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Designing Functional Prototypes Combining BCI and AR for Home Automation

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Abstract. In this technology report we present how to design functional prototypes of smart home systems, based on Augmented Reality (AR) and Brain-Computer Interfaces (BCI). A prototype was designed and integrated into a home automation platform, aiming to illustrate the potential of combining EEG-based interaction with Augmented Reality interfaces for operating home appliances. Our proposed solution enables users to interact with different types of appliances from "on-off"-based objects like lamps, to multiple command objects like televisions. This technology report presents the different steps of the design and implementation of the system, and proposes general guidelines regarding the future development of such solutions. These guidelines start with the description of the functional and technical specifications that should be met, before the introduction of a generic and modular software architecture that can be maintained and adapted for different types of BCI, AR displays and connected objects. Overall this technology report paves the way to the development of a new generation of smart home systems, exploiting brain activity and Augmented Reality for direct interaction with multiple home appliances.

Keywords: Brain-Computer Interface (BCI) · Augmented Reality (AR) · Home Automation · Smart Home · Steady-State Visual Evoked Potentials (SSVEP).

1 Introduction

The developments in the fields of the Internet of Things and smart homes [8] are pushing towards the design of new interaction mechanisms in order to seamlessly operate the multitude of available connected objects. These new interaction mechanisms largely rely on Natural User Interfaces (NUI) involving speech or gesture recognition [10] to enable users to operate the appliances with reduced

efforts. Following this trend, a promising way to interact with smart homes and connected objects would be based on Brain-Computer Interfaces (BCIs).

BCIs enable users to interact with computer systems by the sole mean of their brain activity [40, 35]. Historically, the first prototypes [38] of BCIs were mainly designed as means to assist people with disabilities, by providing them with systems exploiting brain activity instead of potentially damaged, traditional muscle outputs [41]. Although this purpose still represents one of the main objectives of the BCI community, a new trend can be observed in recent literature, with a number of works targeting the design and development of BCIs that can be used as interaction media for the general public, with applications in Human-Computer Interaction (HCI), entertainment [18, 23], or robotics.

Unfortunately, it is currently difficult to argue that Brain-Computer Interfaces are ready for large scale exploitation. Current BCIs suffer from severe limitations in terms of reliability [24], speed and user friendliness [17]. These limitations prevent BCIs from being competitive options with regards to available alternatives for healthy users. Consequently, careful design and realistic specifications are necessary in order to integrate them in any high-end interactive system. As a first step, and in order to pave the way for future systems using BCIs to interact with smart homes, this technology report introduces a prototype combining a BCI and an Augmented Reality (AR) system, in order to integrate them in a home automation system.

In general, BCI and AR are two technologies that can largely benefit each other [34, 14] either through providing user interfaces that are integrated in the environment, or by enabling hands-free interaction. The case of smart-homes is particularly conducive for the development of these technologies, as the increasing number and the heterogeneity of the connected objects and appliances offer a wide variety of use cases adapted to the diversity of BCI systems. Combining AR and BCI for home automation also holds the promise of a higher degree of adaptation to the users mental states, as well as the possibility, on the longer term, to seamlessly interact with their homes.

One of the earliest systems using a BCI to interact with house appliances was proposed by [13]. Their prototype enabled to change TV channels and to turn appliances ON or OFF using the users' brain activity. These appliances were controlled using binary hierarchical menus, in which users navigated by modulating levels of alpha rhythm [3].

In 2009, Edlinger et al. developed a P300¹ [29] prototype to control home appliances [6]. Their prototype relied on a virtual representation of a house, displayed in a CAVE [5] system. Their interface relied on displaying grids of icons representing commands associated to the manipulated objects. The icons were randomly highlighted following the oddball paradigm for P300. Similarly, [1] proposed a P300-speller based system to operate different appliances. Their interface consisted in grids of icons representing the achievable actions, displayed on a computer screen. More recently, Sahal et al. [33] used a custom P300 se-

¹P300 is an Event Related Potential (ERP) usually measured through EEG and that is elicited when a rare and/or attended stimulus is displayed.

lection matrix displayed in AR to enable users to control their environment, specifically aiming at assisting patients with Amyotrophic Lateral Schlerosis.

Following a different approach, [22] used passive BCIs in order to automatically adjust the house environment (night lamps and air conditioner) based on the users cognitive states (drowsiness and alertness), associated with α (8-13 Hz) and θ (4-7 Hz) rhythms.

Using an AR Head-Mounted Display, [12] proposed a system enabling users to operate a distant robot, navigating in a house environment, using brain activity. The robot was equipped with a camera displaying a video feed of its environment where appliances were tagged with fiducial markers. When an object entered the robot's field of view, a control panel that the users could interact with using P300 was displayed. Later on, [37] developed a P300-based AR-BCI system to control multiple house appliances based on the same system described earlier, but through a monocular Optical See-Through AR display instead of the robot.

Using a BCI to control home appliances has also been explored through several prototypes and reviews [19, 16, 15]. Overall, the scope of these previous work differed on the component they put emphasis on. Some of them focused on the EEG analysis while others highlighted the assistance benefits for people with disabilities [43]. For example, [30] proposed a prototype integrating a Steady-State Visual Evoked Potentials (SSVEP) based BCI, an eye-tracker and an Augmented Reality display to operate a smart home environment. They presented users with flickering AR icons depending on where the users gaze, and enabled the control of different appliances. The developed prototype mainly relied on two components: (1) the Head-Mounted Display (HMD) handling the graphical interfaces and the feedback, and (2) a server responsible for the classification of the EEG and gaze data into issued commands. Later, this study was followed by a usability assessment [39]. A similar prototype was designed by Park et al. [27], using an AR-based SSVEP interface for controlling home appliances.

Most of the so-far developed prototypes were realized for lab-controlled experimentation and never exceeded the state of feasibility studies. Up to now, no developed system was able to cross the borders of the laboratories. Hence the questions: What are the requirements and specifications that an AR-BCI home automation system should meet before we can foresee a broadly available system? How to develop such a system to make it operational and useful to the end-users?

To these days, the best performing type of BCIs in terms of ITR (Information Transfer Rate) and reliability [4] are the reactive BCIs (e.g. Steady State Visual Evoked Potentials [44], P300 [28]) which require the users to focus on specific stimulation in order to send commands. Thanks to Augmented Reality, it becomes possible to integrate these sensory (mostly visual) simulations directly into the user's environment, instead of their traditional display on a computer screen.

In this paper, our goal is to introduce a prototype of combining an SSVEP-based BCI with Augmented Reality in order to interact in a smart home environment. We also propose general guidelines towards the development of AR-BCI

smart-home systems, in a way that they would be operational and possible to upgrade with future technological and scientific improvements. The guidelines presented hereafter, are introduced following a top-down approach. We start by discussing the general, functional and technical specifications: What are the technical requirement and the features the system should provide? Then we present a generic system architecture, describing its different components and their interaction and finally, we illustrate the implementation of the prototype by describing a specific operational system that was developed with *Orange SA*, in an industrial context.

The contributions of this technology report are the following:

- Generic guidelines for the development of smart homes based on BCIs and AR.
- An operational smart home system integrated to a smart home platform.

The remainder of this paper is structured as follows: Section 2 discusses the system requirements and specifications of the prototype, introducing in the meantime higher level guidelines regarding the features of such a system. Section 3 describes the implemented prototype in terms of software and hardware architecture while Section 4 discusses the potential impact and presents use cases and future work, while Section 5 concludes the paper.

2 System Specifications and Guidelines

A smart home is ”a dwelling incorporating a communication network that connects the key electrical appliances and services, and allows them to be remotely controlled, monitored or accessed” [20].

When it comes to the specifications of a system combining AR and BCI for home automation, six (6) requirements or features were identified as prominent. These specifications were related to both of the BCI and the AR component of the system and are namely: *operability, asynchronicity, modularity, generalisability, contextuality* and *hardware-independence*. These feature are hereafter described in terms of functional and technical requirement of the design system.

2.1 Operability

The first requirement of the system, is that it should offer the main features of a smart home and enable the operation of multiple devices. The underlying requirement is that the system has to enable the user to select which object s/he wishes to interact with. In addition to the selection mechanism, the system has to allow the user to send the desired command. It is possible to identify two categories of objects: (1) Binary state objects, that can only be switched *ON* or *OFF* (e.g. a lamp, a smart plug, etc.), and (2) Multiple commands/states objects, which can receive more that one command or have more than two states (e.g a television).

In order to meet this specification, a selection and operation strategy has to be provided for both types of objects. For example, *binary state* objects can be automatically switched between possible states upon selection while *multiple command objects* can toggle the display of a hierarchical menu leading to the possible commands.

The operation system should also take into account the possibility to include objects that may require continuous commands instead of discrete ones, even though this type of input is harder to achieve through BCIs.

2.2 Asynchronicity

Interactive systems depend on unpredictable inputs provided by the users [7]. This unpredictability originates both from the fact that users can issue different commands, and that these commands can be issued at any time. Hence, it is important for an AR-BCI based home-automation system to be asynchronous (also referred to as self-paced) in order to enable users to operate the system at their own pace. In other words, this specification means that the system should be able to detect idle or rest states, where users do not intend to operate the system, thus, avoiding as much false positives as possible.

In terms of BCIs, the difficulty raised by this specification originates from the difficulty to detect rest states from the users' brain activity due to the constant background noise from unrelated activity. While several algorithms and signal processing methods have been proposed to detect these states, in several BCI paradigms, it remains generally more difficult to design asynchronous BCIs.

2.3 Generalisability

In most of the cases, BCIs are conceived as a mean to rehabilitate or assist people with disabilities [40]. The first reason for this has to do with the nature of the interaction using a BCI which does not rely on muscle activity. Another reason, is the fact that BCIs are usually cumbersome and tedious to apprehend [11], further associated with lower performance than other User Interfaces (UIs). Given this statement, and the fact that some BCI paradigms are easier to apprehend and operate than others (P300 being easier than Motor Imagery for example), it is important that the system addresses a large group of users, and is not solely dedicated to people with disabilities. In terms of BCI design, this specification implies that the designed system should require as little training as possible, and ideally that it can be operated by naive users. In addition to the choice of BCI paradigm, this may also require the design of robust signal processing and classification methods that are resilient to inter-subject variability.

2.4 Contextuality

One of the main advantages of AR systems is their ability to provide and use information regarding the user context thanks to tracking mechanisms [2]. This

information allows to provide users with the relevant inputs and feedback, depending on their current location in the environment as well as their orientation (gaze direction). In the particular case of smart home systems where the number of interactable objects is typically large, information regarding the user’s context allows to limit the presented inputs to the ones related to the objects which are most likely to be interacted with (at close distance, in the field of view, etc.). Moreover, as the performance of most visual-based BCIs are impacted by the amount of information provided at once, it is important that the system takes the user’s context into account, both to maximize the system accuracy and reduce the potential confusion arising from too many inputs to process. In shorter terms, the system should adapt its AR interface and only display commands related to the objects in the field of view of the user, or the ones that are close enough to him/her.

2.5 Hardware independence

The combination of multiple technologies (AR, BCI and IoT) brings several layers of complexity to the designed system. On the hardware level, multiple choices can be made in terms of hardware components for the AR interface (Head-Mounted Displays, Tablet screens, Optical See-Through Displays, etc.), for the BCI (different EEG headsets are possible) and for the connected objects (several appliances and manufacturers). In order to deal with all these possibilities, it is important for the system to be hardware-independent, i.e abstract its features from hardware considerations. It should, for example, easily integrate new connected objects added to the environment, switch the display of the AR interface from one display to another or work with different EEG electrode configurations. In practice, this can be achieved by adding an abstraction layer to the system to handle the communication between the system’s components.

2.6 Modularity

Given the heterogeneity of home appliances and the different natures of their commands, as well as the rapid developments in the fields of AR and BCIs, it is important for the system to be highly modular. It is for example difficult to conceive a single BCI paradigm that would fit all the use cases met in home-automation scenarios. Moreover, given the current state of the art of BCIs, it is important that the system also enables the easy integration with other input modalities in addition or in replacement of BCIs (e.g. speech and gesture). For these reasons, it is important that the system architecture is composed of independent components that are able to be upgraded or replaced without impairing the overall function of the system.

3 Generic Architecture

In order to meet the previously described specifications, we propose a generic architecture based on four (4) main components: (1) The BCI, (2) the AR sys-

tem, (3) the Home-Automation platform, and (4) the Middleware. The main advantage of this architecture is to maintain a high level of independence between the components as the middleware handles all the communication pathways in the system (see Figure 1). As such, changing the BCI paradigm or headset, the AR display or the home-automation platform should not impact the proper functioning of the system. Our proposed architecture is similar to but extends the one which was successfully used in [27], and which uncouples the BCI from the rest of the system and using a middleware for communication.

3.1 The BCI

One of the specificities of this proposed architecture is not to consider the overall system as a BCI, but rather to include the BCI as one of its components. In fact, the role of the BCI is to measure and translate the brain activity of the users and to transmit the corresponding mental state to the interactive system, through the middleware. The internal structure of this component is based on the traditional BCI processing pipeline introduced by [25]. All the signal processing and classification aspects should be handled by this component, and the result of this analysis is transmitted to the middleware.

In an operational mode, this component should be able to detect changes in the user’s mental state, and send the corresponding information to the middleware in real-time, meeting the *asynchronicity* requirement.

Encapsulating the BCI in a separate block enables to easily update the specific processing pipeline by using with new signal processing methods, changing the BCI-related hardware or the classification methods, without inducing changes in the rest of the components. As long as the detected mental state is transmitted to the middleware, the whole system should be able to operate.

However, some parts of the component, notably the choice of the BCI paradigm cannot be completely uncorrelated from the *AR system* for example.

In particular, reactive paradigms rely, by definition, on the nature and strategy of the stimuli provided by the system which is handled by the AR system display.

3.2 The AR system

The role of this component is twofold. First, it provides the users with information and feedback about the state of the system, as well as the possible commands to send depending on their context (location, objects in field of view, etc.). When developing a system combining BCI and AR, a particular care should be given to the display strategy so that the system is intuitive and easy to apprehend [36]. Second, in addition to the feedback and information, this component is also responsible of providing the visual stimulation (at least in the case of reactive visual BCI paradigms) for modulating the mental state.

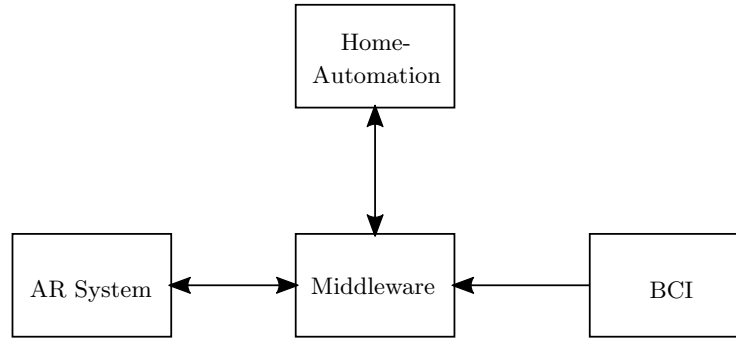


Fig. 1. Illustration of the components of a generic architecture of a home automation system using BCI and AR. The communication between the elements is done solely through the Middleware.

Decoupling this component from the rest of the system allows the designer to change/upgrade the hardware, i.e. the AR display and the AR interface without altering the functioning of the other components.

3.3 The Home-Automation platform

This component is the interface between the system and the connected appliances. Its role is to translate the commands obtained from the interpretation of the user mental state determined by the BCI and the context given by the AR system. The nature of this component depends on the specifications and features of the smart objects present in the house, i.e their network protocol, their API¹ and should eventually allow the interaction with heterogeneous objects. If the available smart objects do not share the same protocols, it should be the role of the Home-Automation platform to adapt the commands accordingly.

3.4 The Middleware

All the components described above have the specificity of being independent from each other. In order to be able to interact, the system architecture has to provide a communication component. Essentially, the role of the middleware is to determine, from the context of the users and their mental state, the corresponding command to carry to the home automation platform.

The general interaction scenario is described as follows: At all time, the AR system provides the user context to the middleware (the location and the appliances detected in the field of view), based on which, the middleware responds with the available commands to provide and display to the user.

¹Application Programming Interface

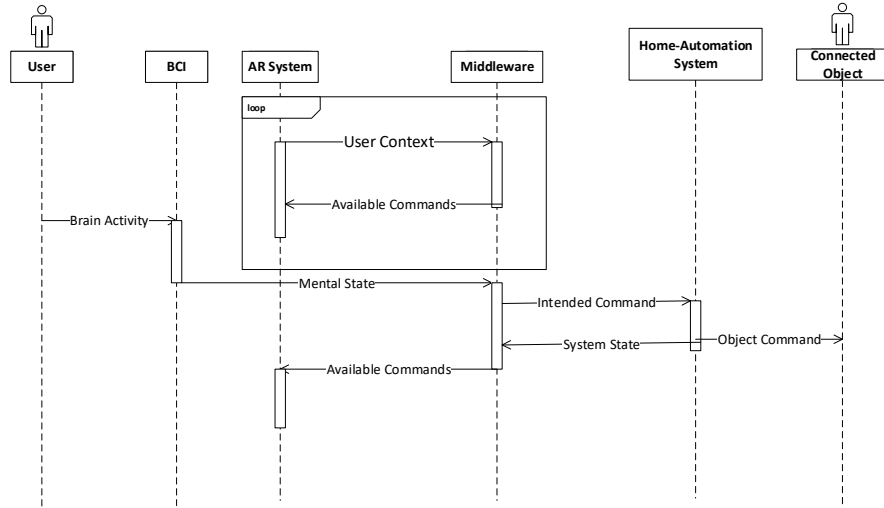


Fig. 2. Sequence diagram [9] of the system, representing the interactions and the communications between the different system components.

Whenever the BCI detects a significant mental state (corresponding to a valid command), it sends the corresponding label to the middleware which, based on the user context, transmits the corresponding command to the home automation platform. As stated before, the home automation platform operated the connected object accordingly, and sends the updated system state to the middleware which in turn, requests the AR system to update the displayed information. This interaction sequence is summarized in Figure 2.

In this type of interaction sequence, it is the middleware that embeds the "intelligence" of the system as it is responsible for aggregating the information originating from the other components, in order to determine the appropriate command. It can also be assimilated to a finite-state automaton as described in Figure 3.

The initial state of the automaton corresponds to the *Wait State* where the middleware is expecting a system event to proceed. Each time a new object is added to the system, the middleware moves to the state *S1*, which corresponds to the update state, in which the middleware updates the available objects and commands and sends them to the AR system, and gets back to the *Wait State*.

Whenever, a mental state is provided by the BCI component, the middleware moves to *S2* which corresponds to the BCI-handling state. In the case of SSVEP for example, the received message is under the form of a detected occipital frequency. If this frequency is not matched to any valid command, the middleware ignores the message and gets back to the *Wait State*. If the received frequency matches a command, the middleware moves to the *S3* state, which corresponds

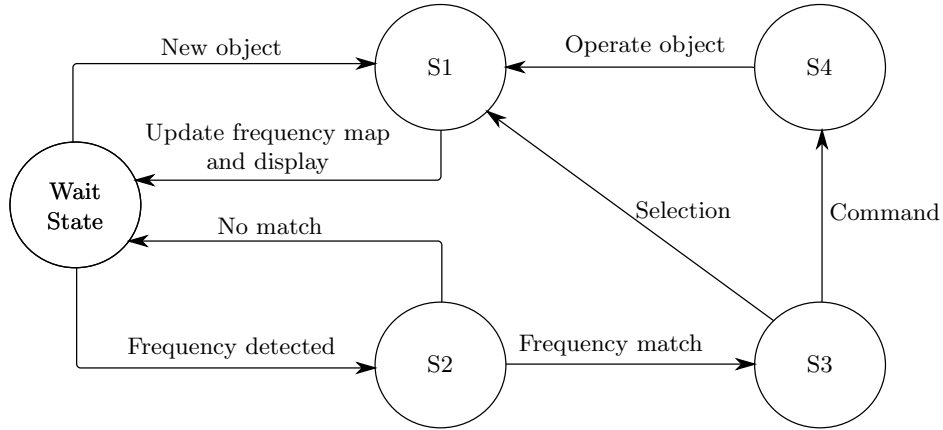


Fig. 3. General Automaton representing the states of the middleware. The default state of the middleware is the *wait state*. All the possible events during the interaction trigger the changing of state, the execution of the corresponding action, then the return to the wait state. S1: Update state, S2: BCI-handling state, S3: Decoding state, S4: Operation state

to the decoding state, in which it determines the type of the received command. If it corresponds to an object selection, the middleware switches to the *S1* state, to update the available commands and the system state. If the command corresponds to an object operation, the middleware switches to the *S4* state in which the middleware transmits the command to the home automation platform, and switches to the *S1* state, where it updates the available commands.

4 Implemented Prototype

As a demonstration of the previously described concepts, specifications and architecture, we designed a prototype of a functional AR and BCI-based Home Automation system (see Figure 4). This prototype was built in the scope of an industrial partnership project, with Orange SA, one of the main Internet Service Provider in France. The aim was to build an operational AR-BCI based home-automation system that would be integrated to their home-automation platform *Home'in*.

In this Section, we describe the conceptual and technical choices that were made in order to meet the requirements mentioned in Section 2.

In the scope of the project, the specific objectives of the project were as follows:

1. **The system had to enable the control of at least 3 types of objects:**
The first requirement was that the developed prototype would enable the online operation of at least 3 objects present in a given environment: a fan



Fig. 4. Illustration of the final prototype. The user can interact online with the three objects in front of him.

(connected to a smart plug), a connected light and a Television. This objective was inline with the *Operability* specification.

2. The system had to integrate with an existing home automation system:

As a collaborative project, the objective was to integrate the global system with the home automation platform provided by Orange. In other words, the outputs of the BCI system had to be issued to the connected objects using the *Home'In* protocol.

3. Commands should require at most 2s to be issued:

The requirement in terms of performance, was that the system had to be able to issue commands in around 2s. This requirement was particularly prominent for the choice of the BCI paradigm, as well as the employed signal processing methods.

4. The system has to be validated online:

Finally, in order to showcase the functionality of the system, and to validate the results, the demonstration had to be performed online.

In the following parts, we describe the implementation of each component of the generic architecture, with regards to the previously introduced requirements, and how our proposed methodology was particularly suited for the design of this prototype.

4.1 The BCI

Considering the number of interactable objects and the possible number of commands offered by the system, and also for its low requirement in terms of user training and its relative reliability, we have opted for the *Steady State Visual Evoked Potentials* (SSVEP) paradigm.



Fig. 5. Illustration of the apparatus used in the developed prototype. (Left) A Microsoft HoloLens AR headset and (Right) an mbt Smarting EEG headset.

In practice, the possible commands that the user could issue at a given moment were represented by targets flickering at different frequencies. Thus, the goal of the BCI component was to determine online, the flickering stimulation frequency that the user was attending and transmit this information to the middleware.

The different possible flickering stimulations and their corresponding commands were stored in a configuration file, namely the *frequency map* and managed by the Middleware. This way, it was easy to upgrade the system by adding more frequencies to the frequency map, or by reutilizing frequencies for different commands. For example, a target flickering at 10Hz could designate a specific command when the user was in a particular room, while this same frequency could designate another command in a different room or context, simply by updating the command associated with the given frequency in the frequency map.

Electroencephalographic (EEG) signals were recorded using a SMARTING amplifier (mBrainTrain, Serbia) with a sampling frequency of 500 Hz and using 5 scalp electrodes: O1, O2, POz, Pz and CPz referenced to Cz and grounded to AFz (see Figure 5).

Before being able to use the system online, multi-class (Common Spatial Pattern) and LDA (Linear Discriminant Analysis) classifiers were calibrated to recognize 5 classes: 4 stimulation frequencies (10Hz, 12Hz, 15Hz and 17Hz) and the idle state, meeting the system’s requirement of asynchronicity.

The signal acquired online was sliced into 4s long epochs every 2s, meaning that a decision from the classifier was issued every 2s. The power of the signal at the neighbourhood ($\pm 0.25Hz$) of each stimulation frequency was estimated and combined to form a feature vector. The trained CSPs were applied to spatially filter the data and LDA was used for classification. All implementation was done using OpenViBE [31].

4.2 The AR System

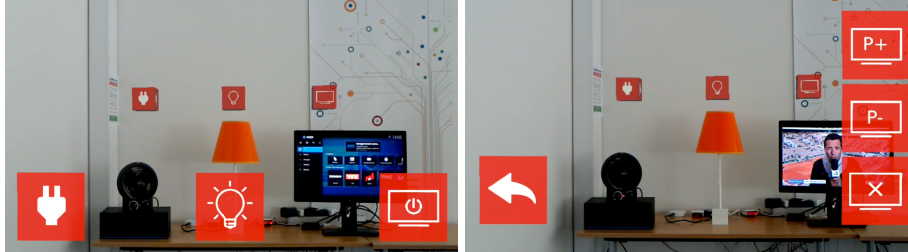


Fig. 6. Illustration of the implemented AR interface. The default view of the system (Left) represents the different objects in the field of view, with associated flickering icons. The fan and the light could be switched ON or OFF with a single command. The interaction with television was conducted through a hierarchical menu. After selecting the TV, the possible commands to issue appeared on the interface (Right).

Given the employed BCI paradigm (SSVEP), the first objective of this component was to provide the AR interface displaying the flickering SSVEP targets, and to provide the user information about the system state. Its second objective was to provide the contextual information about the objects detected in the user’s field of view.

Targets were represented in the form of squared-shape overlays displaying icons representing the associated command. The icon could either represent the state the represented object, in the case of on-off objects, or the commands to navigate into the hierarchical menus for multiple command objects.

Regarding the user’s context, in the scope of this prototype, the spatial positions of the interactable objects were hard-coded in the AR application, meaning that every time one of these positions entered the *fov* (field of view) of the user, the command associated with the object at this position was displayed. Another alternative would have been the use of fiducial markers in order to detect the objects in the *fov* of the user, regardless of their positions.

The AR interface was displayed on a Microsoft Hololens (see Figure 5) using a *frontal ego-centered user-anchored* display strategy [36] implemented using Unity (see Figure 6).

4.3 The Home Automation Platform

The commands carried out from the middleware were transmitted to the *Home’In* smart home platform¹.

The commands were generated by the *Middleware* and carried to the home-automation platform through TCP using the *MQTT* protocol [21]. The selected

¹A Home-Automation platform from Orange SA.

objects for the prototype were: a Phillips Hue connected lamp and a connected plug on which a fan was plugged, to illustrate the interaction with binary state objects. And a smart television was used to illustrate the interaction with multi-commands objects.

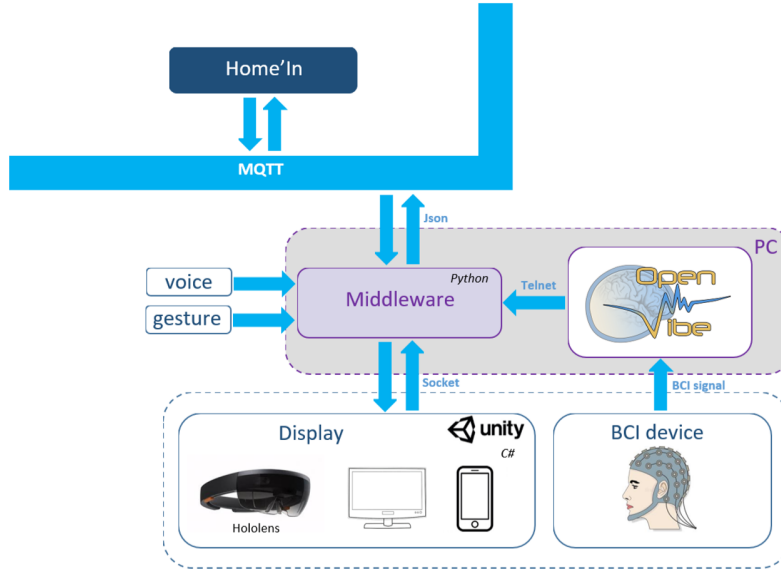


Fig. 7. Illustration of the final prototype architecture. The components are the same as proposed in the generic architecture, and all communications were done through the middleware.

4.4 The Middleware

The middleware was developed as a finite-state automaton using Python. It consisted in several listeners awaiting messages from the BCI component and the AR system, and relaying the appropriate messages to the components.

The implemented architecture of the developed system is summarized in Figure 7.

All binary states objects were considered as switches. A single SSVEP selection switches between their 2 states. In the case of multiple commands objects, the interaction was done through a hierarchical menu. First selecting the object, then selecting the available commands (spec N2.1).

Depending on the number of available commands at a certain time, and the context provided by the AR display, the middleware associates a flickering frequency to each object's icon and informs the AR system to display the flickering

targets. When the BCI notifies the Middleware that a SSVEP command has been recognized, the Middleware notifies the AR system to update the display with the new objects states and change presented icons. The middleware also determines to what object and/or command, the SSVEP stimulation is associated and notifies the smart home platform.

The middleware allows to meet the specifications 2.5, 2.6. Regardless of the EEG system, as long as the BCI provides a detected frequency, the middleware can perform the required action and update the display regardless of its hardware type. In addition, as its role is to receive, interpret then retransmit commands, the middleware can also potentially enable to interact using other modalities (hand gestures, voice etc.) as long as they are simply used to determine the user's intent.

All in all, the BCI system was developed using OpenViBE. The middleware was developed in Python, and the AR system was developed using Unity. All the communications between the BCI, the AR system and the middleware were achieved using TCP (Transfer Communication Protocol) sockets.

5 Discussion

The contributions presented in this technology report are two-fold. First, we provided generic guidelines regarding the development of prototypes combining AR and BCI for home automation purposes. Following these guidelines in terms of functional and technical specifications namely *operability*, *asynchronicity*, *modularity*, *hardware independence*, *contextuality* and *generalisability* we proposed a new and reusable architecture decoupling each component of the system, and relying on a highly configurable middleware to operate the system.

Secondly, we illustrated how these guidelines can be implemented into a functional prototype integrated in a home-automation platform. This prototype, designed and implemented in collaboration with an industrial partner, is part of the global trend which aims at bringing BCIs out of laboratories.

Although the guidelines provided in this technology report are specifically targeting the specifications related to AR and BCI integration in the context of home automation, the field of smart home by itself also represents a challenge in many regards. Selecting the right communication protocol (Zigbee [32] or Zwave [42] to name a few) or the appropriate architecture in terms of software and hardware [26] requires a thorough analysis of the considered application.

In terms of AR and BCI, despite undeniable progress in these technologies, our prototype suffers from several limitations:

- **Performance:** The main limitation of our prototype, similar to many systems involving BCIs, lies in its poor performance when compared to existing alternatives for automation (handheld devices, voice commands) particularly for healthy users. Even though no formal study was conducted to evaluate the objective performance of our prototype, the informal testings showed a high variability in the subjects' performance, and generally remained below the accuracy of more traditional input systems.

- **Cumbersomeness:** Combining a BCI and a AR system, independently from the application, requires the association of cumbersome and bulky headsets which severely limits the use of these technologies over long period of times. A potential improvement may lie in the development all-in-one headsets, integrating easy-to-install EEG electrodes directly into the AR headsets.
- **Environment configuration:** One of the limitations regarding the AR configuration of our prototype was that the positions of the connected devices were hard set in the system. Meaning that moving the appliances from their positions would result in the system not being able to detect them. A workaround solution would be to add fiducial markers to the appliances so that the AR system can detect them regardless of the position. Unfortunately, this solution still presents the drawback of not enabling the users to remotely operate an appliance that is not in his field of view.
- **Field of view:** Another limitation of the AR system was regarding the width of augmented field of view, i.e. the area of the field of view where virtual content can be displayed. Given the employed AR headset (Hololens), the augmented area of the *fov* represented a rectangle of 34deg of visual angle. The size of this augmented *fov* plays a particularly important role with visual evoked potentials, as it may limit the number of displayable visual stimulations at once.

Moreover, associating a BCI with an AR system implies several technical challenges and difficulties to be dealt with. It is for example necessary to ensure the proposer setup of the headsets to prevent noise on the recorded signal, as well as to limit head movements to avoid muscle artefacts. It is also important to reduce the load on the AR core system in order to limit latency and jitter in displaying the stimulation (e.g. ensuring a stable flickering to elicit proper SSVEP responses), and to maximise the synchronization between the components (e.g. to accurately date the events in the case of event-related potentials).

Despite all these limitation, the strength of our approach lies in its high scalability that we believe can take benefit from any advancement in the BCI, the AR or the home-automation components of the overall system. The modularity of the proposed architecture can, for example, easily include any future improvement in the signal processing methods to improve the overall performance or the system. It could also easily benefit from the development of new hardware that can be easily replaced, to improve the user-friendliness of the system.

6 Conclusion

The aim of this technology report was to introduce a new architecture and methodology in building smart home systems based on BCIs and AR. It provided generic guidelines regarding the specifications and requirements that such systems should meet as well as a modular architecture enabling to meet these requirements. It also reported the result of a technological development aiming

at integrating such an AR-BCI system in a home-automation platform that was showcased online. Despite the current limits of the system, the proposed prototype paves the way to the upcoming development and democratization of AR and BCI for non-medical, non-rehabilitation purposes.

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