A 3D-printed Prosthetic Arm with Wireless Sensor Functionality

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***Abstract*— Approximately 2 million people in the United States (1/160 inhabitants) have an amputation. Estimations assuming a similar prevalence indicate approximately 3 million patients in the EU. These numbers are expected to increase. Following this trend, Innovations in neuro-prosthetic limbs have advanced and led to the development of several so-called smart prosthetics, which can improve the lives of millions of patients. When focusing on upper limb prostheses, there have been major improvements in the development of highly functional bionic arms. These devices require complex control mechanisms using embedded and distributed sensors and actuators with tight reliability and latency constraints. Several control mechanisms have been proposed in literature, which are based on sensing and interpreting body signals such as: myoelectric potentials using electromyography (EMG), electroencephalography (EEG), electrocorticography (ECoG) or signals directly from the nerves, limb acceleration and orientation, tensile measurements on the skin, and haptic (tactile and force) feedback. Learning strategies using these mechanisms have enabled very accurate prediction and classification of hand movements. The operation of smart prostheses requires not only sensing and prediction of their movement, but also feedback from the prosthesis. This can be provided by wireless sensors embedded in the prosthesis. It are such sensors that will be investigated in this thesis.**

In the thesis, a complete wireless system is investigated to make a prosthesis that is affordable for everyone and offers more functionalities than other publicly available prostheses. The communication methods between a muscle-worn sensor and the prosthesis are studied in order to communicate EMG data in an efficient way. The state of the art in prosthetics, their sensors, and control modules is examined. The results of the final prosthesis, Bluetooth Low Energy (BLE) modules, chosen processors, cost price, battery life, etc. are discussed as well. The operation of the prosthetic is demonstrated schematically and visually (via video).

***Index Terms*— 3D-printed prosthetics, wireless low power sensors, mechatronics, EMG-sensors, Bluetooth Low Energy**

I. INTRODUCTION

In the year 2005, 1.6 million people had a limb amputation. It is expected that the number of people with limb loss will more than double to 3.6 million by the year 2050 [1]. The leading cause of upper limb loss with adults is trauma, and cancer is the 2nd most common cause. Other causes of upper limb loss are infections, burns and congenital malformations [2]. The war in Ukraine is also likely to contribute greatly to these figures. As a result of the wars in Afghanistan and Iraq, catastrophic injuries from explosives have increased, traumatic amputation is the leading cause of upper limb loss in the military. Transradial amputations (just below the elbow) were the most common amputations with 47% [2].

Since 1500 BC, prosthesis had been the solution for people with amputations to regain their functional independence. With the advances in manufacturing processes in the prosthetic industry over the past 10 years, prostheses can be made in a much cheaper and more sophisticated way to increase their quality of life [3].

The goal of this thesis is to add wireless sensors to a (preferably) publicly available 3D printed prosthetic arm. For this purpose, a wireless module compatible with a publicly available 3D printed prosthetic arm will be developed. To integrate this module into such prosthesis, the prosthesis itself also needs to be modified. This research will concentrate on low-power technologies that can provide significant improvements in prosthesis control.

A system will be developed for wireless control and data transmission from the arm to an off-body node (module for receiving/transmitting data that is at a certain distance from the sender/receiver) that controls the arm and interprets sensor data from sensors on the prosthesis and on the patient.

Finally, it will be demonstrated that wearable sensors can assist in controlling the wirelessly controlled prosthesis through improvements in gesture control/recognition using these sensors.

II. MATERIALS AND METHODS

A. Hussain arm version 1

After research on state-of-the-art in 3D-printed prosthetics, a prosthetic arm was 3D-printed which is named the "Hussain arm", after its initial designer. The first version was an open-source version that was available on [4] shown in Figure 1. We obtained this version on 19/02/2022. In comparison to alternatives such as the HACKberry prosthetic arm [5], this prosthetic arm has the additional ability to turn its wrist automatically with a servo motor and uses thin (0.4 mm) nylon wires to pull and extend the fingers, and is printed using Polylactic Acid (PLA). It also has the ability to use a varying number of servo motors depending on the desire to actuate fingers separately.

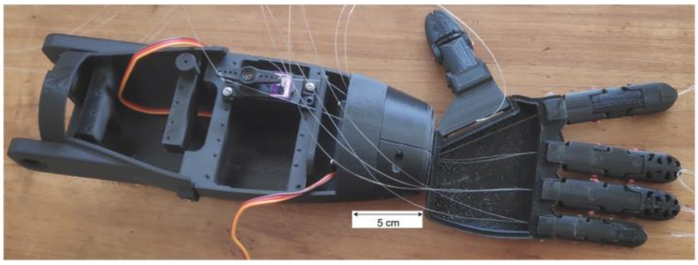

Figure 1: Hussein arm version 1

Our first goal was to demonstrate the full control of the system with this arm. Our second goal was to improve the arm itself.

B. Hussein arm version 2

Several of improvements were possible for the Hussain arm v1, so a second iteration was made with Fusion 360, where three smaller servo motors (EMAX E808MA II) were fitted in the arm (see Figure 2) for controlling the fingers and only one big servo (MG996R) motor for rotating the wrist instead of five big servo motors used in v1. Also, the stronger Polyethylene terephthalate glycol (PETG) was used as 3D-print material, instead of PLA in v1. The arm was made shorter by 109 mm and the thumb was redesigned so that its mechanics worked better. By making the prosthetic shorter, it was ideal for transradial amputations (which is an amputation just below the elbow) and was the most common amputation (47 %) of amputees during the war in Afghanistan and Iraq. The same can be expected of the war in Ukraine.

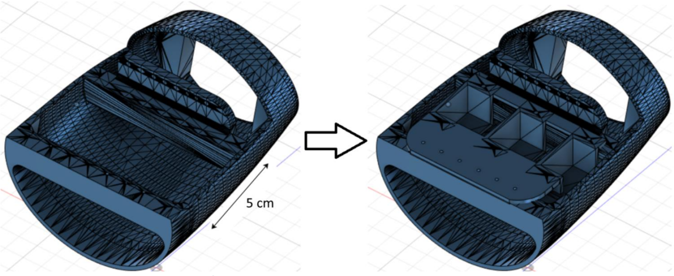

Figure 2: Hussein arm, forearm version 2

C. Sipeed Maix Bit

The literature study showed that the Kendryte K210 processor was an excellent candidate to act as the brain of the prosthetic. A compact, low power and low-cost microcontroller containing this IC was chosen, i.e., the Maix Bit from Sipeed (see Figure 3). The Kendryte K210 has machine learning capabilities which is very interesting to have a trained machine learning model on it to interpret EMG-data and then execute the servo motors trough pulse width modulation (PWM) on the prosthetic. This is a big advantage over more common processors found in other prosthetics like the ATmega328 processor [3].

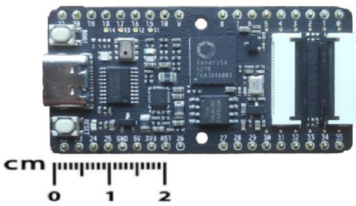

Figure 3: Sipeed Maix Bit microcontroller

D. Sipeed Maix Bit shield

One problem with the Maix Bit is that it could not receive wireless EMG-data. Our literature study showed that such a wireless connection would be beneficial and that BLE 5.1 would be an excellent candidate technology for this wireless communication because it has adjustable data-rate speeds (up to 2 Mb/s), adjustable range and other features that reduce the total power consumption. The benefit of BLE 5.1 is also that it has a direction-finding feature to find the other paired BLE device. After extensive research the NINA-B406 module was selected as BLE receiver for the Maix Bit.

1) Version 1

A shield was developed based on the Arduino Nano 33 BLE that could contain A NINA-Bx module and that fitted the Maix Bit. I2C (meaning Inter-Integrated Circuit) was chosen to transfer the EMG-data from the shield to the Maix Bit, because both devices supported I2C. The shield was powered through its VIN port trough the 5 volt pin of the Maix Bit (see Figure 4). Testing of v1 demonstrated some minor design flaws.

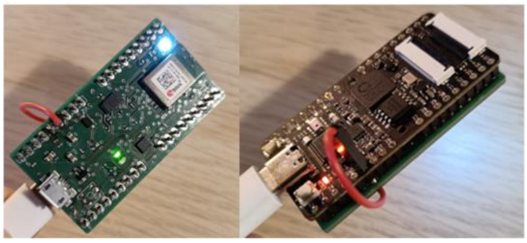

Figure 4: Maix Bit shield (version 1) powered by the Maix Bit

2) Version 2

These issues were resolved with the making of version 2 (see Figure 5) of the shield. External pads were added (on the bottom of the PCB) to upload the bootloader for the shield and a better arrangement of components was used, e.g., the resistors and capacitors were placed closer to the MPM3610 step-down converter to prevent unwanted electromagnetic radiation coming from the feedback pin of the step-down converter.

Figure 5: Maix Bit shield version 2 next to € 1 for scale

In order to be compatible with pre-existing, publicly available bootloaders, a NINA-B306 was used in our final version instead of a NINA B4x module, which has the only disadvantage that it uses BLE 5.0 instead of BLE 5.1, so no direction-finding feature is available. A gyroscope (L3GD20H) was also added to the board so that it could be used as a feature for the machine learning model or as biofeedback for the system.

E. Assignment master, slave and central, peripheral

the setup of the BLE-communication (central and peripheral) and I2C-communication (master and slave) is shown in Figure 6.

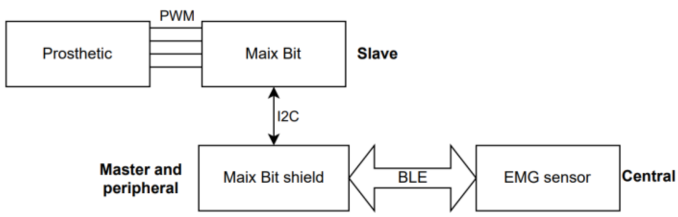

Figure 6: Assignment master, slave and central peripheral

III. RESULTS

A. Full control of the system

The full control of the system means the excitation of the forearm muscle to the actuation of the prosthetic. These include following steps which are visualised in Figure 7:

1. Excitation of the muscle measured by the EMG sensors of the MyoWare Muscle Sensor.
2. Transmit this data trough fixed wiring to the analog port of the Arduino Nano 33 BLE.
3. Send this data through BLE 5.0 to the Maix Bit shield.
4. The shield sending this data through I2C to the Maix Bit
5. Actuation of the servo motors trough PWM coming from the Maix Bit.

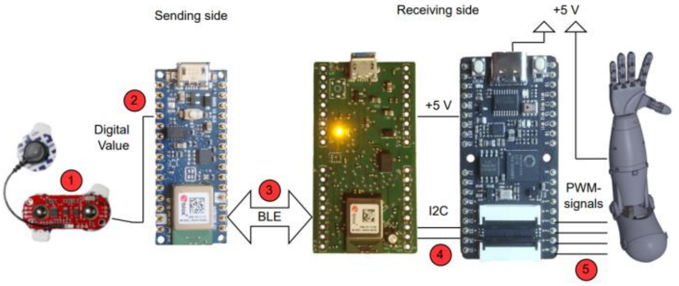

Figure 7: Full control of the system

Two gestures were performed and classified using a threshold-based classification. The video called "excitatie_spier_tot_beweging_prothese.mp4" available on https://doi.org/10.4121/21803991.v2. After performing the same movement correctly 20 times it is concluded that it performs well. This is of course with only two gestures, no machine learning model, use of the gyroscope or the direction finding feature of BLE 5.1.

B. *Power consumption*

A fitting lithium polymer (LiPo) battery was selected to put in the Hussein arm with a capacity of 2650 mAh. Three states were defined, one is when the prosthetic doesn't move, two when the prosthetic is moving and three when a force is applied in the opposite direction than the moving prosthetic. **The first iteration of the Hussein arm will have a battery life of 43.44 h when in rest, 8.69 h when moving and 5.94 h when stress is applied. The second iteration of the Hussein arm will have a battery life of 56.38 h when in rest, 16.26 h when moving and 10.00 h when stress is applied**.
The second iteration shows promising results for real life use, this of course depends on the necessities and age of the patients and clearly outperforms the first iteration.

C. *Speed of excitation muscle to actuation prosthesis.*

Having fast reflexes is important, our calculations, based on measured system reaction times (370 ms) show that the time it takes for a patient to interact with something (young men have an average reaction time of 269.33 ms [5] when something is coming towards them) will be more than double the time than a person without a prosthetic (639.33 ms), see section 3.6 in the thesis. This is of course only when the servo motors need to make a full 180 ° turn. This was calculated with a rotational speed of the servo of 0.12 sec/60°.

D. *Weight of the full system*

The Hussein arm version 2 including the 3D-printed parts, servo motors, nylon wire, Maix Bit, Maix Bit shield, LiPo battery and buck step-down converter has a **total weight of ± 564.03 grams.** Arguments were used in the thesis to reduce this weight even further, also depending on the necessities and age of the patients. Another prosthetic found in literature was the very popular HACKberry prosthetic (and is standard not wireless) and weighs ± 115.03 less than the Hussein arm version 2, but does not have an automatically rotating wrist, and the Hussein arm version 2 has an increase in battery capacity of 42.47 % in comparison to the HACKberry prosthetic.

E. *Cost of the full system*

The full cost of the receiving side (see Figure 7: Full control of the system) including the LiPo battery would be a total of € 108.736.

IV. CONCLUSION

A. *research question*

Out of research, two modules were selected to work with each other to create a state-of-the-art wireless, low power, actuated prosthetic. This was the NINA-B4x series which support BLE 5.1 which supports direction finding of the other paired BLE-device which could improve gesture classification, this in combination with a gyroscope could even give better results. The selected machine-learning capable chip was the Kendryte K210, these two modules fused together (NINA-B4X and Maix Bit containing the K210) promises an interesting low cost, easily made prosthetic for all people in need of an arm prosthetic. Here are some numbers:

1) A total battery life of:
   a. 56.38 h when in rest.
   b. 16.26 h when moving.
   c. 10.00 h when stress is applied.
2) An average reflex time from brain to prosthetic movement of:
   a. 649.67 ms for older men.
   b. 639.33 ms for young men.
   c. 693.33 ms for older women.
   d. 647.33 ms for young women.
3) A total weight of ± 564.03 grams where the popular HACKberry prosthetic weighs 449 ± 1 gram.
4) The full Hussein arm version 2 only costs € 108.735.

B. *Project*

The whole system works as follows: EMG-data is measured and the prosthetic is actuated trough BLE, I2C and eventually PWM. A demo can be found in section III.A. The power consumption, battery life, speed, weight and cost of the prosthetic were investigated and showed promising results, we will only talk about the Hussein arm version 2:

Currently BLE 5.0 is used (because of the NINA-B306) instead of BLE 5.1 (because of the NINA-B406) which only excludes direction finding of the paired BLE-device because no bootloaders are yet released.

C. *Future work*

Machine learning models can be trained on real EMG-data of patients, also the gyroscope and direction find of BLE 5.1 could improve gesture classification and execution even further.

The Hussein arm version 2 has a weak wrist because it is directly attached to the axis of a servo motor.
It is better to use a flat stepper motor with a long axis, or some kind of gearing to not directly attach the servo motor to the palm of the prosthetic.

A 12-bit PWM-servo driver could be used with I2C or SPI (or Serial Peripheral Interface) communication to support more servo motors if necessary.

The BLE 5.0 could be tweaked to reduce the energy consumption and lengthening the battery life expectancy. We can adjust the range and data throughput speed to the needed distance and data troughput. Because LiPo batteries comes in all sizes and shapes, a perfectly shaped LiPo battery could be inserted into the prosthetic to have the maximum battery capacity possible at the expense of weight.

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