1. INTRODUCTION AND MOTIVATION

New advances in both neurosciences and computational approaches have changed the landscapes for smart devices design serving mobility-related disabilities. In this paper we will look at how we integrated affordable robotics and wearable sensors through our mechatronic product platform to enable accessibility of the technology in both the power prosthesis and neurorehabilitation space.

While we believe that our solution will benefit most for those in developing countries supported by the wider maker's community, the project started from a humble student-driven innovation initiative in HKUST in Hong Kong. Sparthan uses a third party EMG sensors, the Myo Armband, to measure electrical activity from muscles to detect gestures made by one's hands. Using a 9-axis IMU, it also senses the motion, orientation and rotation of the forearm. Raw EMG and IMU data are the streamed for on-board processing to drive the motorized digits.

The initial target users will be general needs for hand prosthesis in developing countries, and serving globally children who have lost partial or complete functionality of their hand. Some statistics on the target users:
- More than 40,000 children are born with congenital upper limb defects every year.
- There are 3.5 million upper limb amputees worldwide, 80% of them in developing countries.
- 56 million elderlies over 80 years old suffer from (muscle degeneration).

On the market, powered prosthesis with enabling basic motions are very expensive, starting from USD1000. These solutions are limiting for children with the lengthy fitting process and how quickly the prosthesis are outgrown. Market research shows a gap in the market for a solution that provides affordable and accessible prosthesis; existing solutions and market gap will be discussed in Section 2.

Low cost and accessibility, however, are not sufficient to create meaningful impact in a scalable and adaptable fashion. Within this project, we employ lean product development cycle, machine learning for gesture recognition, and adaptive model-based control to deploy the first version of Sparthan.

2. SYSTEM-LEVEL DISSECTION OF EXISTING SOLUTIONS

In response to the challenges, shortcomings, and high cost of traditional prostheses multiple organizations started to pioneer new and innovative ways to manufacture cheaper prosthetic hands.

2.1. e-Nable Community

Arguably the most influential non-profit in the prosthetic hands space, e-Nable describes itself as a global network of volunteers who are using their 3D printers, design skills, and personal time to create free 3D printed prosthetic hands for those in need – with the goal of providing them to underserved populations around the world.

e-Nable was started in 2013 by a small group of committed individuals offering their 3D printers for manufacturing cheaper, mechanical prosthetic hands, inspired by the work of Ivan Owen. The organization is now the only provider of 3D printed prosthetic hands with a global network completely run by volunteers, offering 4 different customizable hand models and full support on the build process. The mission of the e-Nable community is to provide access to prosthetic hands inside communities that would otherwise not have any other means of doing so. Their devices are not aimed at replacing traditional professionally made prostheses, but at creating an extremely low cost solution that can be beneficial to specific section of the population (i.e. children, patients in developing countries, etc.)

2.2. Million Hands Project

The Million Hands project is an initiative started by the BEST Lab at Berkeley, overseen by Ph.D. candidate Daniel Lim. Million Hand is specifically aimed at lowering the cost of deploying 3D printed prostheses, by engineering better technologies to design and manufacture devices at a large scale. Million Hands has won numerous awards including *Million Hands: Prosthetic Hands for Children through an Open Source Platform, 3D Printers and Sensors* and *Helping Hands - Playground Edition*. While the e-Nable community is focused on creating and maintaining a network of volunteer around the world, Million Hands is mostly working on improving the underlying technologies in the field to support and complement deployment in the future. The University of California Berkeley is also actively involved in the project, supporting the initiative and expanding its scope.

2.3. Open Bionics

Open Bionics is a company based in the United Kingdom, funded by Joel Gibbard in 2014. Joel started working on open source and open hardware prosthetic hands under the \textit{Open Hand project}. The project, started in 2013, was aimed at creating and publishing mechanical designs for a 3D printable prosthetic hand that would be cheaper and more customizable than traditional equivalents. After publishing initial designs, the Open Hand project morphed into a full-fledged company, under the name Open Bionics.

Open Bionics has been the first commercial company to get regulatory approval for using a 3D printed prosthetic arm as a medical device. The main strategy of the company is using the same underlying platform, named Hero Arm, as the functional base of every prostheses, customizing the external appearance through the use of skins and 3D printed covers. Open Bionics has managed to bridge the gap between the open source community and the professional prosthetic market, bringing regulatory approval to 3D printed prosthetics in an unprecedented market shift. Their operations, however, are currently limited to the United Kingdom, since the prostheses are supplied and regulated by the {NHS}, a national institution. Despite this limitation, Open Bionics provides open source designs both for mechanics and electronics in their devices, allowing anyone to improve and continue their work in other countries.

The above solutions all have respective strength merits but there exists a gap in the prosthesis market space that our solution addresses.
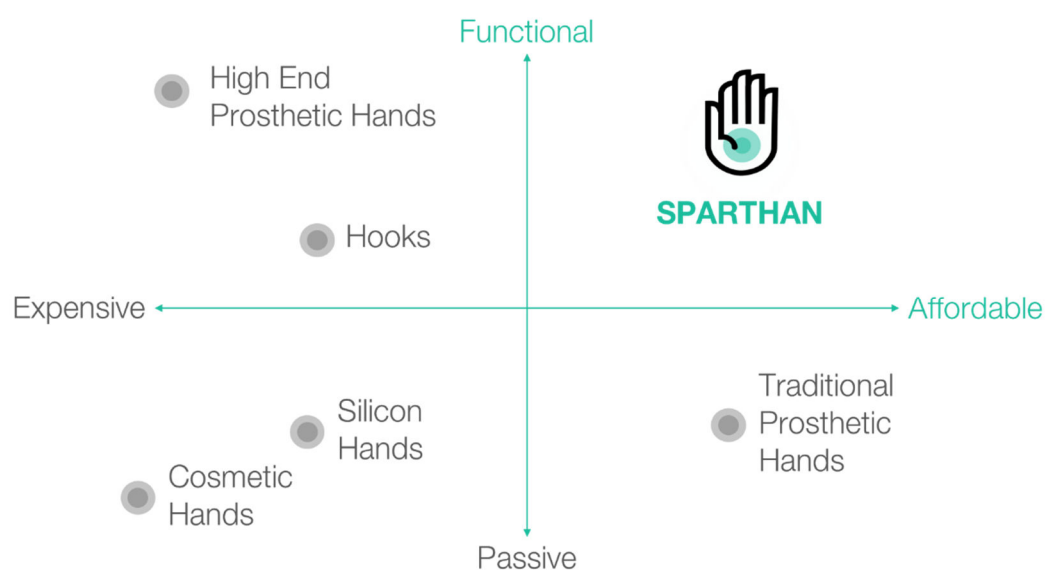

Figure 1. Market Gap filled by Sparthan

3. USERS' NEEDS AND REQUIREMENTS: MODULARITY, SCALABILITY AND HMI

Market research was performed in Hong Kong, Seoul, Beijing and San Francisco Bay Area. Stakeholders including potential users, family members, hospital staffs and local maker community were surveyed and interviewed. Some interesting findings were uncovered to show that beyond simple functionalities offered by prosthesis, the mental benefit of feeling empowered and included by their peers is considered important. Most feels powerless with the disability that holds them back from job and financial security.

The high level needs deduced from the primary market research ranked in order of importance include:
  a. Weight of the product
  b. Functionality of the product
  c. Durability of the product
  d. Appearance of the product

Using Kano model and simplified QFD, three important requirements were further extrapolated.

	Importance	Weight	Power Consumption	Margin of Safety	Degrees of Movement Freedom	Modular Design	Ease of Further Development
Battery life	5	4	3	1	2	0	0
Comfort	8	8	3	3	0	0	0
Intuitive use	6	0	0	0	5	0	0
Price	6	0	0	4	3	3	2
Looks/Design	4	0	0	3	2	1	2
Reliability	7	0	2	9	3	2	2
Reusable Mechatronics	8	1	0	0	2	8	5
TOTAL		92	53	**128**	103	100	74

Figure 2. Simplified QFD prioritization of Sparthan's Product Features

Modularity

Because our solution relies on the local maker's community resources and support, ease of assembly in form of simple electronic and mechanical modules will make the solution accessible and provide more flexible prosthesis fitting experience for the end-user.

Scalability

Our product needs to scale for different sizes of prosthesis (e.g. to fit growing children). This implies that the packaging of the mechatronics should be compartmentalized in small form factors to accommodate different 3D hand models.

Human-Machine Interface

A repeated pain-point voiced by the surveyed users is the discomfort of using the prosthesis due to ill-fitting and time-consuming, poor user-experience of the fitting procedure itself. While making our

product accessible to the end-users give them more control over the fitting procedure, we are also placing ease-of-use design requirements on Sparthan to ensure

- Compatibility with existing 3D hands models by providing multiple versions
- Easy installation procedure for the makers with snap on mechanism and video tutorials
- Intuitive UI interface for app-based DIY process such as 3D scan, gesture mapping, etc.

The ability to incorporate 3rd party solution to process muscles sensor data and translate user intention into hand movements would only generate impact if we can effectively offer customization and advanced control capability; which would be described in the next section.

4. SYSTEMS DESIGN – METHODOLOGIES AND SUBSYSTEMS DESIGN

Creating a module that could interact with existing 3D models was the key to improve their functionality, without changing the dynamics of the open source community. For this reason Sparthan is compatible with all models based on flexible joints printing. This allows makers to access a wide range of resources on assembly and printing of the models, streamlining the makers' experience.

To provide an intuitive user interface we decided to use EMG signals coming from the patient's forearm. Muscles and tendons are still present in the forearm either in the event of an amputation or in the case of a congenital malformation. These leftover muscles can be contracted and controlled directly by the patient, providing an intuitive and fast way to interact with the prosthetic hand.

A micro controller unit in the palm can then process the signals and detect when a particular gesture is being performed, actuating the corresponding fingers through the use of micro electric motors embedded in the palm.
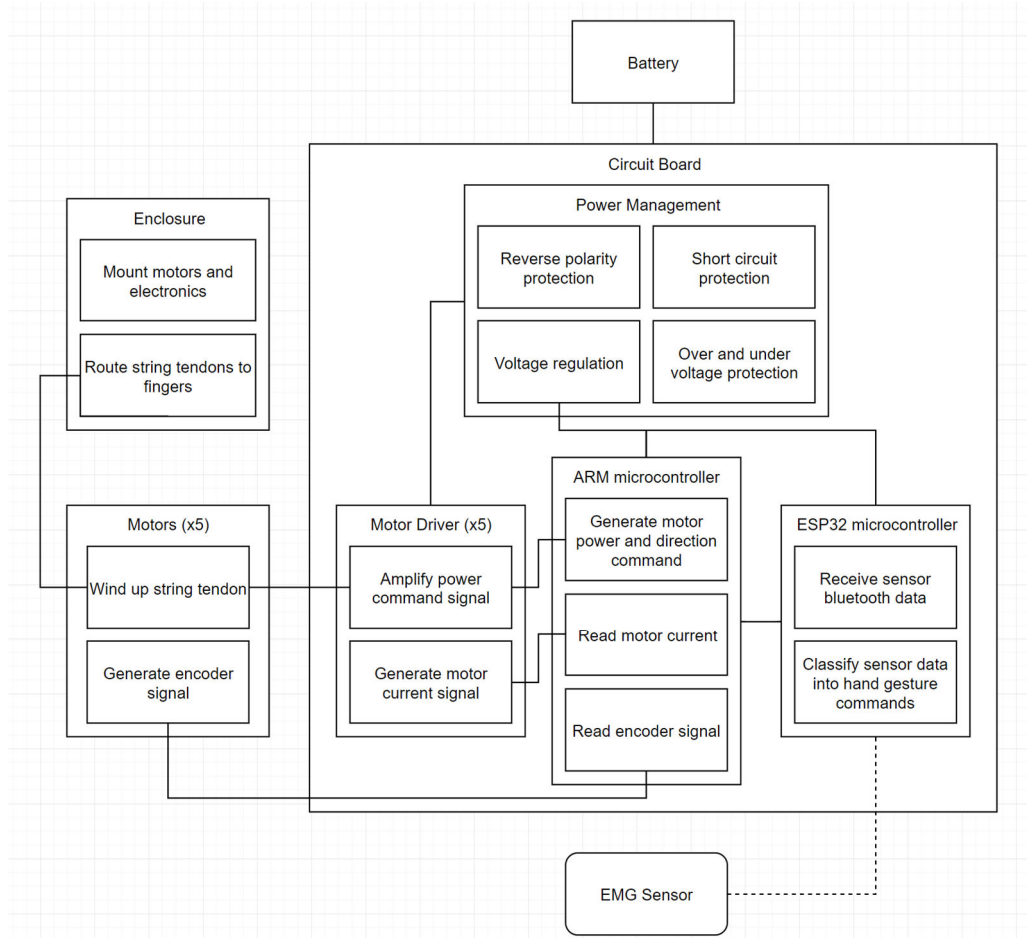

Figure 3. Sparthan's Overall System Diagram

4.1. **Mechanical**

Mechanical design of this project is based on user's need on modularity and scalability. The stringent requirement of fitting in a small form factor of a child's prosthesis drives the design towards small compartments and strategic layout of motor arrangements. In a Sparthan-equipped prosthetic hand, the two main sections of the mechanical system are:

4.1.1. *Sparthan Module*

The Sparthan module enables 3d printed prosthetic hands to be controlled myoelectrically. It houses the Sparthan controller board and five geared DC motors securely. Attached to each geared motor shaft is a roller which pulls or releases a piece of string when the motor spins, allowing the string to act as tendon controlling the movement of prosthetic fingers. Hollow paths routed through the module housing guides the piece of string to the 3d printed prosthetic hand. Additional slots and holes are present in the module housing to allow routing of power and data cables.

The Sparthan module housing is designed for manufacturing. To ensure the Sparthan module can be scalable to meet potential high demand, and varying manufacturing capabilities of makers across the world, the module housing can be produced by either stacking laser cut plastic sheets or 3d printed.

When choosing the housing material, the following requirements were considered:

- Maximum working temperature has to withstand the high temperatures generated by the geared motors.
- The material has to be available in sheet form for laser cutting and in filament form for FDM 3d printing.
- The material has to be durable and impact resistant for rough daily life use.

Driven by the above requirements, polycarbonate (PC) was chosen as the housing material.

4.1.2. *Porsthetic Hand*

The Sparthan module is designed in a way such that it can be easily fitted into 3d printable prosthetic hand models with simple modifications. A Sparthan-ready prosthetic hand model is produced by boolean subtracting the Sparthan module from the original hand model, followed by cutting string paths that join the Sparthan module and fingers. Due to its close resemblance to a human hand, the Flexy Hand 2 prosthetic hand model was chosen as the basis for the first Sparthan-ready prosthetic hand.
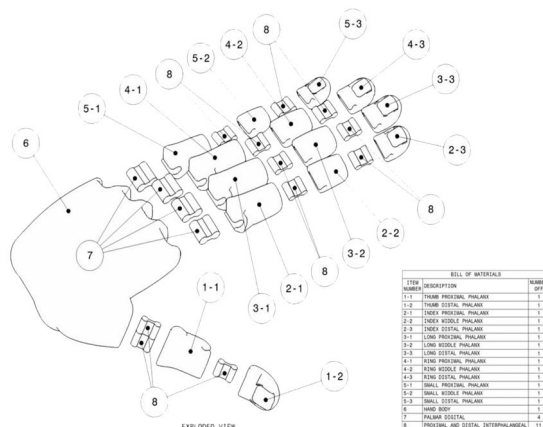

Figure 4. Flexy Hand 2

This particular 3D printable hand combines a very anthropomorphic design with good functional capabilities. The joints in the fingers are printed using flexible filament (e.g. TPU) which allows the fingers to spring back into position after being flexed by the motors.

Potentially, any design which shares this feature is compatible with our module, allowing users to choose and modify existing designs to be used with it.

4.2. Electronics

One of the key differentiating features of Sparthan consists in its ability to electronically control the finger movement through the use of motors. Motorized control is indeed what distinguishes a normal 3D printed prosthetic device from one equipped with Sparthan, and for this reason particular care was taken during the corresponding design process.

The two main functions of the electronics inside Sparthan can be described as:

4.2.1. EMG recording

The signal coming from the muscles needs to be sensed through differential electrodes applied to the skin and amplified with analog circuitry, before being processed to infer the patient's desired gesture. {EMG} signal classification is by itself a very hard task, strongly dependent on the quality of the data recorded as well as on the kind of classification algorithm chosen. For this reason we decided to employ a commercially available device that could record eight different signals all around the forearm and transmit them over BLE to the microcontroller in the hand. This device is the *Myo armband* by Thalmic Labs. This device not only offers high end analog circuitry, but also a custom API for Bluetooth communication, which allows for a very robust connection and lasting battery life.
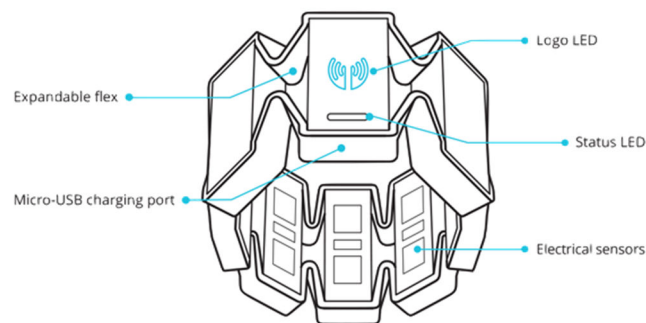

Figure 5. Myo Armband

4.2.2. EMG decoding and actuation

In order to process and decode the signal we designed a custom PCB capable of receiving the data through a Bluetooth module and process it. Designing a custom board [FIGURE:BOARD] allowed us to reduce the components' footprint, while using high end motor drivers directly connected to the microcontroller. The motor drivers we selected present two important features that help to reduce power consumption.

       a. Motor current sensing
       b. Over-current protection

Sensing the current to each individual motor allows the microcontroller to know exactly when the finger is touching the object and the motor is stalling, thanks to the peak in current draw. This peak is limited by the over-current protection and can be used to detect exactly when to stop the motor's motion. The board also provides solder points for the motors, allowing for a direct connection that greatly simplifies cable management. Each motor attachment point has six pins, two for power and four for the Hall Effect magnetic sensor that act as encoders for the motor's rotation.
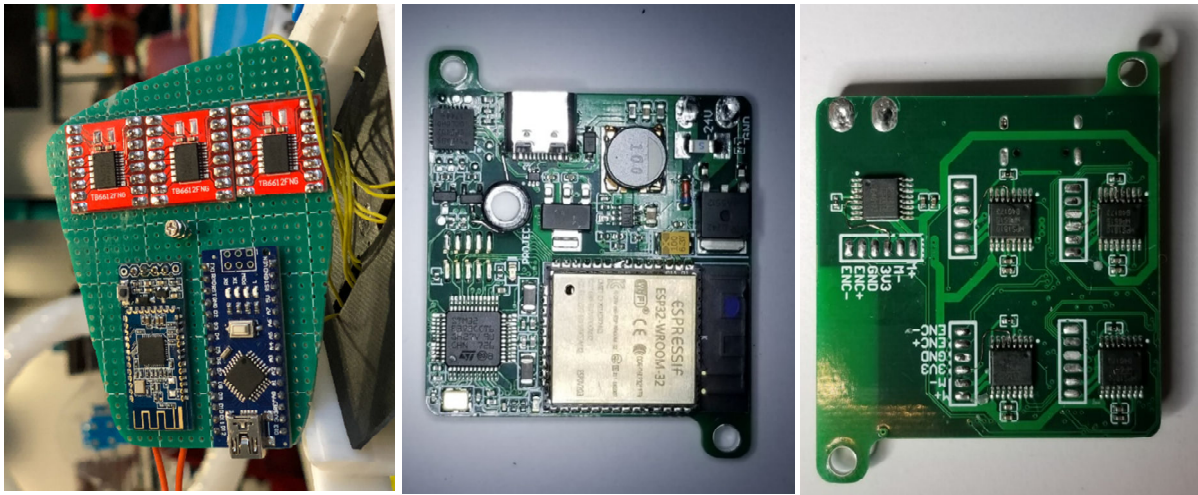
Figure 6. (Left) 1st generation mainboard, (Middle & Right) Optimized 4x4cm^2 mainboard & drives

4.3. Adaptive Model-Based Control

During the proof-of-concept first generation prototype, attention was placed on gesture mapping by running classification algorithms to estimate user intended gestures. Understanding that simple classifiers such as regression or SVM would not offer the desired accuracy, deep learning classifiers are built to optimize high-level motion control for the prosthesis
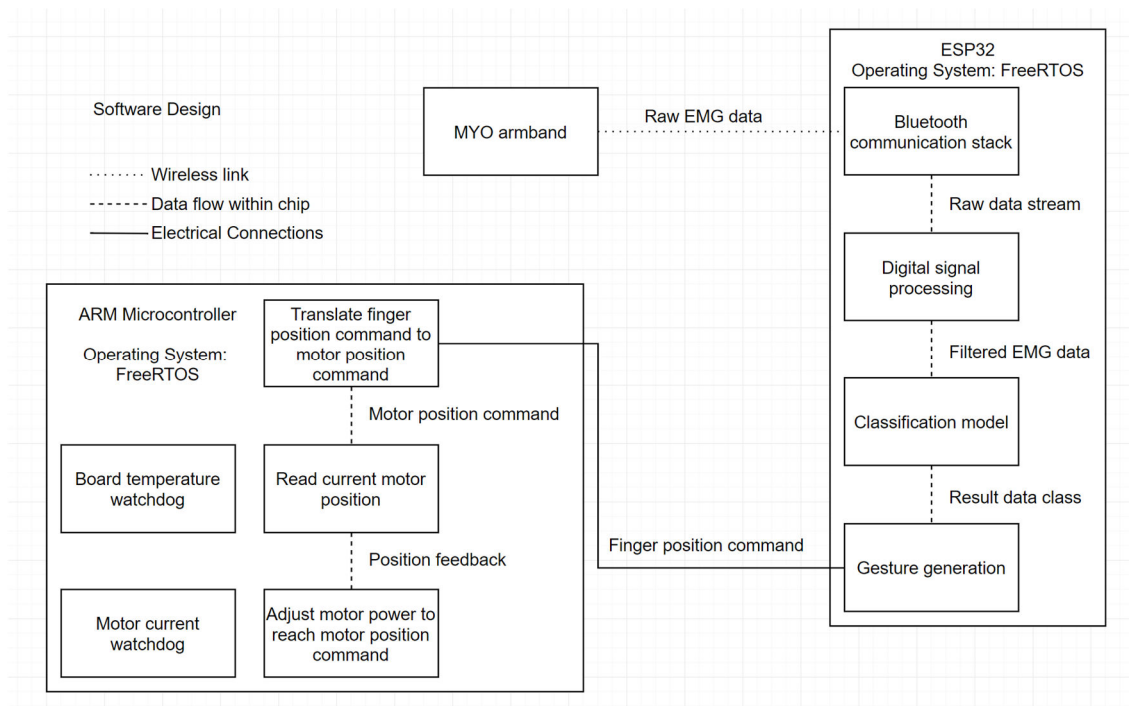.

Figure 7. High level open-loop motion command through gesture mapping from EMG signal

In development is a model-based closed-loop control that fits between the gesture generation and motor command signals to create a truly customized user experience for different users and hardware. Grimmer et al. classifies the control of a prosthetic device into either Computational Intrinsic Control (CIC) with little connection to the user, and Interactive Extrinsic Control (IEC) which is based on afferent feedback as in Sparthan's use case.

Using the classical MRAC (Model Reference Adaptive Control) framework, the individualized plant model can be generated through the use of Matlab Systems Identification Toolbox as applied in Simscape import of the unique prosthetic hand CAD model.
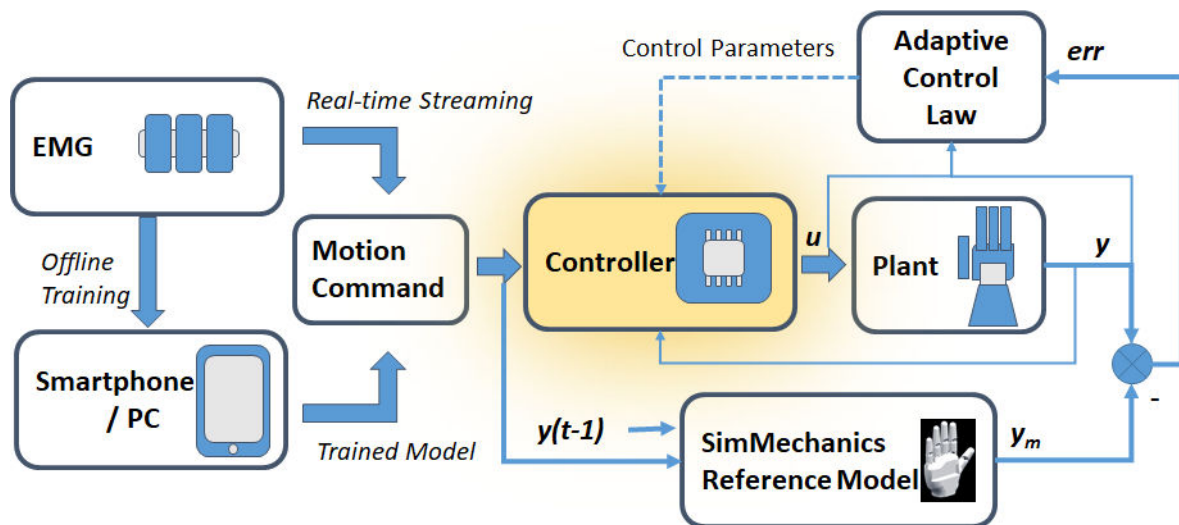

Figure 8. Model-based adaptive control to provide tailored controller design

4.4. User Interface and Experience

A user-friendly app will allow creating a 3D model of the user's body. The images are acquired by a normal smartphone camera and processed to create an accurate 3D model. The custom model will be sent to a 3D printing facility near the user to make delivery even faster.

Figure 9. Sparthan App for scanning hand for rehabilitative application

Partnering with makerspaces and schools enables Sparthan to take full advantage of the already existing network of 3D printers. The electronics are designed to be plug-and-play, meaning that once the hand is printed it's just a matter of snapping the module we will ship in place. The goal is to maximize opportunities for end users to be involved in the fitting process via online tools.

5. CONCLUSIONS AND FUTURE WORKS

Our solution relies on scalability to ensure effectiveness, for this reason we identified as key partners the 3D printing providers, which can use already existing facilities to print such a low volume application at virtually no additional cost. Providing only the electronics module will lower the initial capital needed for manufacturing, creating a platform on which to build more advanced prosthetics solutions. The key value propositions of the Sparthan solution are:

- Compatibility with existing **3D hands models**
- Easy installation procedure for the **3D maker community**
- Intuitive control interface for the **end user**

In 2019, we will focus on introducing the Sparthan kit to beta test with stakeholders; from medical rehabilitation units to prosthetic users. Partnerships with UC Berkeley Million Hands project and local NGOs grant-based social impact deployment are formed to further the project opportunities. The fine tuning of system modelling and adaptive control will be done in tandem to better the overall user on boarding experience. Finally, we also look to employing the mechantronic enabling kit concept to other applications beyond 3D printed hand prosthesis; e.g. motorization of lightweight exoskeleton.

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