A dexterous hand prosthesis based on additive manufacturing

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***Abstract*—Upper limb amputation is a major injury that can strongly affect the daily life of a person. Prosthetic hands that can execute multiple movements are available, but they are expensive and difficult to control. Natural control via pattern recognition is promising but it is applied in real life prosthetics only in limited ways. Additive manufacturing and machine learning can revolutionize prosthetics with affordable and open-source solutions that can include 3D printed prosthetic hands, sockets and dexterous highly functional control. Nevertheless there are still intermediate steps to do into this direction. The objective of this paper is to introduce an ongoing project aimed at the development of low cost and dexterous prosthetic hands to be used in real life conditions based on open 3D models, additive manufacturing and machine learning. The results at the current state of advancement of the project include several versions of the prosthetic hand (powered by six servomotors and based on open design), of the control system (based on open electronic prototyping platforms) and of the socket. Preliminary tests of the hand demonstrate its dexterity, its potential and requirements to improve force. Once fully completed and released, the presented 3D printed, dexterous, open-source prosthetic hand has the potential to improve the life of hand amputees worldwide and to foster improvements in research and for future commercial prosthetic hands.**

***Keywords*—Electromyography, prosthetics, additive manufacturing, machine learning.**

I. Introduction

Upper limb amputation is a serious injury that can have a significant impact on a person's everyday life. According to estimates, 41,000 Americans were thought to have lost most of their upper limbs due to amputations above or below the elbow in 2005 [1].

Hand prosthetics is rapidly advancing, also thanks to machine learning and 3D printing. The combination of these solutions may revolutionize the domain if it is demonstrated to properly work on real life tasks and in a robust way. Although surface Electromyography (sEMG) commercial dexterous prosthetic hands (i.e., prosthesis that can do several movements) do exist, they are quite expensive and frequently difficult to control [2]. Their usage is thus often limited, because the control is frequently not sufficiently easy for usage in practical situations. Over the past ten years, a number of open models for 3D printed hand prosthetic hands have been created. Although 3D printing is one of the key technologies expected to revolutionize prosthetics in the future, open-source strong and dexterous prostheses have been limitedly developed.

Particularly if the amputation is bilateral, hand amputations are among the most physically and mentally debilitating injuries. At the moment, there are three types of hand prostheses: myoelectric, kinematic, and aesthetic. Cosmetic prosthetics provide psychological and esthetic support. Kinematic prostheses also have functional capabilities, since the user may control the opening and shutting of a gripper hand by the motion of the shoulder. In most myoelectric prostheses, two electrodes on the forearm allow the user to control a battery-operated hand using an electrical signal produced by the remaining muscles [2]. Prosthetic hands that can execute multiple movements are available, however they are frequently quite expensive. Few myoelectric hand prosthetics that are now on the market have the ability to replicate a variety of actions, e.g. Touch Bionics i-limb Quantum; Otto Bock Michelangelo; Steeper Bebionic v3; Vincent hand Evolution 2 [2]. Such prostheses are typically priced between \$50,000 to \$75,000, and the cost can further increase when pattern-recognition-based control systems are included. In such, still relatively rare, systems, typically, two or three sEMG electrodes are placed in the socket in relation to particular muscles to regulate them. The prosthetic hand opens and closes using myoelectric impulses, or a rise in the amplitude of the electrical signal released by the muscles. By using particular (for example, sequential) control procedures, the number of motions can be enhanced. Controlling prostheses needs a high level of competence and a dedicaterd training process, making such control tactics still far from being identifiable as natural.

The limited capabilities and acceptance of sEMG prostheses are a result of control issues among other challenges [3], but there are the premises for improvements in a near future. Effective tools for prosthesis control, pattern recognition and machine learning are primarily used in scientific studies [4] and there are currently not many commercially available systems. These techniques typically usually employ a higher number of sEMG electrodes to capture the myoelectric signals produced by the muscles. Utilizing algorithms for pattern recognition, the sEMG activity is examined to categorize the

movement that the subject intends to make in real time [5],[6]. Since 2013, Coapt-engineering[1] made a brand-new real-time pattern recognition-based hand prosthesis control system commercially available. Despite the incredible advancement for the domain, this system still does not replicate a biological hand's natural control and allows controlling usually a limited number of movements [2].
In recent research works, additional sources of information [6]–[8] have been suggested to be incorporated into the conventional myoelectric control, enhancing the controller with autonomous decision-making. Cognolato et al. enriched sEMG with eye tracking and computer vision data [9], [10].

A number of 3D printed hand prostheses have been developed in recent years thanks to 3D modeling and printing [11]. Numerous websites offer open designs that enable users to build their own 3D printed prosthesis[2]. Additive manufacturing processes and rapid prototyping techniques provide many options to quickly design, develop, build, and test functional prosthetic hands in a reasonable amount of time. In comparison to current commercial prostheses, 3D printed prosthetic hands may offer benefits like lower costs and patient-specific size adaptation. Additionally, an open-source architecture enables quick adaption to technological and scientific breakthroughs. An excellent example of the capabilities of this kind of approaches is provided by the HANDi HAND, which was created at the University of Alberta (Canada) [12], which has a number of actuators and a range of sensors (including pressure and positioning sensors) and that was tested in real life conditions by our group [13]. However, the majority of open hand prosthesis designs have only limited functionality (open-close), they are not robust enough to be used in real-world situations often having limitations in stiffness, grasp strength, assembly precision or structural strength and they have only received sporadic testing when combined with pattern recognition on practical tasks [13].

II. Methods

The prosthetic hand presented in this work was designed to allow for the most common hand movements for activities of daily living, with particular focus on the most used movement macro-classes [14]. The prosthetic hand was designed following the requirements of patients and it is composed of a dexterous robotic hand, a socket including eight sEMG electrodes and a control system.

A. Dexterous hand prosthesis

In most cases the available open source hand prostheses designs have limited functionality (open-close), they are not sufficiently robust to be used in real life conditions and they have been limitedly tested in combination with pattern recognition on real life tasks. The prosthetic hand presented in this work was designed to facilitate daily tasks as much as possible.
It is based on previous 3D printed open source hand prosthesis, the HANDi HAND, designed at the University of Alberta (Canada) [12], that includes six actuators and a variety of sensors (including pressure sensors and encoders for finger positioning). However, following a set of real life tasks tests [13], the hand was strongly redesigned to increase ergonomics, functionality for activities of daily living and usability: limitations such as the finger orientation, the zip-tie return spring, surface grasp friction and strength were addressed and intentionally improved.
The prosthetic hand includes six servomotors: five for finger flexion, one for thumb ab-adduction. The fingers are positioned to be similar to real prostheses and to allow functionally grasping objects and they are designed to allow the user predicting their positioning more intuitively. The internal transmission and gear systems were designed from scratch with a desmodromic transmission to reduce friction and to increase grasp force and mechanic life. Several servomotor models were tested as well with the aim of increasing strength. The prosthesis was produced through SLS (Selective Laser Sintering) technique, which allowed the use of complex and detailed geometry. The material used for the dorsal part of the hand is Nylon (PA 12), which provides good mechanical properties and strength. SLS (Selective Laser Sintering) technology uses a laser to sinter and fuse together layer after layer of powdered material, thus creating more robust components compared to the more commonly known FDM (Fused Deposition Modeling). Another advantage is that the non-sintered powdered material acts as support during the 3D-printing process. This allows to produce more complex shapes and eliminates the need for physical supports during the production of the component. The design of the hand will be released open-source as soon as it is finalised.

B. Socket

The socket was designed and made by Playcast Srl[3]. The design of the virtual model of the socket was made on the basis of real data using an innovative 3D scanning technique which was applied to the patient's amputated forearm. The obtained 3D reconstruction is very accurate and in high resolution, allowing limited changes to create the socket using proprietary design tools of the company. Among the changes, adaptation to include eight sEMG electrodes was required to allow empowering machine learning based algorithms and to include the prono-supination mechanism. The socket was then printed with additive manufacturing using the FDM technique and using recycled plastic, with low impact on the environment and it is fully recyclable. The socket is composed of three pieces: one is adherent to the distal stump and activates the hand pronosupination; two make up the outer shell of the socket, facilitate the wearing process and transmit the loads to the elbow epicondyles, by means of low shore paddings. The two pieces are held together by velcro straps.

C. Control system

The prosthetic hand is controlled via eight Otto Bock

[1] http://www.coaptengineering.com/
[2] E.g. http:// openbionics.org/ ; http://enablingthefuture.org/
[3]https://www.playcast.it/

13E200 EMG sensors, which detect the contraction of the remnant muscles in the proximal stump. The signal is transmitted to an open-source electronic prototyping platform (Arduino Mega).

The various possible movements associated with different patterns of contraction of the muscles in the forearm are then analysed to control the prosthesis. Custom made classification algorithms (developed by Dynatec studio[4]) classify the signal associated to four hand postures (fist, wrist flexion, wrist extension, fingers spread, rest) on the Arduino, which is also used for controlling the servomotors for positioning the hand prosthesis. Among the possible grasps performed by the prosthesis, the following ones were tested in different sessions: cylindrical, tripod, index finger extension, rest, lateral, tip pinch.

III. Results

A. *Dexterous hand prosthesis*

The developed hand prosthesis represents an effective application of additive manufacturing to the development of dexterous and high functionality prosthesis controlled via machine learning (Fig. 1).

The prosthetic hand was designed to allow for the most common hand movements for activities of daily living, to facilitate daily tasks as much as possible.

The design and the positioning of the fingers allow a functional and effective grasping of objects of different shapes, including bottles, balls, credit cards, pens. Moreover, the ongoing process of redesigning the fingers has allowed to increase the predictability of their positioning during grasps. The desmodromic design of the internal transmission and gear systems allowed to control actively both the flexion and extension of fingers and allowed to reduce friction and to increase the life of the components.

Among the servomotor models that were tested, six Hitec HS-65MG provided the best compromise between component durability and strength. More powerful servomotors were tested though. Those would likely benefit the usability of the prosthetic hand, but at the current status the authors could not find more powerful components able to provide sufficient durability and reliability.

In general, the 3D printed prosthetic hand showed very good usability in terms of ergonomics, usability and capability to interact with the environment for grasping objects (Fig. 2). It costs less than 600 €, weights 350 grams and it is capable of performing the most useful grasps for activities of daily living and to effectively grasp objects. The current challenge for the team is to improve the grasp strength, to satisfy the requirements of everyday life. According to users, the prosthesis represents an important step in the direction for future prosthetics.

[4] https://www.dynatecstudio.it/

B. *Socket*

The socket was designed by Playcast Srl and offers high adaptability, low making times and costs, relatively good usability and the possibility to include several sEMG electrodes to empower machine learning based control algorithms.

The socket was designed and made with 3D scanning and printing, which allowed to strongly reduce the time required to make it. The obtained 3D reconstruction is very accurate and in high resolution, leading to a good fit to the forearm of the patient. It allows to include eight surface electromyography electrodes and it can be easily connected to the robotic hand prosthesis. The socket includes a wrist rotation system and demonstrated good usability in preliminary tests, it is easier to wear than traditional ones and it offers sufficient comfort for experimental tests. In order to improve the electrode contact with the skin, an elastic armband was used provide pressure on the top of the electrodes.

The socket offers several advantages over traditional ones due to Voronoi holes pattern. First, it is breathable and fully washable; second, it does not require qualified personnel to be made; lastly, it is cheaper than a traditional system and it is made of 100% recyclable plastic, with positive outcomes for the environment). In addition the production cost is limited (less than 600 €) and it weighs only 350 grams.

Improvements are currently being implemented aiming at extending the usability, which is currently limited, for allowing everyday life usage.

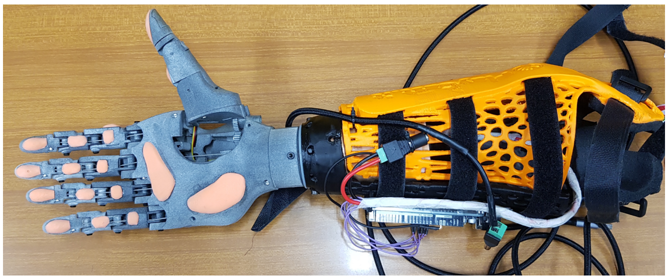

Fig. 1: 3D printed robotic hand and socket.

Fig. 2: Examples of hand grasp tests.

C. *Control system*

The control system is based on eight Otto Bock 13E200 EMG sensors (weight 4.5 g each), one Arduino Mega (cost less than 50 €, weight less than 50 g), one battery and custom-made machine learning algorithms. It demonstrated to perform well in practical tests, allowing to easily open and close the prosthesis in 3 different movements selected among the taxonomy of hand movements [14]. The control system employed in this study experiments used a gesture recognition approach that made it possible to swiftly and automatically identify the required grasp. In addition to controlling the gesture used to open the prosthetic hand, the system was tailored to the characteristics and demands of the patients, enabling them to grip objects.

Controlling the prosthesis in the different movements was very fast and reliable, making its usage almost instantaneous, smooth and pleasant according to the users. The authors are current working to solve challenges mainly related to forearm positioning issues, which are well known in the domain of dexterous prosthetics.

IV. Discussion & Conclusion

The promising findings presented in this paper point to the viability of flexible robotic prosthetic hands based on additive manufacturing, 3D scanning and machine learning based control systems. These technologies are currently more widely available than in the past due to the components' and devices' rising affordability.

Despite the requirement to improve the socket usability and the prosthesis strength, the system demonstrates high usability capabilities and well represents the capabilities of the forementioned modern technologies for the future of prosthetics.

The whole system weighs less than 900 g plus the battery and costs less than 1’400 € excluding the electrodes. The electrodes currently represent the most expensive part of the system, but those could be replaced with open-source low cost solutions in the future. These facts suggest that the experimental setting can be successfully replicated and applied in situations where cost is a major concern, such as in the pediatric population, in underdeveloped nations, and in research teams with limited resources.

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