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System of systems approach and user-centered design to improve the autonomy of people with reduced mobility

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Abstract—In this paper, we propose a methodology for the integrated design of modular technological breakthroughs allowing to improve the autonomy of persons with reduced mobility. Starting from the user-centered design of modules responding to a functional need of a person with reduced mobility, advanced interaction applications are proposed depending on the acceptability by the person of the developed modules. The integral solution is conceptualized by a system of systems approach. An example of application is proposed to illustrate the relevance of the proposed design approach.

Index Terms—System of systems, user-centered design, acceptability, reduced mobility, disability, modeling.

I. INTRODUCTION

The technological advances of the last few years have largely favored the development of technologies to improve the autonomy of people. However, studies show that only a small part of the technologies developed are actually used by end users. This is partly due to the fact that the real need of the end user has not been at the center of the design of the proposed solutions.

According to the World Health Organization, approximately 15 % of the world's inhabitants live with some form of disability and the worldwide estimate of the prevalence of disability is on the rise, in particular due to population aging [1]. Taking into account, the increasing cost of medical intervention, it is now the healthcare professionals challenge to ensure a correct

timing for the solution proposed to the subjects in regards to their conditions. Several parameters should be considered, possibility of evolution, risk of chronicity, missing information [2]. . .

Quantitative and exhaustive functional assessment, according to the International Classification of Functioning, Disability and Health (ICF), therefore proves to be necessary as recommended by the World Health Organization.

During the design of new solutions, assessing the acceptability and acceptance of technologies is definitely a key issue in the design and deployment of technologies. It is necessary for designers to identify the factors and conditions that influence the perception of users. This one may lead to the reject or acceptance of those [3]. To support this perception, it is important to adopt a user-centered design and more specifically a participatory approach involving the users throughout the solution's development.

In practice, the different equipments or applications developed are very often isolated cyber physical systems but which must be brought to realize a common mission; that of improving the autonomy of the Person with Reduced Mobility (PRM). The challenge is to design new modules with such a vision and to choose in an appropriate way a unified approach allowing to study and analyze its different components in interaction with each other and with the person with reduced

mobility. The System of Systems (SoS) approach could be relevant in such a case.

Many SoS definitions [4], [5] has been formulated but none have been recognized as the only one. The SoS engineering (SoSE) remains an area to be developed. We can define a system of systems as a set of many autonomous systems or elements of systems that interact to provide a unique capability that none of the constituent systems can accomplish alone. To meet the demands of an SoS, Maier [6] proposes five specific characteristics :

- **Operational independence** of the constituent systems (CS): if the system of systems is disassembled, the CS must be able to operate autonomously,
- **Managerial independence** of the CS: the constituent systems must maintain a continuous operational existence independent of the system of systems,
- **Geographical distribution** of its constituent systems,
- **Presence of emergent and cooperative behaviors** to achieve a common goal,
- **Evolutionary development process**: a system can be added or removed without changing any of the characteristics of the SoS.

Even though SoS share the same characteristics, some attributes change from system to another, that's why, based on objectives of the SoS, governance, and the inter-relationship between components, SoS can be classified into four types (categories) [7] [8]:

- **Directed SoS**: The system is built for a specific purpose, and centrally managed.
- **Collaborative SoS**: In collaborative SoS, the central management does not have the coercive power to run the system.
- **Acknowledged SoS**: Which shares attributes from both directed and collaborative SoS. These systems have a central management and resources for the SoS, but the components retain their full independence.
- **Virtual SoS**: It emerges from the interaction between components, whereas the objectives are unknown, and there is no central authority. The system is maintained through invisible mechanisms.

Originally identified in the defense field, the application of SoS engineering is now much more present and still expanding in many domains [9]. The SoS concept has been applied in many fields, including military [10]. Better known, the ISTAR system (Intelligence, Surveillance, Target Acquisition and Reconnaissance), an SoS in military aeronautics is developed. Its objective is to collect and share information to create the best possible representation of the mission scenario and improve the decision-making process. There are some SoS applications on robotics [11], transportation [12] [13], crisis management [14], Smart City [15], Health care [16] and Industry 4.0 [17]. In a recent work [11], an SoS in the transportation domain for the optimal management of intelligent autonomous vehicle

(IAV) guidance in dead zones, i.e. where navigation signals are absent is developed. In this context, a cooperation between an IAV and an UAV is observed.

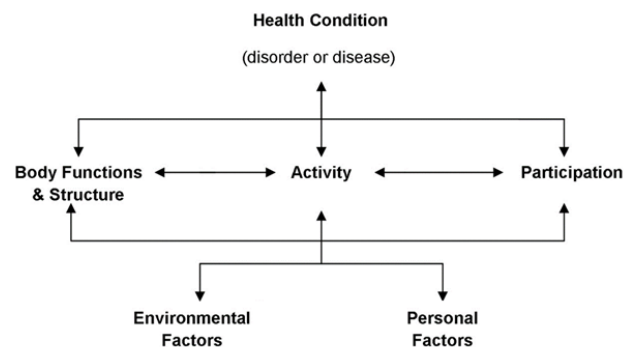
Recent works for new frameworks have been thought of with focus on the transportation problematic from a point to another and [18], [19], to meet these challenges, i.e., to offer technological modules that meet the needs of end-users while being modular and able to work in cooperation, in order to improve the autonomy of people with reduced mobility, we propose an integrated design solution for modules and applications combining the system of systems approach and user-centered design. We will present the methodology in section II, its application in sections III and IV. We will finish with some conclusions and future work.

II. METHOD

A. Definition of disability and ICF framework

Disability has long been considered solely through the medical characteristics of a person, the so-called “medical model” [20], requiring a medical treatment to improve the condition. Contrary to this vision, the “social model” [21] was proposed by considering the external barriers and constraints of the environment inducing a disability situation. According to this model, improving the conditions of people with disabilities must go through political and economic actions. The current approach to the situation of disability, called the “biopsychosocial model”, integrates the two previous models and considers disability as resulting from biological, personal and social constraints and has opened the debate internationally on accessibility issues (c.f. Fig.1).

Fig. 1: General framework of the ICF



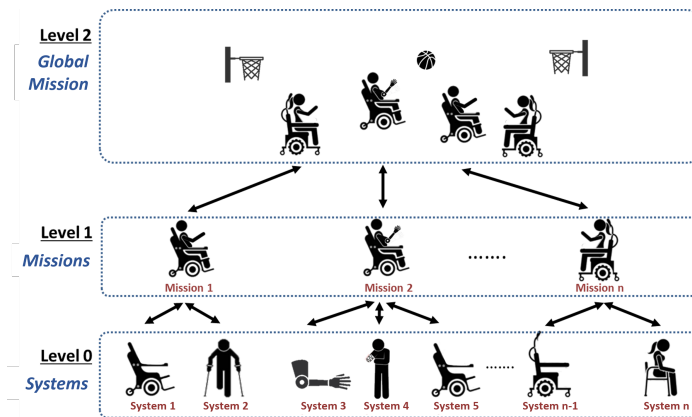
The World Health Organization advocates the use of multi-disciplinary analysis based on biopsychosocial approach as the use of International Classification of Functioning, Disability and Health model (ICF) [22] allowing a standard evaluation recommended by International Consortium for Health Outcomes Measurement. This conceptual model provides a framework for clinicians in assessing and monitoring the level of functioning of patients during the course of their care and throughout their lives. In this way, a common language

is also achieved for all disciplines involved in the care of this population. The ICF model is composed of “body structures and functions”, “activities”, “participation” and “personal factors” domains. These domains yield a categorical profile which represents the functional state of an individual [23]. This may then be used as a guide in rehabilitation goal-setting, intervention planning, and follow-up. With this perspective, this quantitative and exhaustive functional assessment of these people therefore proves to be necessary providing a multi-perspective approach for the classification of disability and aiming to the overall analysis of the patient compared to his disease. The study adds to the body of knowledge on the practicality, clinical utility, and applicability of the ICF in real world settings.

B. Description of the approach

When applying the SOSE approach withing the ICF framework, one must first start defining the levels of systems as represented in Fig.2 (the basket ball game is just an example of a complex multi-agent situation). On level 0, the ICF framework can be used to provide the technical solution in order to solve the physical/functional problem while preserving the subject from future complications (pain, accident...) [2]. Not using this approach at level 0 increases the risk of failure in Human robot interaction [24], ableism (assigning or denying certain abilities for a person living with a disability) [25] or providing only a partial technological solution to a holistic problem [26], [27].

Fig. 2: Various Levels of System of Systems



Starting from the user-centered design of modules meeting a functional need of a person with reduced mobility (level 0), advanced interaction applications are proposed depending on the acceptability of the developed modules by the person. Such low-level interaction between the person and the system can be formalized as purely biomechanical dynamic equations which are often found in the form of a descriptor system [28], [29] as shown in equation 1.

$$\begin{cases} E(x(t))\dot{x}(t) = A(x(t))x + Bu(t) \\ y(t) = Cx(t) \end{cases} \quad (1)$$

This structure is very interesting because it keeps the “natural” form of the problem and avoids the distribution of the nonlinear terms withing the constant matrices hence lowering the conservativeness [30].

At level 1 (see Fig.2), due to the resolution of the functional/physical need of the person with reduced mobility, simple applications allowing the person to perform activities in a given environment are considered. Examples of applications of this level are: autonomous navigation applications, driving assistance applications, gate opening, elevators, etc.

At level 2 and above, complex applications, involving a dynamic environment, human-human, human-robot (collaboration) and robot-robot (cooperation) interactions. The integral solution is conceptualized by a systems approach. Many examples of application are proposed to illustrate the relevance of the proposed design approach.

III. APPLICATION EXAMPLES IN THE FRAMEWORK OF THE CPER RITMEA PROJECT

A. Application example 1: Development of a connected orthosis to improve the autonomy of people with reduced mobility

When designing an orthosis to a person with reduced mobility, the first step in the ICF framework is to go through the categories of the classification. Filling in information can be done through free or semi-structured interviews. Starting with a listing of impairments of body functions (physiological functions of body systems including psychological functions) and body structures (anatomical parts of the body such as organs, limbs and their components). Hence, functions like mental, sensory or neuromusculoskeletal and movement related functions and structures like brain, eye, limbs would be associated to a qualifier to represent the extent of impairments from nothing to complete impairment. This first step is more global than just focusing on a Range of Motion approach as it can be seen in previous works [19].

The second step is to fill the Activity Limitations and Participation Restrictions part (e.g. learning, communication, mobility...). Activity is the execution of a task or action by an individual whereas Participation is involvement in a life situation. Activity Limitations are difficulties an individual may have in executing activities compared to Participation Restrictions which are problems an individual may experience in involvement in life situations. Two distinct qualifiers are then used in this step The first one describes what a person does in their actual environment. The second describes what a person does in a situation in which the effect of the context is absent or made irrelevant (such as in a standardized evaluation setting). “The gap between capacity and performance reflects the difference between the impacts of current and uniform

environments, and thus provides a useful guide as to what can be done to the environment of the individual to improve performance” [22].

Finally the Environmental factors, making up the physical, social and attitudinal environment in which people live and conduct their lives are qualified in positive (resp. negative) qualifiers depending on their impact as facilitator (resp. barriers). Factors such as ”Design, construction and building products and technology of buildings for public use”, Relationships (family, friends...), Social norms and Legal services are examined.

Once all those information have been collected, the opportunity for a co-designed technical solution is at hand. Not only is the designer informed of all past and present qualifiers of the subject, but he also knows his/hers motivations and goals related to the function to regain. Several validated quiz and scales exist to improve the holistic knowledge of the subject like the Assessment of Life Habits (LIFE-H), a tool designed to document the quality of social participation of individuals with disabilities in carrying out activities of daily living and social roles by measuring the level of difficulty and the assistance required to perform a series of life habits [31]. This scale could be used as a direct map to a control law setting as to whether the subject require more or less help in the required motion.

Finally, an easy and quick evaluation would be possible for a back and forth prototyping process through the well known ”System Usability Scale” [32]. This scale, despite being created for marketing purpose rather than scientific ones, has the main advantage of isolating very efficiently extreme positive or negative feedback. Previous works related to rehabilitation devices were concluding that such a structured and generalized protocol for patients would improve the overall acceptance of the device and, consequently, the whole clinical process [33].

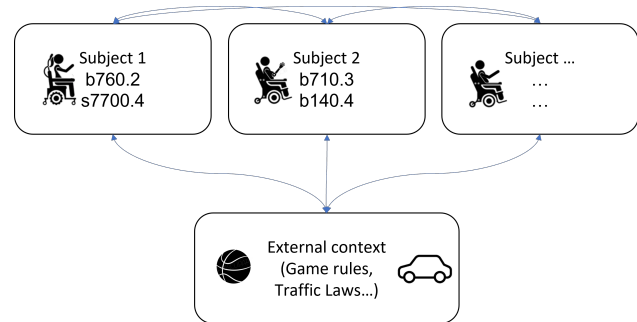
B. Application example 2: Development of a fleet of wheelchair and connected objects to improve the autonomy of people with reduced mobility

In this second application example, the ICF will be considered as a representation of each subject system inside the wheelchair fleet. While the previous application was focusing on the subject and his/hers supplementary device, the current situation requires a broader definition of context and external constraints.

As presented in Fig.3, each subjects of the wheelchair fleet can now be represented through the ICF qualifiers either for body functions, structure of activities, Participation and Environmental factors. A first network of potential interactions are possible between all members of the fleet and a final level of rules and must be considered depending on the external context. For instance, in the case of a basket-ball game, obstacle avoidance systems sensibility can be lowered in order to allow low-intensity collision for defensive purpose. Obviously such collisions are to be prohibited in the context of street mobility

and the avoidance systems sensibility should be reprogrammed as such.

Fig. 3: Relation between subjects in the ICF framework and external application



One challenge in this situation is to allow the subject to use the mobility device while avoiding failures which can be separated into communicating failures (e.g. not moving the joystick in the right direction due to tremors in the hand), perception and comprehension of failures (e.g. not realizing that the wheelchair is still due to a contact with an obstacle), and solving failures (e.g. avoidance failure) [24]. One method to try to reduce those failures patterns could be to inform the subject about specific percentages of reliability as a link was found between perceived reliability and trust in the system: the more the trust in automation increased, the more the perceived reliability increased [34].

Although an efficient proposition would be to let the global motion of the fleet to a purely automated algorithm, it has been shown that when having to choose for an automation level, subjects will prefer automation types offering the best human-machine interactions quality rather than the most effective automation type [35]. Another parameter to consider would be the amount of control allowed by the subject.

Finally, this whole application cannot seriously reach its goal without taking into consideration feedbacks and insights of people with reduced mobility in the complete design process (including when initially setting the supposed goals of the device and its specifications). Due to their small representation in industry and design schools, often leading designers forgot to involve people with disabilities altogether at this stage or will try ”imagining” what the disability feels like [26]. In the specific field of mobility, the dimensionality of displacement is very relevant and almost always silenced in mobility devices [25].

IV. SOME PRELIMINARY RESULTS ON WHEELCHAIRS

In 2023, according to the WHO (World Health Organization), 15 million people will need a wheelchair on a daily basis. By 2030, one in six people in the world will be over 60 years old. Studies show that many people with mobility impairments have osteoarthritis in their hands that prevents them from

maneuvering a manual or electric wheelchair. Some of them use a walker type equipment to move around, this equipment prevents them from having the mobility to open doors for example. Other PRMs have partial or total visual impairment that prevents them from properly maneuvering in a wheelchair. In addition, medical personnel are increasingly concerned about controlling the posture of people with reduced mobility in their wheelchairs. How to develop a set of technological bricks around the wheelchair allowing on the one hand to improve the living conditions of the person with reduced mobility and the working conditions of their caregivers or doctor?

The challenge is to propose integrated, modular, low-cost solutions to see them widely deployed in establishments accommodating these PRM. Based on these real needs and the methodology described in this paper, we have developed a first version of a set of connected objects around the person with reduced mobility for the improvement of autonomy by meeting several identified functional needs. We will present the integrated design of the developed solution.

A. Description of the application

We have developed a set of system components; the robotization of a wheelchair, the development of a driving aid, a fall detector, an automatic recharging system and a set of connected objects around the PMR. The figures 4, gives the SoS architecture of the developed solution.

B. System architecture and Human Machine Interface

In order to allow all the modular technological bricks of our system to exchange information with each other, it was necessary to design a simple and efficient architecture allowing the whole elementary system to interact with each other. The wireless communication should be able to send data to all the SoS components with low latency. The developed architecture is based on MQTT.

The man-machine interface is meant to be intuitive and allows the administrator to control and have an overview of the system. A web interface has been developed, allowing to supervise all the components remotely. Several tests have been done to validate the effective transmission of information. We note a maximum latency of 1 second when sending and receiving data with an average latency of 0.82 seconds for sending (object to HMI) and 0.2 seconds for receiving.

C. Automatic charging station

The goal here is to reduce non-essential travel. Putting the wheelchair in charge can be complex for a person with reduced mobility. Therefore, the aim is to design a system capable of charging different wheelchairs using lead-acid or lithium batteries. The automatic charging system consists of a docking program that will automatically bring the wheelchair close to the charging area. Once the wheelchair is close to the station, a camera attached to the back of the wheelchair allows it to be correctly aligned with the charging pods. Once the wheelchair

is properly aligned, it will plug into the charging pods. An ultrasonic sensor detects the presence of the wheelchair under load (Fig. 5). The developed system has been tested. 93% of the 200 automatic charging tests were correct.

D. ADAS and Autonomous Navigation

The obstacle warning system is composed of a Lidar and 8 Ultrasounds (US). A haptic feedback on the armrests of the chair allows to communicate to the user information on the distance to the obstacle. Also, an autonomous navigation application is developed to move the wheelchair from one point to another. These systems are under development. Other connected objects are being developed to be added to the solution presented here.

V. CONCLUSION

In this paper, we have proposed a methodology for the integrated design of modular technological breakthroughs allowing to improve the autonomy of people with reduced mobility. The ICF provides a holistic way to assess needs and choose the most suitable technical solution for a specific health problem. Starting from the user-centered design, allowing to favor the acceptability by the person, modular applications answering a basic functional need are developed, advanced interaction applications modifying the environment are then proposed. The complete solution has been conceptualized through a system of systems approach. Examples of applications will illustrate the relevance of the proposed design approach. We believe this framework can be used for advocacy and empowerment of people with reduced mobility to develop a prototype of wheelchairs and orthosis connected in the framework of the CPER RITMEA project.

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Fig. 4: System of Systems to improve mobility of persons using wheelchairs

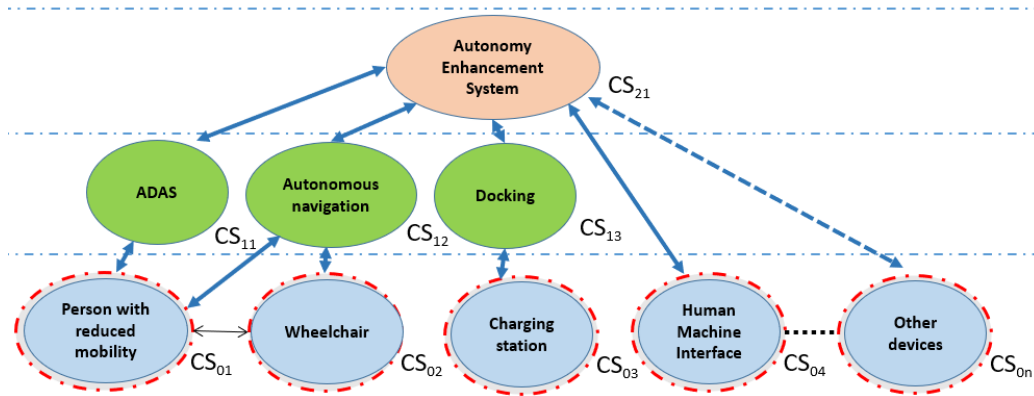
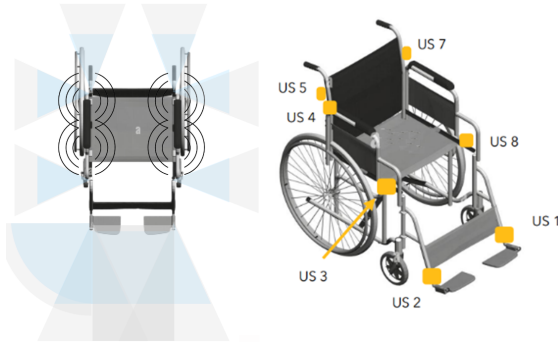


Fig. 5: Automatic charging station



Fig. 6: Obstacle Alerting System (OAS)



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