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Implementation of Smart, Healthy, Age-Friendly Environment Through an Inclusive Robotic Air Purifier

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ABSTRACT

Promoting the health and liveability of the environments in which people live is one of the challenges for healthy and active aging. New design paradigms for "healthy buildings," which determine living comfort, evaluate a variety of factors, including the issue of indoor air quality (IAQ) management. The Coronavirus pandemic has changed people's habits, giving a strong boost to the attention paid on indoor air quality. This trend is also evidenced by the exponential increase in the supply of devices for air treatment. However, these devices have a coverage that is limited to a restricted portion of the indoor space and difficulties in managing or reading the interface often emerge, especially in older users. The paper presents the research project titled "Aplu" which has led to the development of an ion generator robot with the function of vacuum cleaner too. The research aims to test and validate the possibility of providing inclusive support and monitoring tools that can increase the efficiency and autonomy of the device and able to lighten the workload of users, especially the elderly, who are often hostile to accepting invasive technological solutions.

Keywords: Good health and wellbeing, Indoor air quality, Robotic design, Ambient intelligence, Human-centered design, Design for inclusion

INTRODUCTION

A survey conducted in the United States estimates that people spend up to 90% of their time inside buildings (Klepeis et al., 2001). The same lifestyle of being confined predominantly within enclosed spaces is also prevalent in Europe. In this regard, a study carried out in the United Kingdom highlights how inhabitants predominantly distribute their activities between personal houses (41%) and workplaces (34%) (Brown, 1983).

This diffuse habit provides the opportunity and motivation to implement interventions that promote the health and liveability of the environments in which people live or work (Sheldon, 2020). In multiple fields of the design discipline, this translates into a focus on developing quality interior spaces that return comfortable environments for inhabitants to organize, manage, and modulate according to their needs and habits. In fact, indoor environmental quality (IEQ) design has the potential not only to meet basic human needs but also, and more importantly, to help meet higher-level needs with the goal of protecting the health of inhabitants (Crandall et al., 1996). The World Health Organization (WHO) defines health as "a state of complete physical, mental and social well-being." From this definition follows that the concept of "health" mustn't be reduced only to which concerns the "physical" sphere of the individual but should be extended to all those intangible and subjective factors related to the psycho-social sphere; factors that, relating to living comfort, can translate, for example, into perceived feelings of security, self-esteem, positivity, and productivity (Ni et al., 2020).

The new design paradigms for a "healthy building" (Crook et al., 2010) evaluate a multiplicity of aspects that contribute to determine living comfort (IEQ) and the resulting qualitative perception of inhabited space. These aspects certainly include the issue of indoor air quality (IAQ) management, which responds to the problem of indoor pollution. The "inhabitants" of an indoor space are usually exposed not to a single agent, but to a mixture of substances generated by the concurrence of several triggers that combine into a potentially harmful mix for the occupants (Awada et al. 2021). In fact, indoor air quality (IAQ) is affected both by contaminants from outside and by indoor sources as: i) building materials, ii) appliances, iii) excessive humidity, iv) occupants (pets and humans). Major pollutants that can be linked to the sources just listed include: i) organic gases (such as VOCs), ii) inorganic gases (such as ozone and radon), iii) particulate matter (such as mold, asbestos, etc.) (Heinsohn et al., 2003).

Symptoms resulting from the effects of indoor pollution, grouped under the acronym BRI - Building-Related Illness - include specific pathological patterns. In this regard, the numerous studies on SBS - Sick Building Syndrome - are just one of the many concrete examples of the impact caused by a lack or superficial management of indoor pollution (Crook et al., 2010). These pathologies show how acute "physical" symptoms such as asthma, throat and eye irritation or shortness of breath are directly associated with elevated negative emotions, amplified aggressive behaviours, decreased attention and mental fatigue (Awada et al., 2021). The evolution of the Coronavirus pandemic scenario has revolutionized people's habits, stimulating them to reflect on their condition as "inhabitants" forced to occupy enclosed spaces, suffering its negative influence.

This reflection has been echoed by a strong awareness towards the issue of indoor air quality management also evidenced by the exponential increase in the use of air treatment devices (Businesscoot.com, 2021) and sensors to detect pollutants (Awada et al., 2021). Among the countermeasures, in fact, building ventilation, and more specifically mechanical ventilation through the application of air filtration technologies, including portable air purifiers, appears to be among the most effective in providing and maintaining better IAQ by removing pollutants generated by indoor sources and thereby diluting the concentration of indoor contaminants (Awada et al. 2021).

People's increasing attention to indoor air quality management, however, is not to be interpreted merely as an impulsive response to a passing need, but rather as one more step to the broader vision of changing related to the gradual increase in sensitivity to issues concerning the care of mental and physical health in all its facets, from simply reducing risk factors to preventing aging (Coop R., 2021).

A careful analysis of the state of the art of air purification devices, conducted within the research presented in the following article, has revealed the lack of a holistic approach in the design of these products, whose function is often reduced to a mere assembly of components and technologies. The main limitation that has emerged is the predisposition of the devices to be stationary, with coverage limited to a portion of the indoor space, and a difficulty in interface and control by older users.

Aplu was born out of a reflection on this scientific context, and it has led to the development of an ion generating robot, which also functions as a vacuum cleaner. The project aims to increase the usability of a purifier, in terms of effectiveness, efficiency and satisfaction, and to create an inclusive interface, through the development of a new principle of operation, exploiting the integration of advanced technologies, related to the field of robotics and the Internet of Things.

The project has used the "research through design" approach to find innovative solutions for improving the usability in terms of inclusion and user experience, and for simplifying the interaction with an indoor air purification device.

Specially, Aplu's project has had the following specific objectives: i) to increase the efficiency of the air purifier by equipping it with autonomous intelligence; ii) to test and validate the possibility of minimizing the user's burden of managing the product; iii) to provide inclusive support and monitoring tools that can ease the work of users, particularly the elderly; iv) to test acceptability by the elderly, who are often hostile to advanced technological solutions.

METHODOLOGICAL APPROACH

The research project has used design thinking methodology, combined with a human centered approach. The design process has considered the user holistically, focusing on the following points: i) the effective design of a product that addresses the primary need of "having to purify the air"; ii) how the solution can adapt to the user's habits, activities, and lifestyle; iii) how the user can learn to use the solution. Innovation research has focused particularly on the emotional and relational component of the product-service system in interacting with users, whose positive or negative behavioural responses can drastically change the user experience (Tosi, 2020).

Below are presented the steps that has led to the definition of the final solution.

Preliminary Phase: State of the Art Analysis

The first phase of research has been carried out mainly through the qualitative method of state-of-the-art analysis, a method already adopted in several research aimed to study the consumption of "smart technologies" (Ammari et al., 2019). Through the analysis of market benchmarks and innovative concepts, this preliminary in-depth study has allowed to understand the main technologies and the principle of operation of air purifiers, specifically going to understand: i) the basic mechanisms of the "technological product"; ii) the functioning of the applied purification technologies, defining their actual potential and comparing the differences in terms of mechanism and effectiveness; iii) the necessary components for the design of an efficient device; iv) the strengths and criticalities related to the operation of the device.

Empathize Phase

In parallel to the development of comprehensive User Research and the assessment, through the analysis of the context of use, of social, cultural, and technological reference variables, the qualitative method of state-of-the-art analysis has contributed to provide useful details regarding the identification of user tasks and needs in the operational context (Maguire, 2001).

The preliminary analysis of the state of the art, aimed at understanding all factors related to the technical aspect of the product, has provided the basis, in the empathize phase, for an exploratory approach to usability aspects, with the attempt to understand: i) what are the types of users; ii) how existing products relate to the user; iii) how existing products relate to the context; iv) what is the degree of user satisfaction; v) what are the factors that can determine it; vi) what are the usability needs in relation to the context. This exploratory approach has occurred, more specifically, by focusing on the analysis of online reviews, that is a method already used in the context of Smart Objects (SO) (Gao et al., 2018). Thirty products have been analysed, with an average of 500 reviews per device, including ratings and comments, all extrapolated by the same e-commerce.

This exploratory approach has evolved in three consecutive phases: 1) open-coding phase in which reviews has been analysed in order to collect initial information regarding the user's negative or positive experience with reference to some pre-selected air purifiers (light weight, ease of communication, filter maintenance, portability, etc.); 2) axial coding stage in which the themes had emerged in previous stage has been placed within macro groups on the basis of their affinities; 3) concluding stage, in which the maximum level of abstraction of the collected data has been reached. This has allowed to define the macro themes to work on to develop the project.

Finally, the hierarchical task analysis method has been used to structure the amount of information collected. These have been distributed in the sequence of activities related to the interaction with the purification devices, from the purchase phase to the maintenance phase, up to the definition of the critical and strengths points, useful in the development of the design solution.

Define Phase

The analysis of the state of the art has revealed the lack of a holistic approach in the design of air purification products, whose function is often reduced to an assembly of components and digital technologies and the intended use a mere "consequence" of form. This lack does not directly affect the absolute value of the product, but it influences the product's performance in relation to context and user experience. In fact, purification technologies taken individually, offer very high performance, with percentage values of pollutant particles removed from the inhaled air that can reach as high as 99% in the case of, for example, HEPA filters.

However, this is not enough to determine the successful performance of a purification device, whose result depends on a combination of three factors: 1) the choice of purification technology; 2) the flow rate of the device, i.e., the volume of air it is capable of filtering in a given time frame; 3) the design of the airflow path in and out of the device.

The lack of a holistic approach thus minimizes the importance of considering the context of use of these products at the design stage. Confirming this, the devices currently available on the market are mainly designed to be stationary and are also rather bulky, which limits the operation of the purifier, in terms of coverage, to a circumscribed portion of the indoor space. Alternatively, smaller, easily transportable solutions can be found, but these generate other problems, since they have an even smaller coverage than fixed devices, with a very limited range.

As a result, the user is forced to continually move the device or purchase multiple devices with a burden in terms of economics and maintenance.

Critical issues have emerged from the empathize phase regarding the interaction aspect with the device, mainly concerning the control interface and remote management.

In an increasingly technological world, one of the most significant trends today is the Internet of Things (IoT), a network made up of objects that can collect data about their surroundings and communicate with other objects or the user. These Smart Objects (SO) are technological devices that can understand and interact with the environment by acquiring data and producing output, such as a task or interaction (Puntoni et al., 2021). They are also technological devices that differ from more traditional technologies in their ability to exercise autonomy, authority, and agency (Novak et al., 2019).

The latest generation of air purification devices can be considered Smart Objects, as they are generally conceived and designed to connect and share data with third-party devices such as home assistants or smartphones for the purpose of facilitating user management. The devices themselves are capable of processing air quality data, translating it into information for the inhabitant.

Although SO are extremely useful in improving quality of life, including in relation to inhabiting one's indoor space, it is evident that senior users tend to use technologies less than other social groups, leaving a digital divide emerging between older and younger generations (Anderson et al., 2017).

Research has identified the different barriers to technology adoption by senior users, such as: i) physical or cognitive difficulties, ii) lack of knowledge (LeRouge et al., 2013); iii) scepticism toward technology (Bianchi, 2021); and iv) viewing technology as a threat to one's identity (C. Li et al., 2020).

Aplu has directed the design toward the idea of a purifier intended as SO, taking into consideration the barriers described above and thus, as Mostaghel argues, the need to solve the challenges faced by the elderly related to the effort of learning to use technology (Mostaghel, 2016).

RESULTS AND DISCUSSIONS

Air Purification in Aplu

Aplu is the result of the transition from a static device to an independent robot in the management of its functions. This transition has been defined by reflecting on the concept of "movement" by exploiting the integration of advanced technologies, linked to the field of robotics and the Internet of Things. The result has led to the development of an air purifying robot (ion generator) which also has the function of a vacuum cleaner; a robot able to move independently inside the house, going to cover the entire indoor space in its air purification and surface cleaning activities thanks to the detection capabilities of specific sensors.

The integrated mechanism, that combines the functionality of a robot vacuum cleaner with an ion generator air purifier, results in three distinct working modes of Aplu. The main mode, called "hybrid", is determined by the simultaneous operation of the two functions: the air aspirated from the lower surface passes through a filter placed at the end of a small tank for collecting dust, then the sucked air flow is "ionized" and exited through a ring opening located on the top surface of the device. The other two modes offer an alternative to the main hybrid solution in order to better manage the various circumstances of use of the product and reduce consumption to a minimum. In fact, it is possible that situations may arise in which it is not necessary for the product to work by exploiting both functions simultaneously, but by activating only one of the two autonomously.

A Tangible Robot for Intangible Information

To design the product-user interaction has been essential to understand how people tend to approach the use of an SO. Some research, in this sense, has focused on the analysis of "consumption journeys" (Cho et al., 2019), highlighting how in the early stages of possession, users are committed to experimenting with the innovative functions of the devices, while in the medium to long-term, enthusiasm and utilization may decrease

Figure 1: Design solution: aesthetics and schematization of the functioning of Aplu.

(Lopatovska et al., 2019). This happens for the most disparate reasons, related to the loss of interest, frustration or change in habits induced by the device (Cho et al., 2019), or because the initial phase of use is often characterized by an "experimentation" where users challenge the personality, knowledge, and intellect of SO (Sciuto et al., 2018).

It has been essential also to consider the emotional-relational aspect of the user. In fact, some research shows how the interaction between SO and users is more similar to the human one than to the traditional one between user and technology. This is because the exchange of information places the two interlocutors almost on the same level thanks to an increasingly less centralized interaction on a single device (Volpentesta, 2015) and to the sharing of the same communication languages (O'Leary et al., 2017).

The project has been developed to minimize the need for "forced" user interaction with the device, aiming to lead the latter towards a "natural" interaction by transforming the episodic use of the product in an integrated use in the daily life of users (Porcheron et al., 2018). This intention has taken its form in the following choices: i) to develop ad hoc sensors and connectivity with other SO that allow Aplu to be autonomous not only in movement, but also in programming and communicating movements to the user; ii) to design a clear and immediate interface that allows the user to control the "work" of the device, facilitating the reading of the information; iii) to develop a software for configuration and remote control of the Aplu work.

- *Direct interaction between product and user*) The design of direct interaction has highlighted the need to make the "invisible" problem of indoor pollution "tangible", making the user perceive the actual work and usefulness of Aplu. The result of the interface has derived from iterative usability tests, with a small number of users (3 elderly people; 1 caregiver; 2 expert designers). The interface has been conceived as a means of active, simple, and continuous communication. The choice of the position of the interaction display has proved to be crucial in the design of the direct product-user relationship and has made it possible to give the mobile device, that moves independently around the house, an even more "human" attitude. The display is in fact facing upwards, placed in the upper part of the device, framed by the empty ring space that allows the purified air to escape. This position allows an extremely natural and immediate interaction that permits the user to "simply look down".

Finally, the design of the interface, on a circular surface, allows a centralized and hierarchical organization of the information to be transmitted to the user, facilitating the reading of the data. At the centre, the value of the IAQ provides the user with immediate feedback on the quality of the device's work, around it, some icons summarize the essential information regarding the battery status and work settings. Finally, on the circumference of the display, a luminous ring indicates the remaining working time, calculated in real time by Aplu's intelligence using the data collected by the sensors and the data shared by any other connected devices.

- *Remote control as an opportunity for assistance and training)* The multiple functions of the SO push designers to dedicate part of the planning to the

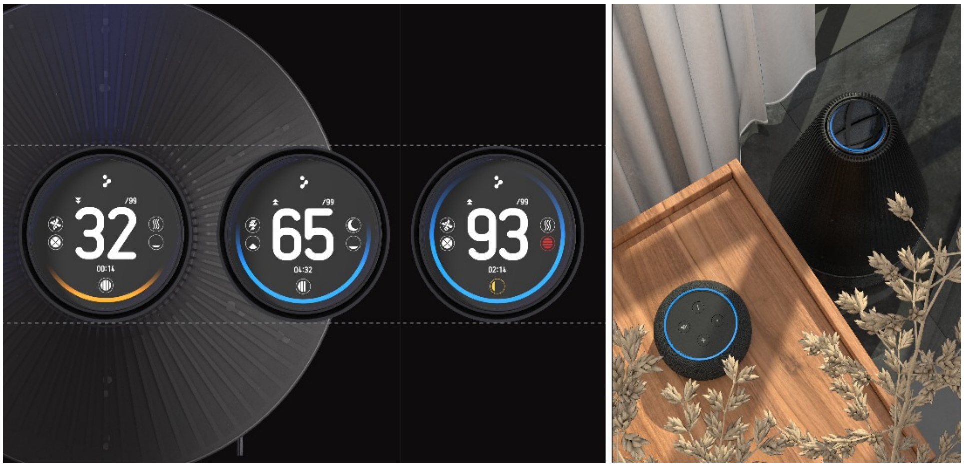

Figure 2: Design solution: Aplu's interface and interaction with other SO.

development of specific software which, in the complexity of a home automation system, allows the user to manage and configure his own product, especially during the purchase phase. This phase of the design process has provided food for thought regarding the issue of user assistance and training. Bypassing the configuration phase, the development of software for the management of Aplu has become an occasion for "designing" user training. The information system developed by Aplu tries to provide knowledge that helps the inhabitant of the indoor space to improve personally, filling the need for "healthcare", highlighted by current social trends (Coop R., 2021). This translates into a software that assists the user by providing him with information on the management of the natural ventilation of his indoor space, and information on how to remove pollutants detected and on their origin. The software also sends daily or weekly reports on the IAQ trend of the indoor space and provides information on the type of pollutants detected.

The data are a further step in the development of a "human" interaction and make the robot "friendly", "paternal", like a guardian of the house who wants to protect its inhabitants by instructing them in the exercise of new habits aimed at correcting wrong behaviours.

Remote control also turns out to be a valuable support tool for older categories of users and provides the possibility of alleviating the workload of any caregivers (Sheldon, 2020), whether they are provided by healthcare personnel or belonging to the family unit. The software provides remote access to useful resources for remote monitoring, control of air quality data and assistance in using it, confirming the fundamental role that the family unit and qualified persons have in enabling senior users to adopt and learn to use SO devices (Mostaghel, 2016).

CONCLUSION

The research project here presented has been conducted with a design thinking approach, which led to the identification of technological opportunities, latent needs of users in a "for all" perspective, allowing the development of a pilot project to test the validity of targeted solutions to elderly users. Some usability tests have been conducted on a small number of users, to validate solutions regarding to the interface and the acceptability of the advanced technological solution with autonomous intelligence. The project has achieved a TRL4 laboratory validation. The product provides information on the requirements and technical characteristics that can be achieved by integrating advanced technologies (IoT and robotics) to a purifier to make it inclusive and performing even for aged users. It constitutes valid basic research for the development of a higher TRL project, necessary in the future to test the validity of the solution also in operational contexts.

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