Design and development of an IoT system for audiovisual self-administered tests

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Abstract
Technological advancements, such as those brought by the IoT should be adopted as supporting tools in the definition of a new society that places humans at its center, and that balances economic advancement with the resolution of social problems. Being the human at the center of this new society, we strongly believe that health sector is one of the main sector that can profit from technological advancement. The possibility to rely on technology can support humans in taking care of their own health directly at home.

In this paper we report on a project we conducted within the UNICAM OMiLAB node in which we make use of tools coming from the OMiLAB community to conceptualize a scenario that involves people and smart devices. Then we report on the design and implementation of an IoT system that allows a user to self-administer audiovisual tests. Such tests can be performed directly within the comfort of the user's home with the support of low budget IoT devices.

Our objective with this system is to contribute in providing support to help people improve self-awareness on their health conditions, fostering early detection of possible illnesses and suggesting doctor visits only when they are really needed.

Keywords
OMiLAB, Conceptual Modelling, Internet of Things, Healthcare, Audiovisual tests

1. Introduction

The *Society 5.0 vision*[1] was presented in the Japan 5th Science and Technology Basic Plan as a future society that Japan should aspire to. It aims at creating a human-centric society [1]. A society that makes use of technological advancements (e.g., big data, artificial intelligence, robots, and IoT) to solve people's problems, bringing humans back into a central position. The intention of pursuing a new society is also shared by the United Nation organization with the adoption of seventeen *sustainable development goals*[2] proposed in 2015 as Agenda 2030 - a

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[1]Society 5.0: https://www8.cao.go.jp/cstp/english/society5_0/index.html
[2]United Nations sustainable development goals: https://sdgs.un.org/

call for action by all countries — poor, rich and middle-income — to promote prosperity while protecting the planet. Also, the European Union is pushing forward a change in society that is mainly linked to the term *Industry 5.0*[3]. For making industry become the provider of true prosperity, its true purpose must include social, environmental and societal considerations [2].

Among all the fields, we believe that ***healthcare*** could benefit more than others from technological advancements to improve human well-being. For instance, enabling a comfortable living of people by means of IoT devices to provide living support and conversation partners, promoting healthy living and early detection of illnesses through self-administered and automatic health checkups, and using robots to ease the on-site burden of healthcare and caregiving.

Driven by the push towards the development of a new society that makes use of technological advancements (e.g., big data, artificial intelligence, robots, and IoT) to solve people's problems, bringing humans back into a central position, a group of professors, researchers and students of the Computer Science Department at the University of Camerino gathered together, within the ***OMiLAB@UNICAM***[4] node, to conceptualize and develop an IoT system that could support users in self-administering audiovisual tests taking care of their own health directly at home. The OMiLAB@UNICAM node aims at fostering collaboration in the sector of model driven engineering and IoT favouring the development and the put in practice of model driven engineering approaches. The **idea** behind our contribution was born during the Covid-19 pandemic (2020-2023). During that period, we experienced different restrictions that limited people's possibilities to travel and to stay in contact with others. In similar scenarios, IoT systems can be useful to support human activities that normally require people to reach crowded places such as doctors' waiting rooms or hospitals.

To contribute helping people to improve self-awareness about their health conditions, fostering early detection of possible illnesses and suggesting doctor visits only when they are really needed, we report in this paper the design and development of an IoT system for performing ***self-administered tests*** of audio and visual perception. We first applied design thinking to the design of the system, then relied on a combination of open-source software and IoT devices to develop a prototypical implementation.

The paper is organized as follows. Section 2 describes a selection of IoT self-administered tests that we implemented in our solution. Section 3 reports the conceptualized scenario. Section 4 describes the IoT system architecture and the acuity test workflow that we conceptualized. Section 5 reports on the implementation of the IoT system. Section 6 reports a selection of related works. Section 7 concludes reporting on current state of development and future work.

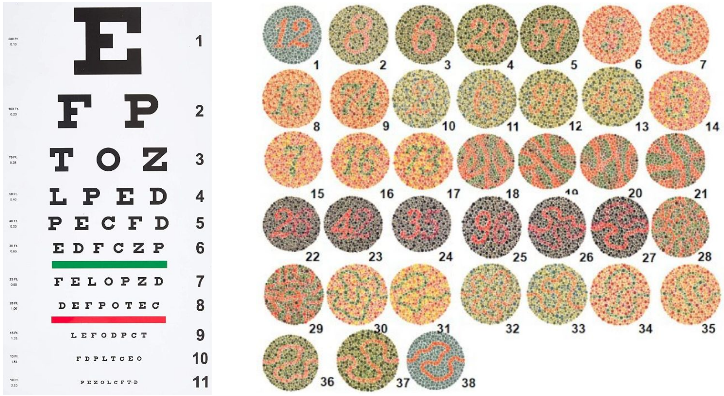
2. Considered self-administered tests

In this section we report a selection of self-administered tests that we implemented in our solution.

Visual tests. Referring to visual tests, we focused on acuity and color blindness tests. With the term *acuity*, we refer to the ability of the human eye to identify and perceive the smallest

[3]https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en

[4]https://www.omilab.org/omilab_nodes/unicam/



(a) (b)

Figure 1: (a) Snellen chart, (b) Ishihara plates.

details of an object at a certain distance as a consequence of the level of image sharpness projected on the retina.

Scientifically, visual acuity is the measurement of the minimum angle under which they must be seen two separate points. Visual acuity therefore indicates the capacity of the eyes to distinguish two neighboring points as separate and distinct. Visual acuity is normally measured in tenths and an acuity test is conducted by asking a patient to read the lines of a Snellen chart[5], that is a chart present in every eye clinic with printed letters of different sizes, see Fig 1 (a). The test is carried out by covering one eye at a time and reading the lines with letters or symbols of decreasing size. If the patient is able to read the letters from a proper distance, his visual acuity will be 10/10 tenths; otherwise, with a lower value, the user might need an optical correction.

With the term *color blindness* we refer to a condition where a person has a reduced ability to distinguish between colors compared to the standard for normal human color vision. To carry out the color blindness test, the Ishihara test[6] is used, which consists of a series of plates composed of images formed by circles of different color but same brightness; the person examined must recognize numbers, or paths that are evident to those who own a normal sense of color but difficult or impossible to recognize for those who cannot see well colors. These plates are useful for diagnosing congenital defects of vision colors especially for the red/green axis. The exam takes place by asking a patient to read the number on the plate or by requesting to follow the path visible in it with a finger. The complete test consists of thirty-eight plates, where the first twenty-five contain numbers and the others contain a path to follow. In our case we only consider the first twenty-five plates. From the obtained answers, it is possible to assess whether the subject has red/green axis disturbances.

Audiometric test. An audiometric test is used to assess a person's hearing ability. The tonal audiometric examination consists of determining the hearing threshold for several volumes of pure sounds within the limits of audible sounds. The person being tested is asked to raise their hand or point with a *yes* when perceiving the sound. Perform the audiometric test, which

[5] Snellen chart is named after Hermann Snellen, a 19th-century Dutch doctor

[6] Ishihara test named after Dr. Shinobu Ishihara professor at the University of Tokyo.

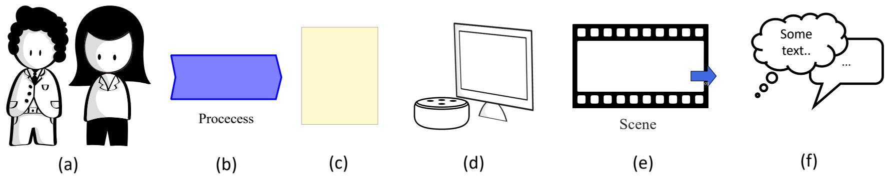


Figure 2: Storyboard objects: (a) people, (b) process related to the story, (c) note, (d) technological devices, (e) scene, (f) thought and talk.

means searching for the minimum intensity of pure tones for each frequency perceived by the subject and comparing it to standard thresholds. As a convention, the *Zero decibel* has been defined as the faintest sound that a person with *Normal* hearing ability can hear; audiologists consider a level between zero and fifteen decibels as a *normal* hearing threshold in children and between zero and twenty-five for adults [3].

For a matter of space, we will only refer to the visual acuity test while illustrating our contribution. A similar approach and implementation have been adopted for the other tests.

3. Scenario conceptualization

In this section we report the conceptualization of the scenario we considered in the design of our IoT system. We adopted a Conceptual Modeling approach, an established methodology for capturing, representing, and exchanging knowledge. In our case, we used the Scene2Model tool[7] [4, 5] that allows, by means of graphical elements and storyboards (see Fig. 2) to model and reason about a scenario that involves actors, objects, and processes. A storyboard consists of a series of scenes that represent the key moments of a story. Each scene is represented by the involved people, the objects they interact with the speeches and the thoughts that induce people to interact with the system. Processes emphasize the activities carried out, adding specialized knowledge to the scenes.

We used Scene2Model to design the scenario that emerged from an interactive session within the *OMILAB@UNICAM* node. We report in Fig. 3 the storyboard related to a possible self-administered acuity test conducted by a person suspected of having vision problems.

The story begins in *Scene 01* with Liza and Mike talking about an appointment marked on the calendar. Mike gets the day wrong by confusing the numbers on the calendar, and Liza points out that perhaps a vision check might be useful. *Scene 02* illustrates how Mike uses the system to select and start the acuity test. We imagined that Mike interacts with a home assistant using a natural voice to request the execution of the test. He receives instructions on how to perform the test and obtains the results at the end. The scene also includes a link to the acuity test process that we describe in Section 4. *Scene 03* illustrates the interaction between Mike and the system. The home assistant guides Mike in reading the Snellen chart displayed on A smart TV connected to the system. *Scene 04* illustrates the home assistant communicating the test's result. Mike is suggested to contact a doctor.

[7] Scene2Model: https://www.omilab.org/activities/scene2model/

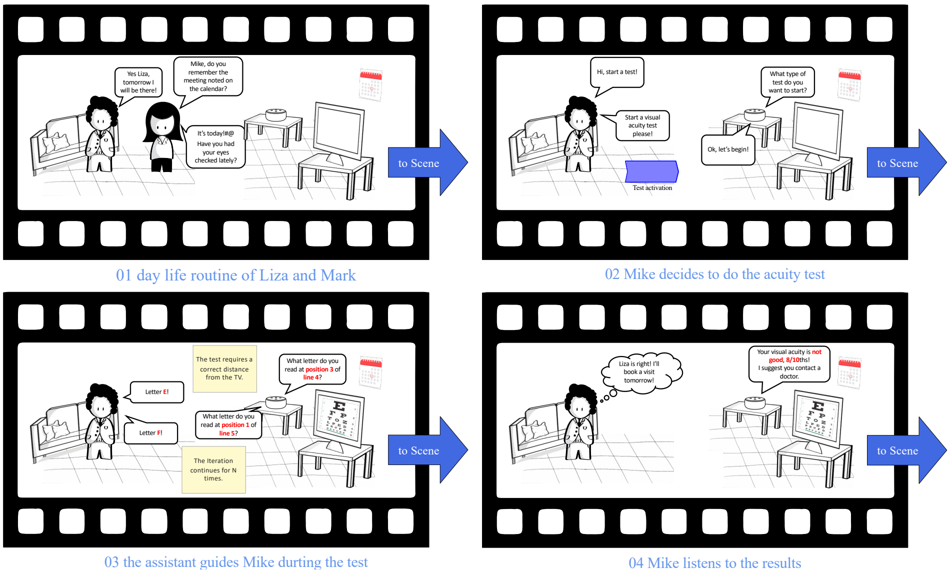


Figure 3: Storyboard of a user interacting with an IoT system for the self-administration of a visual acuity test

4. IoT system and acuity test design

In this section we describe the conceptualization of the IoT system and the detailed description of the acuity test according to the storyboard.

After some interactive sessions we conceptualized a possible ***IoT System Architecture*** that could support the scenario illustrated in Fig. 3. We focused on the design of a system that could allow tests to be executed at home directly in a living environment, leveraging the technological objects that people normally use in their lives. A schema of the IoT system along with the related components involved in the tests execution is reported in Fig. 4.

The core component of the IoT system is the *Test Controller*. The Test Controller implements the execution logic, data collection, results calculation, and communication with the other devices. A *home assistant* handles the interaction with the user by means of vocal commands. The home assistant receives commands and forwards requests to the Test Controller which elaborates them. By means of the home assistant, the Test Controller is able to respond to user commands, providing instructions about how to execute a test, acquire data during the execution, and communicate the final results when the test is over. To display visual information to the user, the Test Controller communicates with a local *smart TV*. In this way the Test Controller is able to provide all the necessary information for the execution of the test, such as displaying the Snellen chart, guiding the user in reading images during the color blindness test, etc. A mobile app is also introduced to communicate configuration details (e.g., user credentials, connection endpoint addresses, etc.) to the Test Controller in order to correctly define the test environment.

In Fig. 5 we report the ***acuity test workflow*** we conceptualized to describe the details of the storyboard we presented. We adopted the BPMN notation[8] which is a recognized standard for

[8]BPMN: https://www.bpmn.org/

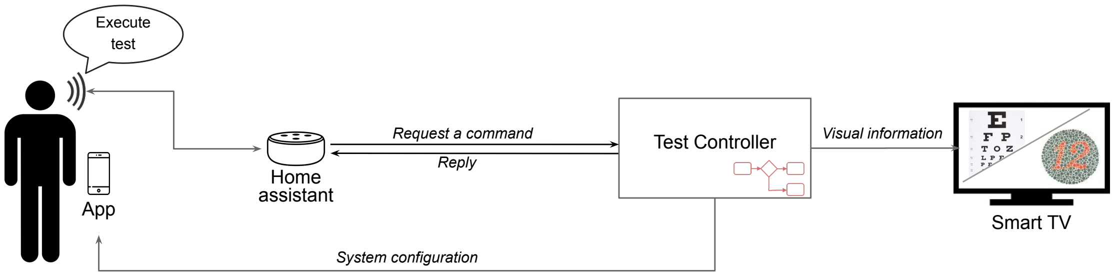


Figure 4: Schematized IoT System.

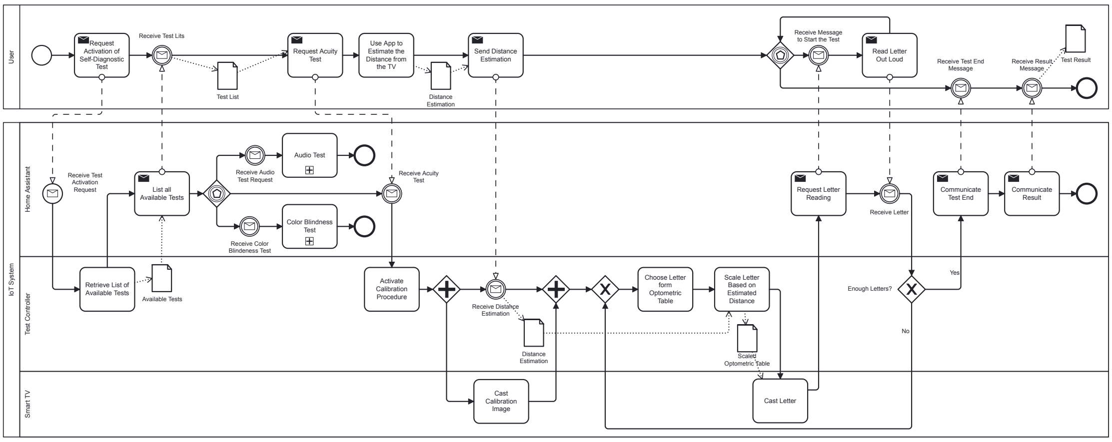


Figure 5: The acuity test workflow represented using the BPMN notation

the modelling and visualization of activity workflows and is often used to model IoT related scenarios [6, 7, 8].

A test is activated by a user who requests the home assistant to activate a self-administered test. The Test Controller retrieves the list of available tests and the home assistant communicates them to the user. The user then picks one of the tests, which in this case is the acuity test, and request it out loud. When the Test Controller receives the estimated distance from the TV and the user through the mobile app, it select a letter from the Snellen chart, scales it based on the estimated distance and casts the letter on the smart TV. The home assistant asks the user to read the letter. This part of the workflow is repeated until enough letters to provide a results are red. Then the results are communicated to the user. After the test finishes it will be the user's responsability to evaluate the results and establish whether or not to schedule an appointment with a doctor.

5. IoT system and acuity test implementation

In this section, we describe the implementation of the system depicted in Fig. 4. The acuity test described in Fig. 5 can be executed by this system. A demonstration of the IoT system with all implemented tests is available on the PROcesses and Services Laboratory YouTube channel https://youtu.be/Kzz_fKOzcG4.

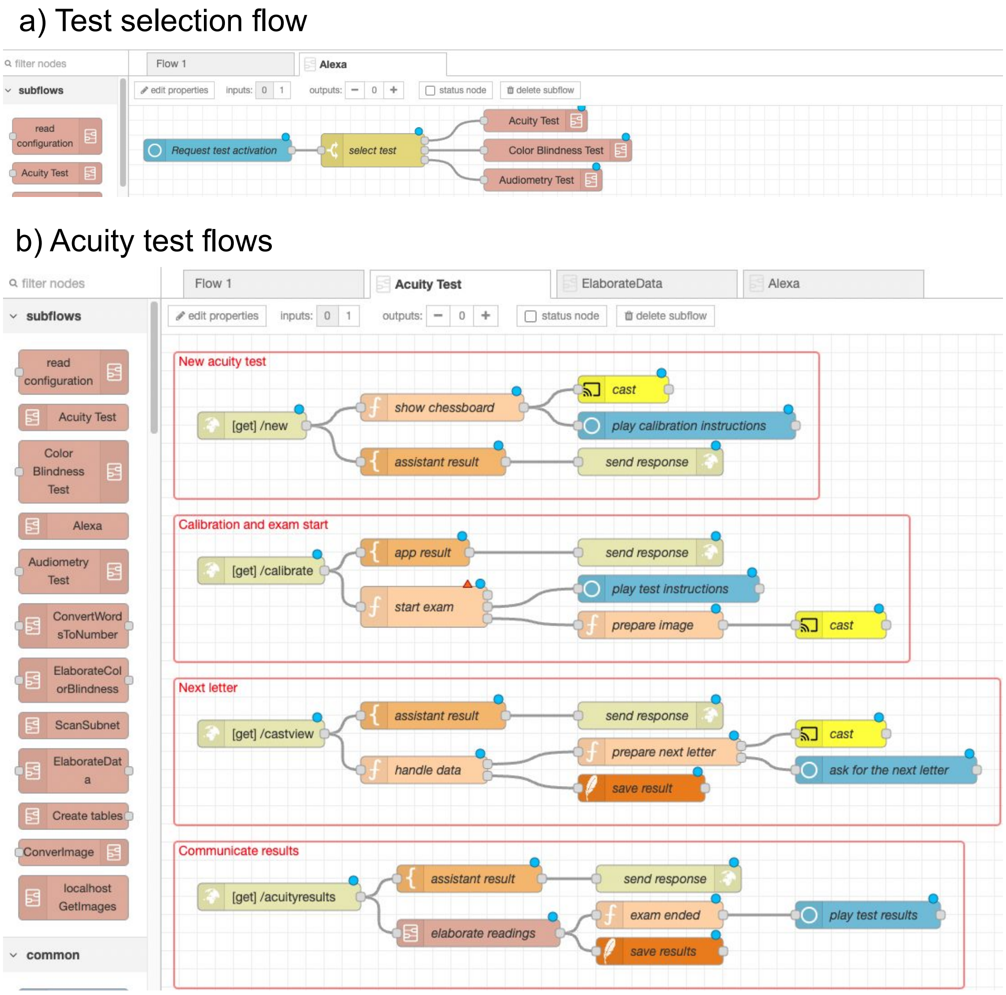


Figure 6: Node-RED implementation of test selection and acuity test.

For implementing ***the home assistant*** we relied on Amazon Alexa[9], a virtual assistant capable of interpreting natural language (STT - Speech To Text and TTS - Text To Speech) and of conversing with people. Alexa can perform a number of preset functions or custom functions a user can develop using *Alexa Skills Kit*[10]. We used Alexa to develop three skills, one for each supported test: acuity test, color blindness test and audiometric test.

For implementing ***the Test Controller*** we used Node-RED[11], a well-known low-code open-source development environment for the definition and execution of IoT applications [9]. The execution logic is expressed using *flows*. Each flow consists of a set of chained nodes that allow

[9]Alexa: https://www.alexa.com/
[10]Alexa Skills Kit: https://developer.amazon.com/alexa/alexa-skills-kit
[11]Node-RED: https://nodered.org/

users to connect to external systems, expose custom REST APIs to receive incoming data and requests, and apply computation to IoT data. A set of additional *nodes* can be installed to extend the basic functionalities of the tool.

In Fig. 6 we report an excerpt of the flows we implemented. The flow in part a) of Fig. 6 starts when the user asks Alexa for a test execution. The flow receives as input the speech-to-text translation of Alexa used to select the correct sub-flow of the test to execute.

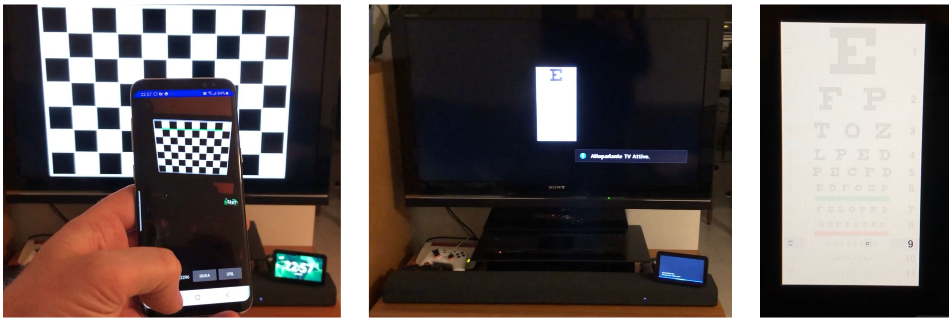
Part b) of Fig. 6 reports the flows that implement the acuity test, according to the model we described in Section 4. The first flow reports the REST API invoked by Alexa to start a test. Upon the request, the *show chessboard* node prepares the image of the chessboard to send to the smart TV through the *cast* node. The *play instructions* node will request Alexa to play the calibration instructions. *Assistant result* and *send response* are the nodes used to generate the HTTP response of the REST API. The second flow describes the REST API used by the app to transmit calibration data, necessary to calculate the user's distance from the smart TV. The *prepare image* node uses the estimated distance to scale the image correctly based on the smart TV dimension. Finally, the scaled images are sent to the smart TV through the *cast* node. The third flow reports the test execution of the user's letter reading. In each iteration, Alexa invokes the REST API to send the just-read letter that will be saved in a database with the *save result* node. The node *prepare next letter* scales the next letter image to send to the smart TV through the *cast* node. The node *ask for the next letter* requests Alexa to ask the user for the next letter. The fourth flow reports the conclusion of the test. When Alexa invokes the REST API, the *elaborate readings* node analyzes all the readings. The final score is calculated based on the correct readings recognized during the test. Alexa then communicates the results to the user.

We implemented an Android ***app*** that provides users with the possibility, by using a smartphone, to configure the IoT system, which includes authenticating on Alexa, configuring the Node-RED server IP, connecting to the same WiFi network as the smart TV, etc. The app also has the role of calibrating the distance between the device and the smart TV before any image can be displayed. To estimate such a distance, the app integrates the OpenCV computer vision library (opencv.org). In particular, we applied Equation 1 [10]:

$$Distance(mm) = \frac{f(mm) \times real\_object_{height}(mm) \times image_{height}(px)}{object_{height} \times sensor_{height}} \tag{1}$$

Where $Distance$ is the distance between the camera and object, f is the focal length of camera, $real\_object_{height}$ is the real object height, $image_{height}$ is the image pixel's height, $object_{height}$ is the object height detected with OpenCV, $sensor_{height}$ is the vertical resolution of the camera sensor.

While the device camera information (focal length, sensor resolution) are available through the OpenCV APIs, a calibration process is required to map the real object size to the image size acquired through the camera. The solution we used relies on the chessboard pattern [11]. By displaying a black and white checkerboard of known size on the screen like the one in Fig. 7-(a), it is possible to calculate the spatial points' positions between two pairs of squares, correlating them to the image's coordinates. OpenCV implements the chessboard pattern and enables the recognition of these spatial points to reconstruct the chessboard's dimensions. Knowing the screen dimension, it is possible to calculate the distance formula. The app will send the computed value to Node-RED in order to correctly scale the images as shown in Fig. 7-(b) and 7-(c).



(a) (b) (c)

Figure 7: (a) distance calibration, (b) and (c) examples of the acuity test execution.

6. Related work

Healthcare is one of the application domains in which IoT technology is extensively being adopted. Sensors and IoT-enabled medical devices transmit data to healthcare specialists without the need for human intervention [12].

IoT systems have been used to enable the monitoring of patients and communication with doctors. In [13] the authors propose an IoT-based device for monitoring human vital signs. They present a solution to communicate between networked devices wirelessly, which would help the patient get better treatment or better consultation from the doctor without physically consulting it. In [14] recent research on IoT-based health monitoring systems have been reviewed in a systematic way. The paper provides in-depth information on their benefits. IoT wearable things in healthcare are also considered providing a classification of health-monitoring sensors, including the challenges and open issues regarding security and privacy and Quality of Service (QoS). In [15] authors provide a review of various IoT architectures, different methods of data processing, and computing paradigms. A comparative analysis of wearable technology in healthcare is also discussed. The review also analyses the problems faced by IoT-assisted wearable sensor systems and the optimization issues to consider in healthcare.

IoT is also used to provide healthcare support at home, especially in the delivery of health and social care services for the elderly [16]. Several projects, like the one in [17, 18, 19] attempt to integrate home automation, telemedicine solutions, and smart objects in the same house. This, to enable smart monitoring services that allow recognizing humans health conditions by monitoring vital signs and humans performed activities [20, 21, 22] while also providing support for facilitating activities of daily living. However, most of the time dedicated hardware is required that is not commonly available.

Approaches that focus on providing support to users for conducting self-administered tests are also present. In [23] smartphone-based acuity tests has been proposed. The solution relies on a smartphone device and requires a specific application. However, its effectiveness varies based on the smartphone device. In [24] authors propose a fully automatic and computerized self-vision-screening system. However this requires specific equipment for the test execution.

The role of AI is being actively investigated by researchers, particularly in understanding how AI can be leveraged by healthcare systems to reduce costs and minimize unnecessary medical visits. In [25] authors provide a review to map the literature surrounding the use of artificially intelligent self-diagnosing platforms that use computerized algorithms to provide users with a list of potential diagnoses. Especially the use of chatbots is currently investigated [26].

We distinguish from the previously reported literature as follows. In our work, the proposed IoT system aims to replicate the tests conducted in a doctor's lab. Our solution does not require specialized devices. This allows the solution to be widely used in real-life applications. In our solution, we do not exclusively target elderly people, as is often the case in other works. The proposed IoT system aims to facilitate human-computer interaction by relying on a voice-user interface. The solution we propose is intrinsically scalable and adaptable to other types of use cases. The low-code approach allows for easy definition and addition of new types of tests, with the possibility of also integrating other IoT devices.

7. Conclusion and future work

In this work, we presented an IoT system developed within the OMiLAB@UNICAM node of the University of Camerino for conducting self-administered tests for vision issues (acuity and color blindness) and for hearing problems. The system leverages devices commonly available in modern daily living environments, namely a home assistant (Alexa in our implementation), a smart TV, and an Android smartphone. We also defined a dedicated Test Controller that implements the test execution logic using a low-code programming approach, by means of the Node-RED tool. The solution is highly compatible with standard home-edge devices like the Raspberry PI. With respect to test validation, we conducted proof of concepts experiments and we envision to conduct a proper validation with the involvement of specialized doctors. The developed code is available on GitHub at https://github.com/PROSLab/SelfTest-atHome.

As future work we want to investigate the adoption of model driven engineering approaches that leverage the role of models which after refinement operations can be used to derive actual software applications. For instance, in our case, the development of the Node-RED flows could be automatized by following approaches that allow after modelling the IoT system to automatically generate Node-RED flows [27, 28]. We also intend to explore interoperability between ADOxx and Node-Red by using existing tools such as Bee-Up[12]. This would further accelerate the development of new test scenarios.

We envision additional self-administered visual tests such as the Amsler test, used to evaluate central vision and the contrast test to determine the sensitivity to contrast. With the addition of other IoT devices such as a smartwatch, we could extend the kind and amount of test. We could track people parameters while sleeping in such a way to evaluate their quality of sleep and possibly identify sleep disorders such as obstructive sleep apnea. We can also envison the integration of specific smart medical devices such as smart glucose meter for daily monitoring blood sugar level.

[12]Bee-Up: https://bee-up.omilab.org/

To make the system distributable, we envision the possibility to "pre-package" the entire system and install it on a Raspberry Pi to distribute. We are also inspecting the possibility of moving the entire application logic from an external Raspberry Pi to the user's smartphone, which could take place by developing custom applications or by installing Node-RED directly on the Android device.

We are exploring the Digital Twin concept [29] as a further step to create a digital replica of people and the room where they conduct the tests using a dedicated digital twin platform [30]. This could help doctors better monitor the conditions of the people remotely, support simulation features of the living environment to guide potential home rehabilitation activities, and much more.

A more comprehensive evaluation of the system will be carried out within the VITALITY project[13], a research initiative funded by the National Recovery and Resilience Plan (PNRR), in which the University of Camerino is leading activities focused on the innovation and safety of living environments and personal well-being in the digital transition era. The evaluation will involve participants using the system in real living environments, providing valuable feedback on its effectiveness. This will also allow us to assess the application of the conceptual modelling approach to define new services in emergency management scenarios [31].

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