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Modular and Distributed Architecture using an Embedded Digital Twin for Assistive Technologies Adaptation.

Aurélian Houé, Cédric Seguin, Florent Frizon de Lamotte, Nathalie Julien, Willy Allègre

Abstract Access to and use of assistive technologies will become a more important issue over the coming decades, as the population ages and the number of people with disabilities increases. To meet the particular needs of various disability situations, specific assistive solutions need to be developed. This paper tackles the problem by proposing a system that adapts to each person and their particular disability. It will rely on a distributed and modular architecture to modify usual assistive devices providing a new ability to respond dynamically to user needs. To control reconfiguration and communication with the environment, the architecture will be orchestrated by an embedded digital twin of the assistive technology.

Key words: Embedded Digital Twin, Distributed architecture, Modular architecture, Assistive technologies.

1 Introduction

In 2021, 1 in 7 person older than fifteen was identified as having a handicap in France, according to the study lead by the DREES (French Directorate for Research, Studies, Evaluation and Statistics) organism [1]. This study brings also that with the elderly increasing number, the proportion of people with special needs is also rising, with 25% of 60 and older people facing a high restriction in their daily life. If this assessment is true at country level, globally the same situation can be drawn.

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According to the 2019 UN (United Nation) report on world ageing in population, 1 in 6 people will be over the age of 65 [2] in 2050. Thus, giving an access to assistive technologies for those people is necessary. Some actions and instructions have been proposed in this way, for instance the strategy for disability inclusion of the United Nations [3] poses the questions of accessibility, participation, accommodation and organizational culture to promote integration of the people with disability.

ICF (International Classification of Functioning) [4] and PPH (Processus de Production du Handicap) [5] define a formal structure to understand the situation of people with special needs. In these models, disability is considered as the interaction between the person, its habits and its physical and social environment. It results in specific needs expressed by the person varying in time along with its handicap. Thus assistive devices or technologies are designed to modify those interactions in order to improve the situation of people with disabilities. In France, the 2020 report on assistive devices [6] reveals that 30 to 40 % of these devices are discarded within the first purchasing year. They raise the issue of the correct response given to the person's needs through the device prescription and so, the importance of assessing reasons for end of use to provide a device more suitable to the patient. Even power wheelchairs are not spared, with a disuse rate of 5% during the first year [6]. In order to propose a solution, it has been decided to divide the handicap specific needs as it is proposed in CML (Concept Maturity Level) model. This model, initially used in space industry, is a promising method to conceive medical technologies [7] by evaluating the conception maturity following three axis. First it evaluates the "Needs" axis, then the "Schedule" axis for the administrative and economic project maturity and finally the "Technical axis" to evaluate the solution development. In the handicap domain, as it was highlighted before, needs are both various and variable because of the strong evolution of the person with its environment. Economically speaking, handicap can be considered as a niche market because of its needs diversity, as a suitable solution for a person at a time may be inadequate for another or become inadequate later. Thus, it results on a huge variability requiring specific development for each person with disability. Following this statement it has been decided to answer this problematic taking into account the assistive technology adaptability.

In Chapter 2, the state of the art shows that many of the architectures proposed for designing assistive technologies are fixed [8], with no possibility of adaptation for the patient. Chapters 3 and 4 present a new solution for designing assistive products through adaptation, in order to adapt a single architecture for several assistive devices. Based on use cases defined by healthcare professionals, a modular, distributed software architecture is presented in Chapter 3, and its hardware is described in Chapter 4. Experiments and results are presented in Chapter 5. The hardware design of this architecture and several tests of its basic functions have been carried out as a proof of concept. Chapter 6 concludes the paper.

2 Related Works

Assistive technologies are an important field of study due to the many challenges their conception faces. The IoT (Internet of Things) systems development and the need to improve people with disability life and access to assistive technologies have resulted in many types of system and disabilities being explored in literature. The most treated impairments [8] are vision disabilities, mobility issues as well as hearing impairments. For instance, [9] proposed a system acquiring images from a low-cost camera, processing them on a Raspberry Pi to extract texts and to read them with a text to speech system. In [10], authors presented a system aiming to facilitate communication with hearing impaired people. The system is based on a mobile app sending text to an Arduino UNO and displaying it on an LCD screen. In [11], a mixed control wheelchair is presented, aiming to help paralyzed people controlling it, through enhancement with low-cost sensors. With an Arduino UNO it acquires data from accelerometer, ultrasonic sensors and servo motors. The Arduino is connected to a Raspberry Pi and using a camera acquiring eye movement, the person with disability can control its wheelchair.

Nonetheless, many systems developed in the literature are based on the same architecture types, using fixed sensors and micro-controller unit or a micro-computer as Raspberry Pi to control actuators and to treat data [8]. Moreover, for different disabilities, the system architectures are still almost the same. Those systems, as it can be seen in [9], [10] and [11], are in many cases immutable, even though from one people to another with the same disability, needs can change.

Thus, a question that could be addressed is related to the architecture adaptability. In [12], authors conclude by approaching the research guiding principles in smart wheelchair domain. They recommend that the best parts of wheelchairs prototypes *“should be fused into a modular upgradable system that can be marketed to the millions of people who need PWs (Power Wheelchairs).”* The flexibility can also be a mean to make the architecture responds to the needs of as many people as possible and with a better accuracy. For instance, in [13], authors proposed a system aiming to help therapists treat rheumatoid arthritis thanks to a glove acquiring data with flex and force sensors through an Arduino. They conclude their study by expressing the needs for their system to adapt to the patient’s situation, by adding more sensor flexibility. Some research as in [14] have been made in the adaptability direction, here in smart wheelchair area or in wearable systems with [15] proposing a wearable modular electronic system named “VibroWear” for health monitoring. In order to guide further developments, technologies used in those articles are listed (as well as their purpose) in Table 1.

Table 1 Related works overview

Application	Papers	Sensors/Actuators	Controllers
Text-to-speech	[9]	Camera	Raspberry Pi
Wheelchair control	[11, 14, 17]	US sensor, Accelerometer, Buzzer, SPO2, Temperature sensor	Arduino, Raspberry Pi
Textual Communication	[10]	LCD display	Arduino
Navigation	[16]	Led, Water sensor, US sensor	Arduino
Diagnostic Help	[13]	Force sensor	Arduino

3 Modular and distributed architecture approach

3.1 Case study definition

As this architecture aims to respond to needs expressed by professionals, a list of promising assistive devices for use cases has been defined. The need for variability can come either from the product type or from the person's disability. For instance cognitive handicap and motor handicap may have access to the same assistive device but will not need the same functionality on it. Table 2 presents the different results brought from discussions with occupational therapists and biomedical engineer experts.

Table 2 Use cases

Assistive device	Aim	Needs
Adapted glass	Grab the glass	Usage tracking, dehydration feedback, gesture learning
Adapted fork	Grab the fork	Usage tracking, gesture learning
Adapted sport equipment	Use the equipment	Usage tracking, gesture learning
Adapted wheelchair joystick	Use the joystick	Usage tracking, gesture learning, wheelchair enhancement
Adapted pen	Use the pen	Usage tracking, gesture learning

Usage tracking and gesture learning are the two needs identified in each cases, indeed they could offer occupational therapists important feedback on the device use and on the improvement of the patient condition. Furthermore, two specific use case scenarios have emerged, from table 2 : a better suited glass to help the patient stay hydrated and a power wheelchair enhancement. Our works will focus on those cases.

As adapted wheelchair joysticks are among the most produced devices by the professionals that have been questioned, enhancing them will have a positive impact in many patients lives. Plus, literature shows that wheelchair enhancement is a hot topic as mentioned in [12]. It concludes on the lack of adaptable system to

upgrade power wheelchair. When upgrading them, authors mainly focused on one objective producing specialized architectures ([11], [13]), using basic sensors that could be integrated in our adaptable structure. Furthermore, as many patients may have a wheelchair but with different handicap, the adaptability is of at most importance because they will not have the same needs. Some people could only need a usage tracking, and others a whole system that could be used to control their environment, using sensors as RFID (Radio Frequency Identification), ultra-sonic sensors or through an HMI (Human-Machine Interface).

Adapted glass is also an interesting use case due to its simplicity and to the various use scenarios that illustrates the whole architecture interest. Table 2 shows that dehydration feedback and usage tracking are two important adapted glass evolution. It was decided that this use case would be used as a first proof of concept.

3.2 Distributed architecture

In order to respond to these objectives, a focus on the development of a distributed architecture has been made. The main difference between a monolithic and a decentralized architecture is the computational power which is, in the first case centralized in a control microprocessor and in the second case distributed. Each component, node, or block has a specific role and communicates with other nodes to perform the system function. This statement is the hearth of modular robotic principles as in [18], presenting an homogeneous modular robot in which each component has the same function. Heterogeneous robots also respect this principle but each node has a specific purpose, which is closer to the architecture that was designed. As stated in [19], in a decentralized computational structure, one of the main issue is to exchange information and coordinate all the controllers to achieve the structure goal.

Following this idea, structural nodes is decomposed in two types 1) "control block" and 2) "sensor-actuator blocks". On the one hand, control module implements the coordination system gathering information, executing fundamental behavior and redirecting information to the devices. On the other hand, sensor-actuator blocks are composed of a control unit and one or several functions depending on the sensors or actuators connected on the module. To answer the information flow issue between blocks, a communication protocol to allow control block managing several heterogeneous sensor-actuator blocks, with special needs, had been formalized.

The method proposed in this paper is inspired by publish-subscribe communication protocol as MQTT. On these message patterns, when connecting to a central node (called the broker), devices subscribe to a number of "subjects" produced by the broker in order to receive updates when necessary. On the other side, the broker is receiving data from the devices, which are either analysed and redirected to the subscribed devices or just redirected. These protocols are mainly used in IoT systems through remote communication as WiFi, as they offer a great flexibility with regards to the data flow [20]. These concepts have been applied, in our architecture, to wired communication: the control block being the central node and the sensor-

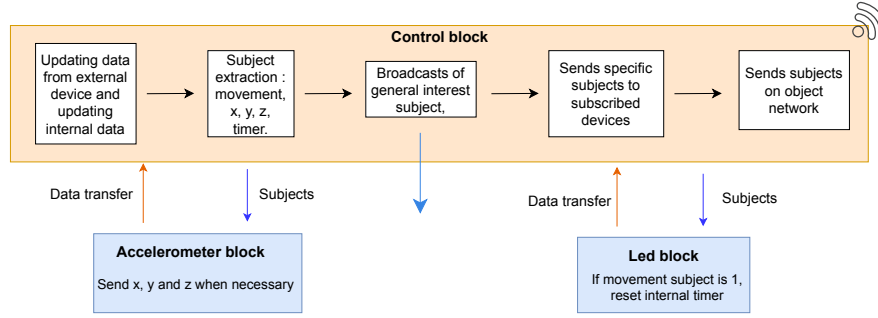


Fig. 1 Publish-subscribe communication between blocks

actuator blocks being the editors and subscriber subjects. The control node handles the new device connection by requiring their configuration at first in order to save it in memory. Then, the communication can begin between the device and the control unit, which receives its data and redirects them to subscribed blocks. This way, sensor-actuator nodes are able to exchange information and adapt their behaviour regarding received data.

Figure 1 describes this protocol operation for an example. The accelerometer block and the led block are required to send data if necessary (red arrows). After collecting these information, the control node updates its internal values. Then, subjects as x, y and z accelerations, timer or more conceptualized subjects as movement are extracted from current data. Following extraction, they are sent using broadcast for timer (big blue arrow), direct transmission for movement (thin blue arrows) or network transmission if needed. When the led block receives movement information, it can update its status if there was movement (object has been or is being used) or not. Thus, regarding the state of the accelerometer node, the led node can modify its behaviour. In order to follow the entire system operation, and interact with it either passively (to observe it) or actively (to modify it) it has been choose to develop a digital twin module embedded in the control block and exchanging information with the controller module.

3.3 Embedded Digital Twin Module

The digital twin (DT) concept is mainly used in manufacturing or industrial applications because it offers a powerful tool to control factories, predict errors and avoid them. Thus, the first definition and structure was proposed in those domains in 2014, by Grieves in [21], and it is still a hot-topic in Industry 4.0. Since then, DT technologies have gained interests in other domains like the healthcare industry [22] or in smart cities. Consequently, plenty of definition for DT have been mentioned as it can be seen in [23]. The definition proposed in ISO 23247 is more suited to manufacturing applications, so the definition proposed in [24] has proved more suitable.

The DT is defined as a dynamic virtual representation of an object (product, process or service). They also highlighted basic characteristics that must be included in a DT: a continuous connection between physical and virtual space, the ability to manage suitable data, an architecture allowing in-line and off-line twin modification, its physical counterpart control, learning ability and prediction ability. Thus, an important aspect of DT that is underlined in those features, is its dynamism. This concept is at the center of our architecture, which is why it was considered that this technology would act as a conductor for our whole system.

Embedded Digital Twin (eDT) is a topology where the DT and its physical counterpart share the same computing power, as described in [25]. Among the other topologies, the embedded solution was the most relevant considering that collaboration between assistive technologies within the person environment. Using an embedded DT, acquired data from the different nodes of one device are directly transferred from the controller module to the DT module using a shared memory. Then, the DT can share, if necessary, those information with human or DT collaborators. Furthermore, an efficient power management strategy, that will rely on the embedded DT decision, is being considered. Being as close as possible to the device allows it to easily change its current configuration through the shared memory. This, in order to either modify the operation of the system (changing a threshold for instance) when receiving the instruction to do so or to guarantee that the assistive device is using the necessary amount of power. Another situation is that the system will sometimes need to collect more data (in an hazardous or unknown scenario) and the DT will be the lever for the architecture to adapt and collect cleverly data as described in [26].

To be compliant with DT standards, our objectives and the DT architecture is aligned to the standard ISO 23247 standard [27]. It proposes a DT architecture for manufacturing applications, that needed to be adapted to our purpose taking into account the embedded aspect of the DT. Figure 2 represents the three main actors that were identified which are 1) ITs, 2) the person with the disability and 3) occupational therapists and their interaction with the assistive technology. The DT entity is embedded in the Shared Computational Entity of the Physical Twin and can be accessed by therapists and ITs through an Interface Functional Element. It interacts with the Controller Entity using the Shared Memory Entity. It integrates the communication functionalities in order to collaborate with the environment and functions to manage the whole device. The Controller Entity delivers DT module orders to sensor-actuator blocks and controls the data flow presented in Figure 1.

Using ISO 23247 nomenclature and literature elements, [28] proposed a description tool named the “digital twin typology” to put a first step into a DT design methodology using eleven criteria. Applying this approach, elements of our DT typology are summarized in table 3. One criterion (Smart Manufacturing System) was discarded because it was not relevant in our project. Using this tool, the functions that will be implemented in the first version of our DT and the users with whom it will collaborate, were expressed.

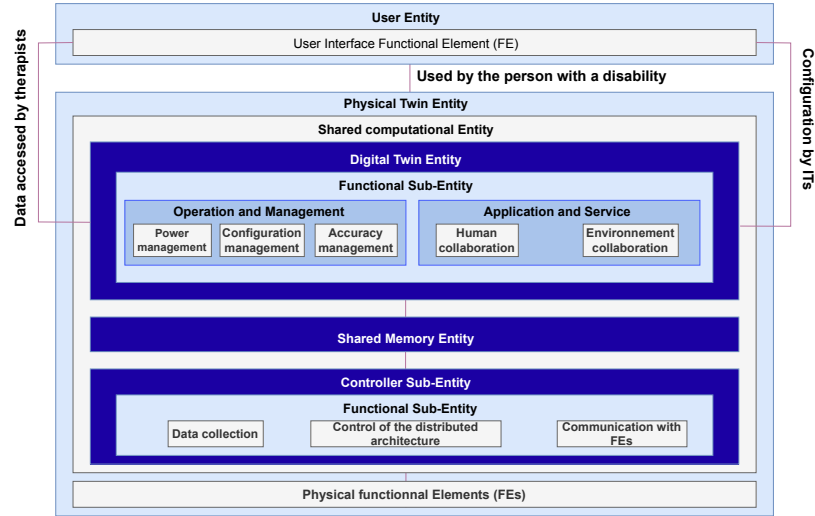


Fig. 2 Embedded digital twin architecture

Table 3 Embedded digital twin typology

Criterion	Description	Value for the Digital Twin
Physical Element	The physical twin	One assistive device
Type	Prototype, instance or aggregate	Instance
Level	Hardware technological level: system of systems, system, equipment or component	Equipment
Maturity	DT role in the system: control DT, cognitive DT or collaborative DT	Control DT
Topology	Connection between cyber-physical space: joint, disjoint and embedded.	Embedded
Decision loop	Human place in the DT decision process. Can be open (human interaction), closed (no human interaction) or mixed	Mixed
Synchronisation	Data harvesting method. Synchronous or not	Asynchronous, event based
Users	Collaborators of the DT	Technicians, occupational therapists and patients
Usages	Basic functions implemented by the DT	Analysis, comparison, collaboration
Applications	Global goal reached using these skills	On-line reconfiguration, real-time control, off-line analytics

4 Hardware design

The modular and distributive architecture will be deploy on a hardware system illustrated on Figure 3. The control block consists of a microcontroller, communication peripheral, external memory to save collected data and a battery. It is the one em-

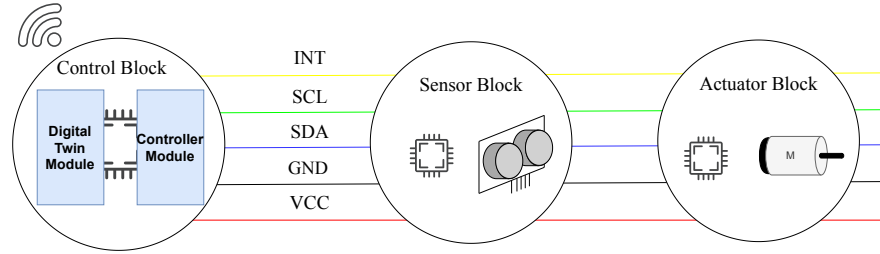


Fig. 3 Hardware structure illustration

bedding system DT module and the controller module. Following the related works study results in Table 1, an ESP32 to embed the DT has been choose. It is a low-cost and widespread MCU like Arduinos, which has the advantage to integrate WiFi and BLE. Device blocks are composed of a smaller microcontroller and functionalities that can be sensors or actuators. This MCU should be able to communicate with the control node and carry out minimal computational functions on data such as simple comparison. To be compliant with the results in Table 1, a few devices to be implemented in the first experimentation which are the accelerometer, the joystick, the ultra-sonic sensor, the leds and the buzzers has been choose.

For the data communication between control node and device nodes, several choices were possible but the four main were SPI (Serial Peripheral Interface), I2C (Inter-Integrated Circuit), CAN (Controlled Area Network) and UART (Universal Asynchronous Receiver / Transmitter). The use I2C over CAN bus was preferred because even though it seemed to be a good choice regarding the architecture communication logic, it is not, by nature, available on all ESP32. UART might have been a more standard choice but the development would have been far more complex than with I2C, because it is not a native master-slave communication protocol. SPI protocol could have been used, because it is faster than I2C, nonetheless, each device connected to the main block requires a chip select pin. Whereas, with I2C only two cables are used to connect the device on the bus, using software addresses to differentiate two modules. Finally, I2C offers the possibility to broadcast data to slaves thanks to address 0, making it a suitable choice for our application and experimentation. As it can be noticed on Figure 3, another communication cable named "INT" to handle node connection and disconnection to the central unit is added. Indeed, I2C does not allow slaves to send data to the master node, this third signal is required to warn the control node when user want to change the physical configuration.

5 Experimentation and Results

To evaluate architecture design choices, experiments have been led on the adapted glass use case. Figure 4 illustrates the different cases that have been focused on. In



Fig. 4 Adapted glass use cases

the first case, the glass is equipped with control block and usage tracking capacity that can be achieved with an accelerometer. It gathers data about the object use and allow health professionals to know if, when, and how the device has been used. In the second scenario, a feedback capacity is added. If the glass is not used on a regular basis, it will send a feedback to remind the person to drink. This feedback could take several forms as visual or sound effects. Even if the feedback is still luminous, adaptation could be achieved by switching the effect using “sub-capacities” to change from one behaviour to another. In the luminous feedback case, professionals could decide that a static light is better than a dynamic one. Finally, the third scenario illustrates the case when the feedback capacity is faulty. In this situation, the DT could decide to communicate with an other equipment in its environment, to fulfill its warning goal. This second object, could decide to accept or decline this demand, depending on the situation.

The communication protocol between control and sensor-actuator blocks was successfully developed, broadcasting general interest data on the I2C bus which are correctly received by devices. Control block is able to request information from them in order to extract subjects to which some devices are subscribed. When a new device is connected, the control block asks for its subscriptions, those that were configured before the sensor-actuator node was programmed. Devices connection and disconnection was successfully implemented and managed by the control block. Power management was not tested directly on the architecture but previous works on the system have shown that it is functional as well as data saving. First scenario is still under development. Second scenario has been fully tested. Third one requires more works on the implementation of the wireless communication before it can be tested.

6 Conclusion and future works

Adaptability in the development of assistive technologies could be a great improvement to simplify their access and conception. Most of the architectures found in the literature are based a similar structure with sensors and actuators even thought they are used for different purposes. Using the distributed and modular architecture presented in this paper, healthcare professionals have been offered a innovative way of creating multiple assistive devices for different disabilities using the same technology. Embedded DT will help to control the object reconfiguration and com-

munication and will be a lever to help occupational therapists study the use of assistive devices and to decide if changing it is required. First developments have been carried on to evaluate the proposed architecture, and some fundamental functions have been successfully implemented. Preliminary works on data-logging activity of assistive objects, that initiated our researches, still need to be implemented on our modular and distributed architecture.

To implement the third use case scenario presented on Figure 4, future developments will be focused on integrating and testing the communication between several assistive technologies, and other smart objects from the person environment. Then, our next works will be focused on smart wheelchairs as it offers a more complex use case with a wide range of adaptability options, and it could also benefit to a larger number of people. Finally, occupational therapists have shown great interests about helping patients with feedback about the gesture learning, thus, “computational blocks” with a higher computational capacity could be implemented, in order to analyse the gesture and to generate information about its quality or improvement. In the same way other type of nodes might be implemented in the future.

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