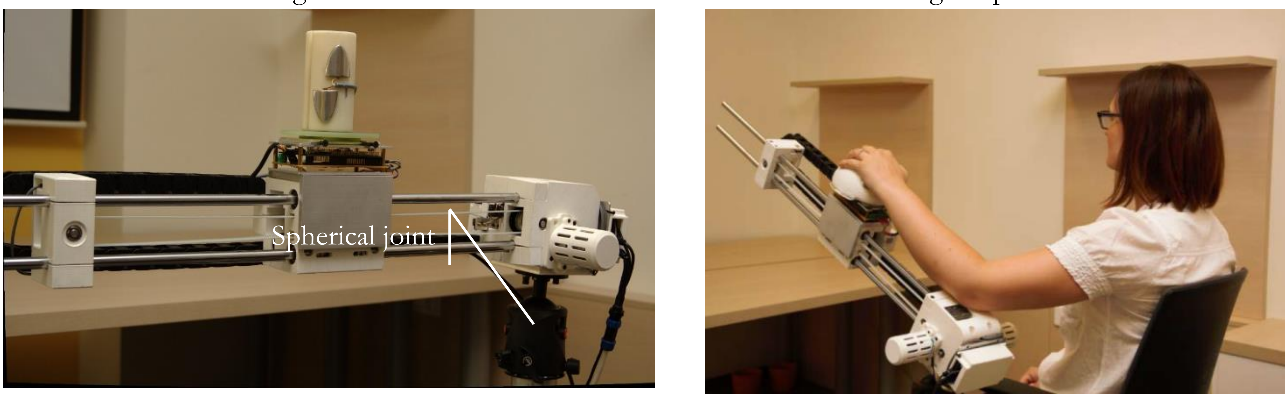


Fig. 24: The direction of LINarm2 is constrained by a spherical joint.

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