An Affordable Open-Source Multifunctional Upper-Limb Prosthesis with Intrinsic Actuation

Julio Fajardo†, Victor Ferman†, Ali Lemus and Eric Rohmer

***Abstract*—The strict development processes of commercial upper-limb prosthesis and complexity of research projects makes them expensive for end users, both in terms of acquisition and maintenance. The advent of 3D printers and the internet, allows for distributed open-source research projects that follow new design principles; these take into account simplicity without neglecting performance in terms of grasping capabilities, power consumption and controllability. We propose a simple yet functional design based on 3D printing with the aim to reduce cost and save time in the manufacturing process. Its modular, parametric and self-contained design is intended to be fitted in a wide range of people with different transradial amputation levels. Moreover, the system brings an original user-friendly user-prosthesis interface (UPI), in order to trigger and increase the amount of customized hand postures that can be performed by the users. Surface electromyography (sEMG) control allows the user to consciously activate the prosthetic actuation mechanism, a graphical interface enables the possibility to select between different sets of predefined gestures. A five-fingered prosthetic hand integrating intuitive myoelectric control and a graphical UPI was tested, obtaining great mechanical performance, in addition to high accuracy and responsiveness of the sEMG controller.**

I. INTRODUCTION

The function of human hand plays an important role on activities of daily living (ADLs), mainly because focal thumb movements that presumably perform a significant job in human evolution due to greater manipulative abilities and value added of its powerful flexion useful on most prehensile movements such as those involved in the manufacture and use of tools [1,2]. The last world reports on disabilities show that there are at least 30 million people with amputations residing in developing countries and most of them do not have possibilities to acquire prosthetic care, neither can they afford leading commercial upper-limb prosthetic with a price tag higher than $25000 [3,4]. Because of the limitations of conventional steel hook prostheses, the elevated cost of commercial myoelectric prostheses, their heavy weight, the elevated cost of maintenance and difficulties to repair [5]–[7]. Many open-source projects based on 3D printing technologies were recently released [7]–[10] focusing on reducing the cost and weight. Meanwhile, in research laboratories, the trend is to focus on improving dexterity and biomimetics of prosthetic hands, dealing with the complexity of control systems and UPIs of sophisticated prostheses [11]–[15]. Reducing manufacturing costs encourages large-scale donations and widespread distribution of prosthesis through global networks of volunteers. However, its low functionality, inappropriate aesthetic and poor controllability influences patients to stop using them. This phenomenon also occurs even with commercial myoelectric prosthesis that, in most cases, are activated via myoelectric controllers that require long periods of training and adaptation [16].

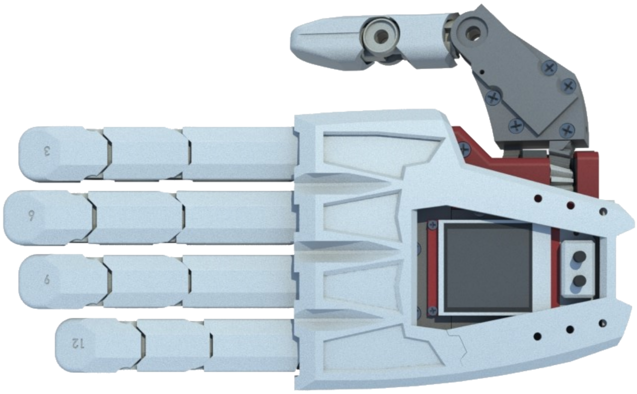

Fig. 1. Galileo Hand, 15 DOF under-actuated 3D printed bionic version.

Galileo Bionic Hand is an affordable, open-source, anthropomorphic and under-actuated myoelectric upper-limb prosthesis for below elbow amputees, designed to be easily built and repaired thanks to 3D printing technology or other rapid prototyping techniques, focused on using readily available materials in developing countries [10]. Furthermore, the design is intended to easily be integrated on sockets previously made for social security, in order to reduce cost and accelerate manufacturing time. Its parametric and modular design allows for modification of palm and fingers sizes in an easy manner, with the aim of increasing the range of target users. Moreover, its six intrinsic actuators and the self-contained embedded controller inside the palm, add flexibility to be fitted on subjects with different amputation degrees [15,17]. In order to replicate the six movements of human thumb [18,19], a design implemented with two actuators has been proposed.

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Methods involved in the design of an open-source, anthropomorphic and underactuated prosthetic hand, with a weight below $360g$ which allow for an affordable and highly functional prosthesis end device with a price about \$350 are described in Section II. Electrical design and details about the prosthesis-user interface implemented through a hybrid sEMG activated controller is proposed and described in Section III. This approach allows to achieve more and complex customized actions, such as individual finger motions, time based sequential actions and most common types of grasping based on Cutkosky grasp taxonomy [20], using a non natural control system, to satisfy a trade-off between simplicity, robustness, durability, low-power and cost.

II. GALILEO BIONIC HAND DESIGN

The merit of intrinsic actuation pattern (IAP) prosthetic hands is to provide more flexibility for people with different amputation degrees [17], this way the project can reach more users. It is essential that the length of the amputation plus prosthesis must be equal to the length of the preserved limb so that amputees feel comfortable and encourage the use of the prosthesis. The placement of actuators and electronics inside the palm helps achieve symmetry between the two extremities, because the prosthesis does not take up space within the socket [17]. Nevertheless creating an intrinsic design will increase the mass of the prosthetic hand, at the same time, the total mass needs to be less than a biological hand, since it will be attached to softer tissue of the amputated limb instead of been directly attached to the human skeleton which will be perceived heavier by the end user [8]. The prosthetic design is under-actuated with the aim to simplify and make it easier to manufacture and assemble. However, we can achieve adaptive grasping explained in [21,22], to hold objects in the ADLs. All structural and mechanical parts were fabricated using 3D printing ABS polymer excluding DC gearmotors, shown in Fig. 1. Furthermore, the design has fifteen Degrees of Freedom (DOFs) and six Degrees of Actuation (DOA).

A. Palm Design and Mechanisms

The requirements for the design were set with help of a volunteer suffering from transradial amputation on his left arm; therefore the dimensions of the hand were selected for a male anthropometry, however the design can be modified using tools provided by any slicing software to create the right hand version and a set of fingers will work in both versions. Initially the use of miniature RC servo motors was proposed, as other open source prosthesis, they worked fine in laboratory conditions, but they lack power, strength and durability to drive the mechanism for long periods of time or real-world conditions. Now the design implements miniature brushed DC gearmotors with an output torque around 60 oz-in. The palm has three different sections, each one with a separate cover to have direct access to each one for easy maintenance. Palm design consists of:

1) One gearmotor responsible for abduction and adduction of the thumb.
2) Four gearmotors to drive the fingers: index, middle, ring and little finger respectively.
3) Main PCB board controller including microcontroller and three dual H-Bridges.

A top view of the modular palm design is shown in Fig. 2.

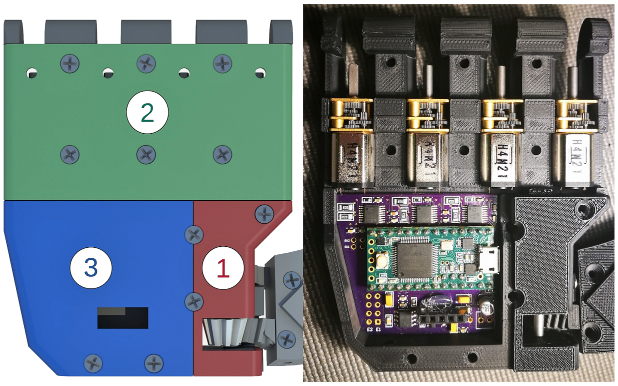

Fig. 2. Top view of modular palm sections of the prosthesis.

B. Thumb Movement Characteristics

The thumb has been designed to recreate the six movements described in [18], this was achieved by designing a finger with two DOAs. One actuator is located inside the thumb metacarpal phalanx and it is in charge of adduction and abduction actuation of the proximal and distal phalanges. The second one, at the base of the thumb metacarpophalangeal (MCP) joint is in charge of rotating the thumb around an axis 15 degrees away from plane of the palm. The joint aforesaid is built by a bevel gear and a helical gear working together to transmit the torque from the actuator, their axes are intersecting in a 15 degree angle, creating a beveloid gear pair [23] as shown in Fig. 3. In this way the axis of rotation is shifted without the need to place the actuator at an angle, allowing it to perform a larger prismatic grasp [20], at the same time saving space inside the palm and making it easier to print.

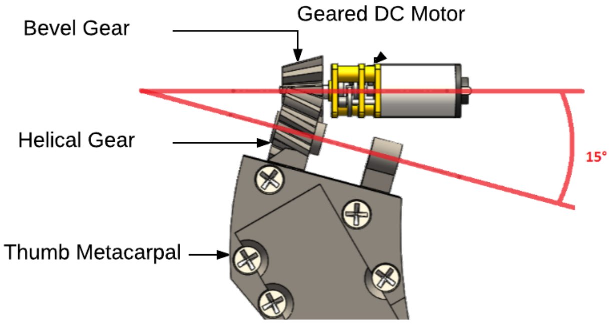

Fig. 3. Thumb Mechanism side view, beveloid gear pair

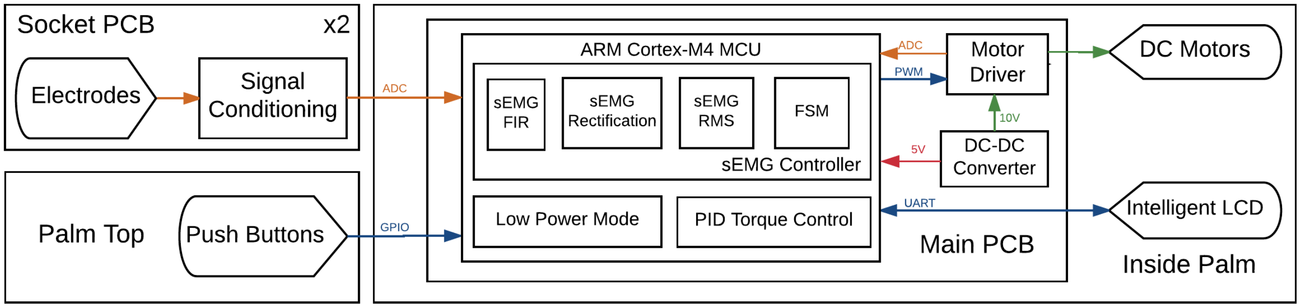

Fig. 4. The system block diagram showing an original myoelectric controller with a user friendly UPI.

C. Finger Design

Each finger has three phalanges (Proximal, intermediate and distal) for each finger except for the thumb, to mimic the biological hand. The fingers were designed to withstand the stress created by the actuators during ADLs, however each piece of the finger can be easily reprinted and reassembled using common 3D printing polymers. The parametric design of the phalanges allows modifications in the length of the fingers[1]. For the purpose of creating a simpler design, fingers can be manufactured regardless of whether they belong to a right or left hand prosthetic.

The fingers are tendon driven by geared DC motors, besides the flexion and extension of each finger is actuated by a nylon cord and a round elastic cord respectively, such that the first one goes through the front face of the finger and the second one through the back face of the finger. Furthermore, each phalanx is coupled with an outer shell, in this manner the exterior of the fingers can be modified not only for aesthetics but also for usability reasons, e.g. printing the outer shells from a flexible thermoplastic to provide better grasp. Moreover, each phalanx and each shell is enumerated to simplify the assembly process.

III. ELECTRICAL DESIGN

A flexible and original myoelectric controller is implemented with a low cost and high performance microcontroller unit (MCU) based on the ARM Cortex-M4 architecture. This MCU has signal processing capabilities, because of its SIMD instruction set, ideal to perform the type of tasks required to develop a high-efficiency, responsiveness and user-friendly controller [10]. Three custom PCB boards are designed in order to achieve a self-contained embedded controller that allows flexibility to be fitted in subjects with different amputation degrees. The block diagram proposed in Fig. 4 shows the system architecture of a simple and self-contained embedded controller that perfectly fits on the palm of the prosthesis.

A. User-Prothesis Interface

The controller is implemented with an intuitive and graphical user-friendly PUI, with the aim of improving functionality and increasing the number of customized hand postures performed by simple myoelectric on-off controllers, that are still used by most commercially available powered prosthesis, as shown in Fig. 7. Because of the limitations of simple on-off controllers, that can only perform a reduced number of postures that never exceed to three per channel [16,24], an intelligent LCD module (1.44" TFT LCD screen) from 4D systems is used because its internal controller provides modularity to the design through an easy communication protocol between the LCD the prosthesis main controller, allowing for selection between different sets of predefined gestures by pressing push buttons strategically placed on the top of the prosthesis. Moreover, this approach allows for consciously activated predefined postures through a Finite State Machine (FSM) of four states, implemented to activate postures by detecting contractions on flexor muscles of the forearm and deactivating by detecting contractions on extensor muscles, in order to release the fingers returning to rest posture [10]. Details of the implementation of FSM are shown in Fig. 5, where S_0 waits to activate predefined gestures through the motion controller implemented in S_1, S_2 waits to deactivate the gestures through the motion controller implemented in S_3, t_0 and t_1 are given by a simple on-off sEMG controller described below, finally p_0 and p_1 are given when the desired motion is finished.

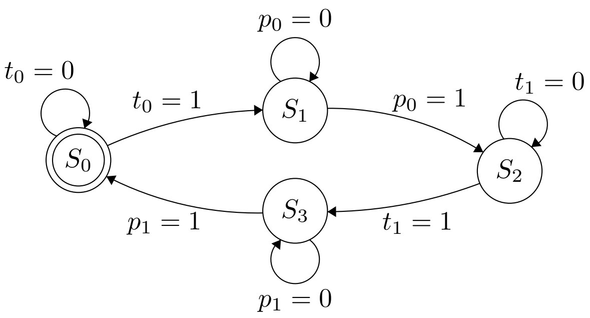

Fig. 5. Finite State Machine implementation for user-prosthesis interface using the sEMG Controller.

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[1] The length of the proximal and middle phalanges start from $22mm$, and $20mm$ for the distal phalanx.

B. sEMG Control Design

A simple on-off sEMG controller using time-domain features to trigger transitions of a FSM is designed in order to implement an intuitive user friendly control without compromising functionality and with the aim to achieve more customized hand actions without long periods of training.

1) sEMG Signal Acquisition and Conditioning: In order to save cost, two bipolar channels implemented with nickel-plated copper rivets as surface mounted electrodes are placed on palmaris longus and extensor digitorum muscles, focusing only on below elbow disarticulation [9,10]. Since the bio-potentials acquired are about $\pm 25\ \mu V\ to\ \pm 10\ mV$ with a bandwidth between $30\ to\ 2000\ Hz$ and in most of the cases are affected by mains power line noise and ground potential variability, a signal conditioning stage with single supply operation was implemented based on Texas Instruments (TI) INA326 high-performance rail-to-rail precision instrumentation amplifier and with TI OPA335 with an active low pass filter (LPF) configuration. Therefore, in order to sense the action bio-potentials of muscular fibers with an output signal span in the range of $0\ to\ 3.3\ V$ and a bandwidth between $0\ to\ 500\ Hz$, with the aim to collect useful sEMG data from the residual limb of the patient [10,25,26].

2) sEMG Signal Processing: The digital signal processing (DSP) involved in the sEMG controller is implemented on a custom main PCB board based on the Teensy 3.2 development board (PJRC) based on NXP ARM Cortex-M4 Kinetis K20 microcontroller, two channels of sEMG signals are collected using the on-chip ADC with a $1000\ kHz$ sample rate, and then are processed in order to eliminate the interference caused by AC frequency $(50 - 60\ Hz)$ of the mains power line with a window-based Finite Impulse Response (FIR) band-stop filter designed in Matlab software and implemented with the CMSIS-DSP software library for ARM Cortex-M4 processor based devices taking advantage of its SIMD instruction set [27]–[29]. Frequency and phase response are shown in Fig. 6.

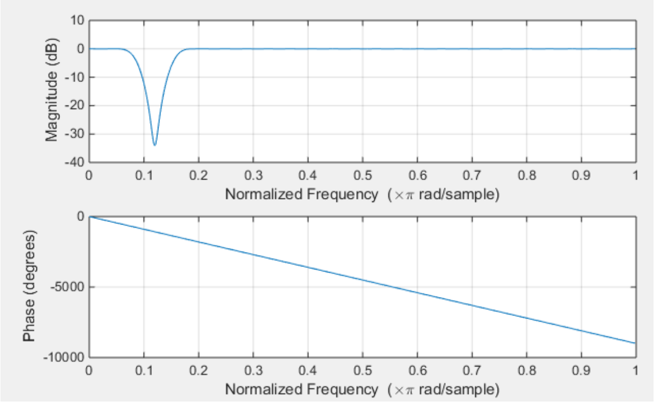

Fig. 6. Frequency and phase response of FIR stop-pass filter.

A single-threshold method is used to detect the On and Off timing of the muscles, comparing the Root Mean Square (RMS) value of the rectified signals with thresholds whose optimal values depend on the mean power of the background noise of each channel [30,31]. Once, the offset measured from the bias voltage reference was removed, fifty samples were rectified in order to determine the sEMG signal envelope to finally calculate its RMS value; and with the aim to detect the intended hand action used to trigger the transitions of activate and deactivate states of the FSM implemented on the user-prosthesis interface [10,32].

C. Motor Control Design

A complementary and center-aligned Pulse Width Modulation (PWM) method is used in order to drive brushed DC motors through h-bridge motor drivers based on TI DRV8833, providing active braking, in addition to speed and direction control of the six motors using fewer pins from the MCU. The motion controller is implemented to drive each finger independently also to achieve torque control by using PID algorithms through current sense feedback directly from the motor drivers. Since the design is intended to be simple and low-cost, torque is measured using current sense resistors placed between the H-Bridges and ground, this way the small voltage is sensed by the on-chip ADC of the MCU, when the internal counter of the timer reaches the middle of the wider pulse width of each complementary PWM signals. Once, the current is measured, a PID controller is implemented in order to drive the fingers until the motors are in a stalled position caused by the grasping of objects or by the mechanical limits of each finger, and then triggers p_0 in the FSM. The time to complete a stable grasping was measured for each finger, in order to drive back the motors, releasing the fingers the same amount of time to achieve the rest posture, and then triggers p_1 in the FSM.

IV. RESULTS

The prosthesis was tested performing basic prehensiles defined in the taxonomy of grasps proposed by Cutkosky: Power, hook, precision and lateral grasps [8,15,20]; the test was performed with everyday life objects, achieving satisfactory results, as shown in Fig. 9. The minimum size of the palm can be $98\ mm$ of palm length, $69.6\ mm$ of palm breath and $25\ mm$ of palm thickness accordingly. Likewise the phalanges are parameterized with minimum length of $22\ mm$ for the proximal and middle phalanges and $20\ mm$ for distal phalanges. The weight of the prosthesis terminal end device has remained below $360\ g$, not taking into account the socket and the $11.1\ V$ LiPo battery that must be placed in the waist belt. The estimated cost is around \$350, including 3D printing materials, electronic components and mechanical materials, as pins, screws, elastic thread, etc. Moreover, the minimum flexion and extension time of the MCP joint of the fingers is about $800\ ms$ and $600\ ms$ respectively, also for the abduction and adduction of the thumb MCP joint is around $150\ ms$; the test was performed with DC motors at full throttle.

Fig. 7. Graphical UPI on Galileo Hand performing power grasping.

Besides, power grasp force was measured with results up to $50\ N$, also each finger can hold loads below $5\ kg$ when the DC motor is not driven and it can drive loads below $3.5\ kg$, as shown in Fig. 8. The thumb has achieved performance for four of the six movements of a human thumb listed as follows: abduction, adduction, extension and flexion, In addition, the thumb MCP joint was designed with a range of 85 degrees increasing the result in the Kapandji test, obtaining a score of five; i.e, thumb tip is able to meet up to the ring finger tip. The interaction between subject and the UPI was tested successfully on three patients with different level of transradial amputation. Five postures were elected (Power Grip, Precision Pinch, Hook Grasp, Lateral Pinch and Pointing) and performed twenty times each achieving perfect accuracy; for this test a single-threshold method has been used to detect the On and Off timing of the muscles, considering that time domain features are preferred because of low computational benefit [10,27,32].

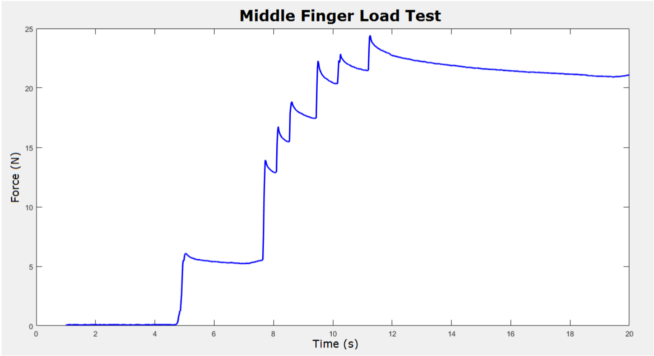

Fig. 8. Load testing results for middle finger with DC motor driven.

V. CONCLUSIONS

It is important to create a lightweight prosthesis device without compromising the grasping capabilities, robustness and durability, encouraging the users to use it more frequently in their activities of daily living; the weight of this design is below the commercial prosthetics that are compared in [8,17,33]. The hand size can be modified in order to adapt to a wider range of users, issues can occur when trying to create a small size prosthesis; because the actuators and electronics will take up most of the space inside, since it is an intrinsic design that allows to cover different levels of transradial amputations. Therefore the design is better suited for adults with below elbow disarticulation. However, a user with one transradial disarticulation does not need to perform complex tasks with his prosthetic device, since anyway he will use his healthy hand to develop these kind of tasks. Therefore, a simple and intuitive prosthetic device was designed to satisfy a trade-off among low-cost, low-power, good aesthetics, low weight, dexterity and performance. The results obtained testing the different hand gestures and prehensile were successful and experimentally validated, by grasping a range of objects commonly used in real life (e.g. water bottles, credit cards, toolboxes, etc.). Moreover, the dexterity test in terms of full closing time and speed involved in the flexion and extension of the fingers reached speeds around $112 - 125^\circ/s$; these results are very satisfactory compared with the results of research and commercial prosthesis presented in [8,15,17,33]. The thumb MCP joint has an individual actuator providing more than the needed torque allowing the mechanism to achieve speeds around $590^\circ/s$ with full throttle. In addition, in terms of force, the results from the test about holding force also were satisfactory, keeping its results in desired range compared research and commercial prosthesis, as shown in [8,15,17,33,34]. Furthermore, it is shown that the methods used in the UPI has advantages over traditional systems, because of its user-friendly interface that increases the amount of customized hand postures that can be performed. This allows the manufacturer to keep the cost range below $350, without compromising functionality and performance of the controller, as mentioned in [10]. On the other hand, sophisticated sEMG controllers allows the user to consciously perform the desired actions in the most natural way, like the research proposed in [11]–[15]. However, this sEMG controller is a great solution to let the system trigger a wide variety of predefined gestures with perfect accuracy.

Fig. 9. Galileo Hand is performing power grasping and the peace sign.

The sEMG controlled described has been tested on three below elbow amputees. Finally, this prosthetic achieved great functionality while maintaining a low-cost using rapid prototyping processes. Also the design is intended to extend time between maintenance periods to create a reliable prosthesis. The design is easy to personalize because it comes with removable shell covers for each individual phalanx and palm section.

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