The New Architecture of *ModGrasp* for Mind-Controlled Low-Cost Sensorised Modular Hands

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***Abstract*— *ModGrasp*, an open-source virtual and physical rapid-prototyping framework that allows for the design, simulation and control of low-cost sensorised modular hands, was previously introduced by our research group. *ModGrasp* combines the rapid-prototyping approach with the modular concept, making it possible to model different manipulator configurations. Virtual and physical prototypes can be linked in a real-time one-to-one correspondence.**

In this work, the *ModGrasp* communication pattern is improved, becoming more modular, reliable and robust. In the previous version of the framework, each finger of the prototype was controlled by a separate controller board. In this work, each module, or finger link, is independent, being controlled by a self-reliant slave controller board. In addition, a newly redesigned multi-threading and multi-level software architecture with a hierarchical logical organisation is presented. In this regard, a new programming paradigm is delineated.

The new architecture opens up to a variety of possible applications. As a case study, a mind-controlled, low-cost modular manipulator is presented. In detail, the user's levels of attention and meditation are monitored by using an electroencephalography (EEG) headset, the *NeuroSky MindWave*. These levels are used as inputs to control the hand. Since the manipulator features 11 DOFs, a synergistic control approach is chosen to map inputs with outputs with such a different dimensionality. Related simulations and experimental results are carried out.

***Index Terms*— Modular Grasping, Software Architecture, Brain-Computer Interface.**

I. Introduction

The idea of modularity is adopted when simple identical modules are used to build linkages in order to realise versatile robots that can support multiple modalities of locomotion, manipulation and perception. From a mechanical point of view, even if it is not the most efficient design approach, modular robotics still meets the requirements of standardisation, modularisation, extendibility and low cost. Restricting the focus to robotic grasping, the modular approach allows using only the necessary number of degrees of freedom to accomplish the grasp. In this way, it is possible to find a trade off between a simple gripper and more complex human-like manipulators [1].

When developing modular manipulators with different configurations, rapid-prototyping can be beneficial from a design point of view. Development time can be significantly reduced, the main grasp properties can be analysed and the quality can be assessed. With this in mind, *ModGrasp*, an open-source virtual and physical rapid-prototyping framework that allows for the design, simulation and control of low-cost sensorised modular hands was introduced in [2]. By combining the rapid-prototyping approach with the modular concept, different manipulator configurations can be modelled. A real-time one-to-one correspondence between virtual and physical prototypes is established. Different control algorithms can be implemented for the models. By using a low-cost sensing approach, functions for torque sensing at the joint level, sensitive collision detection and joint compliant control are possible. A 3-D visualisation environment provides the user with an intuitive visual feedback.

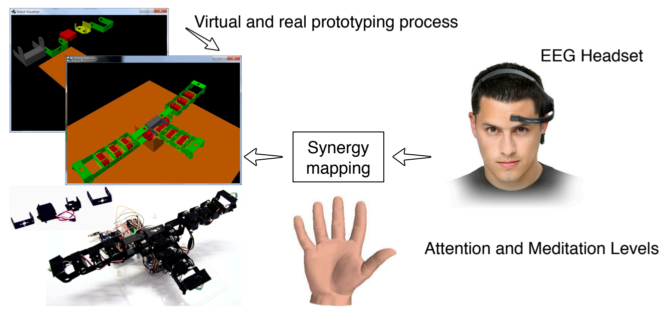


Fig. 1: To show the potential of the new *ModGrasp* control architecture, a mind-controlled, three-fingered modular manipulator is presented. A demo video is available on-line at `http://youtu.be/2CIYboez9r0`.

In this work, we aim to improve the robustness of the prototypes designed with *ModGrasp*. For this reason, the concept of modularity is stressed even more than before concerning the control architecture. In particular, the *ModGrasp* master-slave communication pattern is modified. In the previous version of the framework, each finger of the prototype was controlled by one slave controller board. In this work, each module, or finger link, is independent, being controlled by a separate slave controller board, which directly communicates with the master controller board. The resulting prototypes are extremely robust to hardware failures. For instance, if one or more modules break or are disassembled from a prototype, the manipulator keeps working with the remaining functioning joints. In addition a newly redesigned multi-threading and multi-level software architecture is presented. In this regard, a new programming paradigm is outlined. The control of each module is efficiently split in highly specialised processes (threads) that are hierarchically organised in different logical levels. To show the potential of the new control architecture, a mind-controlled, three-fingered modular manipulator is presented as a case study. In particular, the user's levels of attention and meditation are monitored non-invasively from the scalp through an electroencephalography (EEG) headset, the *NeuroSky MindWave* [3]. The underlying idea is shown in Fig. 1. The user's levels of attention and meditation are used as inputs to control the hand. Since the manipulator features 11 DOFs, a synergistic control approach is chosen to map inputs with outputs with such a different dimensionality. A demo video is available on-line at `http://youtu.be/2CIYboez9r0`.

The paper is organised as follows. A review of the related research work is given in Section II. In Section III, we focus on the description of the redesigned framework architecture. In Section IV, the considered case study is presented. Related simulations and results are shown in Section V. In Section VI, conclusions and future works are outlined.

II. Related Research Works

Modular hands present a great potential in terms of versatility, robustness and low cost. However, programming such robots for specific grasping tasks can be challenging. For instance, one of the limitation of the previous version of *ModGrasp* is that it was not possible to easily define different processes and logically independent layers within the control software that runs on each module (finger link). In this regard, a software architecture that fully exploits the concept of modularity is required. Over the past few years, the possibility of creating such a kind of software framework for robotic hands has been investigated by several research groups. For instance, in [4], a control system architecture for the DLR Hand II of the German Aerospace Center was presented. A multilevel, modular structure of the whole hand system was also introduced in the hand's software architecture. The developed concept of modular levels was designed mainly to perform multiple different tasks on a higher abstraction level. Another notable example of modular control architecture was presented in [5], where the application of a virtual decomposition control approach to modular robot manipulators is discussed. A high-speed data-bus with a data rate of 100 Mbps is used for necessary information exchange among the modules. The dynamics-based control is fully handled by the local embedded controllers, whereas the host computer handles the kinematics related computation. The stability of the entire robot is rigorously guaranteed.

However, most of these previous works mainly focus on building a framework that often applies to a specific modular system, while the idea of simplicity, the objective of practicality and the concept of rapid-prototyping are often neglected in the design of the control architecture. In the opinion of the authors, the extreme versatility of the modular grasping requires a completely new paradigm concerning both hardware and software design. To the best of our knowledge, a flexible software architecture that takes advantages of the underlying modular hardware with simplicity in mind is still missing.

Concerning the possibility of controlling robotic hands by using a braincomputer interface (BCI), several researchers are recently trying to concentrate their efforts and investigations on this topic. In particular, with the latest advances in the technology that allows for monitoring and processing the human electroencephalographic signal, increasingly promising and non-invasive approaches are attracting more attention. Nonetheless, few studies have demonstrated practical BCI control of robotic modular manipulators. Most of the previous works focus on the control of prosthetic devices that do not exhibit a modular design in terms of both hardware and software. For instance, in [6], an EEG-based motor imagery BCI was presented to control the movements of a prosthetic hand. The hand was instrumented with force and angle sensors to provide haptic feedback and local machine control. Using this system, subjects demonstrated the ability to control the prosthesis's grasping force with accuracy. In [7], the design of a wearable mind-controlled prosthetic hand, based on the use of a commercial EEG headset, was presented. Decision-making methods, intelligent control of the prosthetic hand and the man-machine coordinated approaches were studied. The hand was equipped with pressure sensor arrays to imitate the touch and slip feelings. Besides, an accelerometer sensor and an angular velocity sensor were used to acquire the feedback of the prosthesis's position and orientation.

However, from a computation point of view, these previous works involve quite demanding control algorithms, which can be hardly distributed on a modular architecture. In addition, different sensors are required to achieve the control objectives. These characteristics do not easily match with the principles of minimalism, simplicity and low-cost that are at the base of modular robotics.

III. New Framework Architecture

In this section, the first contribution of this work, which is on improving the architecture pattern presented by our research group for *ModGrasp* in [2], is outlined. In order to achieve this, the same, generalised manipulator module is taken into consideration.

The concept of modularity is stressed even more then before concerning the control architecture. The newly proposed

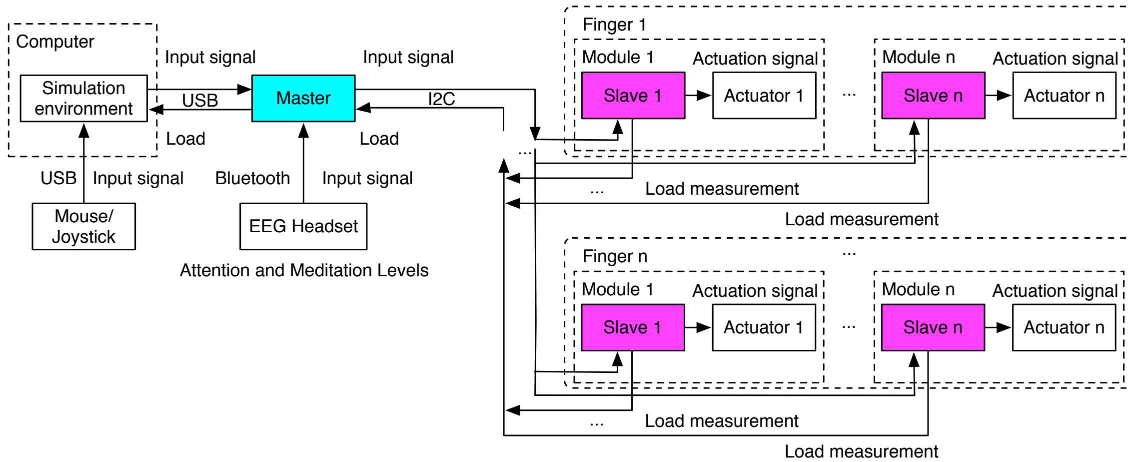


Fig. 2: The *ModGrasp* master-slave communication pattern is modified. In the previous version of the framework, each finger of the prototype is controlled by a slave controller board. In this work, each module, or finger link, is independent, being controlled by one separate slave controller board, which directly communicates with the master controller board.

architecture is shown in Fig. 2. In detail, the control framework is derived from the master-slave communication pattern used in *ModGrasp*. However, the *ModGrasp* architecture was semi-distributed. In fact, in the previous version of the framework, each finger of the prototype was controlled by a separate slave controller, which communicates with a master controller board. In this work, each module is independent, being controlled by a self-reliant slave controller. In this way, the new control architecture is:

- fully distributed, to support decentralised control and avoid single module failures (if one or more modules break or are disassembled from a prototype, the manipulator keeps working with the remaining functioning joints);
- dynamic, to be able to easily adapt to the topological changes and support different gripper configurations;
- scalable, to work for any configuration regardless of the shape and size. As such, a trade-off between simple grippers and more complex human-like manipulators can be reached.

In the following, the key elements of the newly designed framework are presented.

A. Controllers and communication protocol

On the hardware side, an *Arduino Uno* board [8] based on the *ATmega328* micro-controller is used as the master, while one *Arduino Nano* [8] board is used as a slave to control each module, instead of each finger as it was in the previous version of *ModGrasp*. *Arduino* is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. Using *Arduino* boards simplifies the amount of hardware and software development needed to get a system running. On the software side, *Arduino* provides a number of libraries to make programming the micro-controller easier. The choice of using *Arduino* boards makes the rapid-prototyping framework easy to maintain and makes it possible to add new features in the future.

As it was in the previous version of *ModGrasp*, the standard I^2C [9] is used as a communication protocol between the master and the slaves. However, each module has its own communication capacity in the new version of the framework. This protocol is chosen because it is relatively easy to set up and it also supports slaves having different addresses, thereby meeting the requirements of the framework architecture. In addition, the physical manipulator models communicate with a simulation environment through the serial interface of the master controller board.

B. Control methods

Just like the previous version of *ModGrasp*, the user is free to implement different control methods based on specific needs. The design of the proposed prototyping framework is not affected by the possible implementation of certain control features. A possible approach is briefly outlined in this subsection so as to introduce the reader to the case study discussed later in this paper.

Conventional robotic control design tools and equations may be sufficient for simple prototypes with a low number of DOFs, but when the complexity of the modular model increases, a highly flexible and general control algorithm is needed. This can happen in the case of an increase in the number of DOFs or when different modular configurations must be controlled independently of their specific morphology. A *synergistic* control method based on actual human grasping could be a promising approach, as highlighted in [2]. The key equations necessary for studying the kinematics of *synergistic* control methods are briefly recalled here. A more

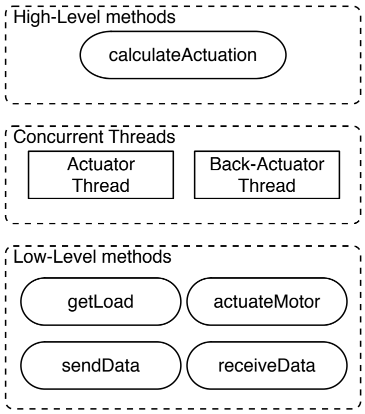


Fig. 3: The newly redesigned multi-threading and multi-level hierarchical system.

detailed presentation of this problem is described in [10]. According to a model inspired by the *synergies* of the human hand, we presume that a number of inputs whose dimension is lower than the number of hand joints is used to actuate the hand. In particular, let the manipulator be defined by the joint variable vector $\mathbf{q}_h \in \Re^{n_{q_h}}$, with n_{q_h} representing the number of actuated joints. We then assume that the subspace of all configurations can be represented by an input vector of a lower dimension $\mathbf{z} \in \Re^{n_z}$ (with n_z denoting the number of inputs and $n_z \leq n_{q_h}$), which parameterises the motion of the joint variables along the *synergies*. In terms of velocities, one gets:

$$\dot{\mathbf{q}}_h = \mathbf{S}_h \dot{\mathbf{z}}, \tag{1}$$

with $\mathbf{S}_h \in \Re^{n_{q_h} \times n_z}$ being the synergy matrix.

C. Low-cost sensing and joint compliance

The low-cost sensing feature from the previous version of *ModGrasp* is adopted in this work. However, in this version of the framework, each module implements its own sensing capability. The current is continuously measured in order to monitor the load. This feedback signal is fundamental in improving manipulator dexterity. A more accurate grasping of objects of varying stiffness is possible without squeezing or damaging them, thanks to current sensing at the joint level. By measuring the input current to each servo motor, the servo torque can be calculated and a back-actuation action can be taken according to the current needs. Moreover, sensitive collision detection, compliant control actions and other crucial functions are possible.

D. Multi-threading and multi-level hierarchical system

In the architecture that was previously presented with *ModGrasp*, each slave was running a monolithic control approach with only one thread taking care of all the logical functions for one entire finger. According to our new architectural design, each module is controlled by a corresponding slave controller that runs a multi-threading and multi-level control program, as shown in Fig. 3.

Multi-level hierarchy: three different levels are defined for the control pattern of each module:

- the *Low-Level methods* layer includes the low-level functions that are used to actuate the motor (*actuateMotor*), to sense the motor load (*getLoad*), and to communicate with the master (*sendData* and *receiveData*);
- the *Concurrent Threads* level is the layer where the concurrent processes are implemented. This level can access both the *Low-Level methods* as well as the *High-Level methods*;
- the *High-Level methods* layer includes the high-level and distributed control function, *calculateActuation*, which determines the joint actuation according to the adopted control method.

Multi-threading: to improve the performance of the proposed architecture, a multi-threading pattern is adopted. Essentially, two concurrent processes are considered:

- the *Actuator Thread* takes care of the motor actuation by calling the underlying *actuateMotor* method;
- the *Back-Actuator Thread* is responsible for the joint back-actuation when the servo load reaches a predefined threshold. The motor is programmed to step back slightly (according to a predefined step-back value) in order to reduce the torque.

From an implementation point of view, the *mthread* library [11], which is an Arduino-compatible multi-threading library, is chosen.

IV. A Mind-Controlled Modular Hand

The second contribution of this work, which concerns the possibility of controlling the modular manipulators by using an EEG headset is introduced first in this section. Based on this new feature of *ModGrasp*, a mind-controlled, low-cost modular manipulator is successively presented as a case study.

A. EEG control input

In the old control framework of *ModGrasp*, the modular manipulators could either be controlled directly from the simulator environment by means of a computer mouse/joystick or they could work stand-alone and be controlled by means of a set of potentiometer shafts that were used as input controllers. The new feature that is provided in this new architectural design consists of using an EEG headset as input device. In particular, the *NeuroSky MindWave* headset [3] is adopted. This EEG headset is wirelessly connected to the master board by using the Bluetooth protocol and is used to generate the input signal allowing the manipulator to be used with or without running the simulation environment. The choice of using an EEG headset is motivated by the wish of the authors for providing a more intuitive control interface to

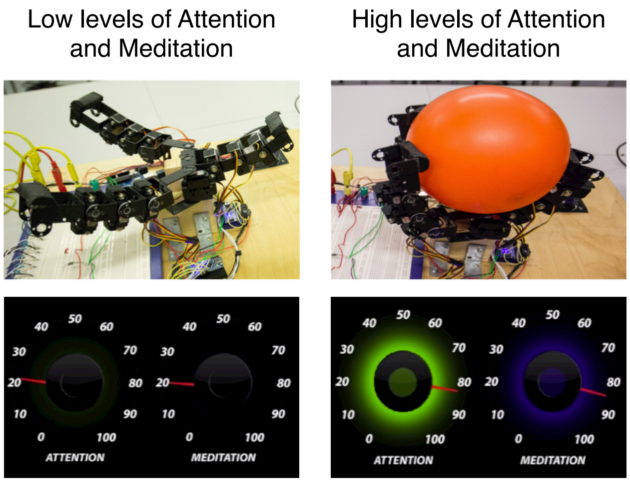


Fig. 4: The control objective idea: by monitoring the user's *Alpha Waves* and *Beta Waves*, successful grasping operations can be performed.

the developed prototypes. This choice opens up to a variety of possible applications including the development of modular prototypes for mind-controlled prosthetic hands.

The human brain is made up of billions of interconnected neurons. As neurons interact, patterns manifest as singular thoughts such as a math calculation, and broad emotional states such as attention. Every interaction between neurons creates a miniscule electrical discharge, measurable by EEG machines. By themselves, these charges are impossible to measure from outside the skull. However, a dominant mental state, driven by collective neuron activity created by hundreds of thousands concurrent discharges, can be measured. Different brain states are the result of different patterns of neural interaction. These patterns lead to waves characterised by different amplitudes and frequencies. As examples, brainwaves between 12 and 30 hertz, *Beta Waves*, are associated with concentration, while waves between 8 and 12 hertz, *Alpha Waves*, are associated with calm relaxation.

In the proposed architecture, the user's *Alpha Waves* and *Beta Waves* are monitored by using an EEG headset and used to generate the input signal. The control objective is that when the user start focusing, for instance by starting reading or doing some simple math calculation, the levels of attention and meditation increase causing the controlled manipulator to close the fingers so that grasping operations can be achieved. Once the user loses focus, the controlled hand will open up the fingers again and release the grasped object. The control objective idea is shown in Fig. 4.

B. Manipulator Model

The same three-fingered modular hand that was considered in [2] is adopted in this case study to be controlled with an EEG headset. In Fig. 5, the hand model is shown. It consists of a 3 DOF thumb, which opposes the other two fingers, each

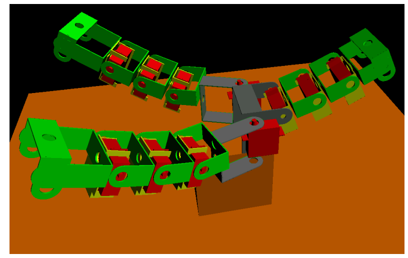


Fig. 5: The three-fingered modular manipulator model.

having 4 DOFs. The fingers are directly attached to a wooden plate that is used as a base. This particular configuration was chosen for simplicity and as a heuristic design in order to accurately describe the most significant grasping models that mimic human hand taxonomy, as outlined in [12]. Since the hand features 11 DOFs, a *synergistic* control approach is chosen to simplify the control algorithm. The *synergy* matrix, determined by following the mapping approach proposed in [13], is:

$$\mathbf{S}_h = \begin{bmatrix} -0.7 & 0 \\ -0.2 & 0 \\ -0.1 & 0 \\ 0 & -1.6 \\ -0.7 & 0 \\ -0.2 & 0 \\ -0.1 & 0 \\ 0 & 1.6 \\ -0.7 & 0 \\ -0.2 & 0 \\ -0.1 & 0 \end{bmatrix} \begin{array}{l} \left.\vphantom{\begin{matrix} a \\ a \\ a \end{matrix}}\right\} Thumb \\ \left.\vphantom{\begin{matrix} a \\ a \\ a \\ a \end{matrix}}\right\} Finger1 \\ \left.\vphantom{\begin{matrix} a \\ a \\ a \\ a \end{matrix}}\right\} Finger2 \end{array} \qquad (2)$$

In this particular case, an input vector, $\mathbf{z} \in \Re^2$, is used to select the first two principal *synergy* components. This input vector contains the two mapped signals coming from the EEG headset monitoring the levels of attention and meditation.

V. Simulations and Experimental Results

Related simulations are carried out in order to test the framework architecture within the particular case study of the three-fingered modular manipulator. Particularly, a balloon is selected for use in performing a grasp and release experiment, as shown in Fig. 6. This experiment aims to perform a grasp that a human would consider "stable". To achieve such a kind of task, extensive training is required for the user in order to efficiently control the appropriate attention and meditation levels. The time plots of the EEG inputs and of the corresponding estimated torque values for the joints while grasping and releasing the balloon are shown in Fig. 7-a and in Fig. 7-b, respectively. Note that a low-pass filter is applied to reduce the noise from the collected data. As expected, the

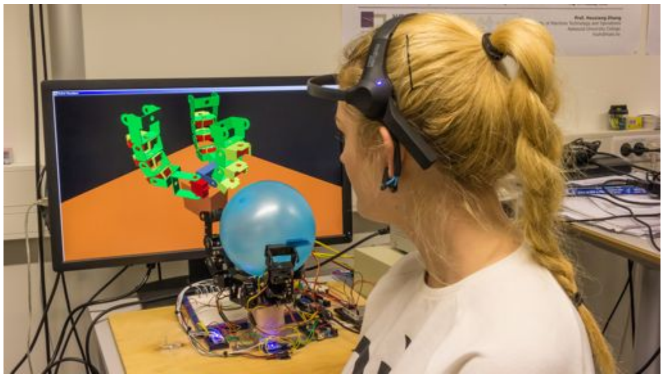


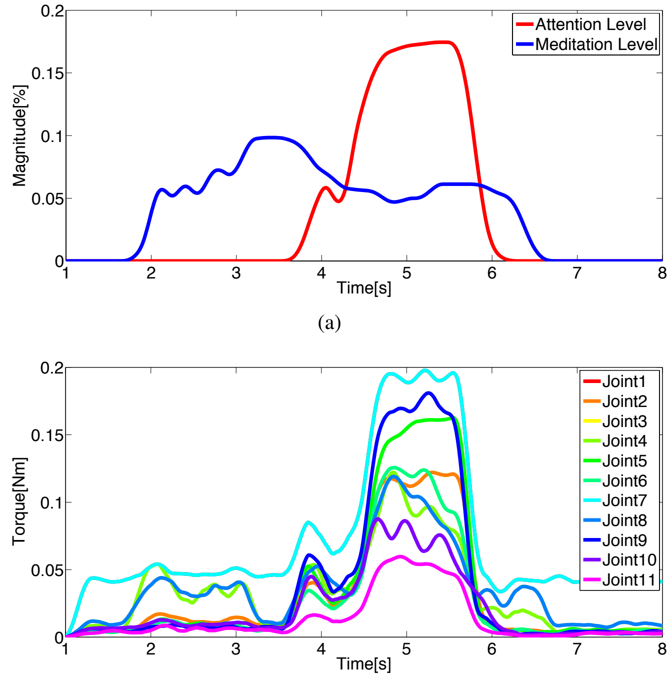
Fig. 6: A balloon is selected for use in performing a grasp and release experiment.

torque values increase when the contact is made with the object to be grasped. In addition, symmetric patterns in the torque values can be seen between symmetric joints while executing the grasp. It should be noted that grasping a balloon is a particularly challenging task for a robotic hand. With this experiment, our framework demonstrates effectiveness in designing hands that are capable of performing such a kind of task with sufficient dexterity.

VI. Conclusions and Future Work

In this paper, several improvements to the *ModGrasp* communication pattern have been presented. In particular, each module is now independent, being controlled by a self-reliant slave controller board. In addition a newly redesigned multi-threading and multi-level control pattern with a hierarchical logical organisation is used. A case study has been outlined to show the potential of the new framework: a mind-controlled, three-fingered modular manipulator.

This work highlights the potential of the modular grasping approach. However, the simulation environment is still in the early stages of development and currently, only free-hand motions are possible. In the future, integration with a physics engine would allow for the simulation of controllable forces, object displacements, manipulability analysis and the addition of other grasp quality measures.



(a)

(b)

Fig. 7: (a) the time plot for the EEG inputs showing the attention and the meditation levels, (b) the corresponding estimated torque values for the joints while grasping and releasing the balloon.

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