Received June 25, 2020, accepted July 9, 2020, date of publication July 15, 2020, date of current version August 10, 2020.
Digital Object Identifier 10.1109/ACCESS.2020.3009167

Integration of the Mobile Robot and Internet of Things to Monitor Older People

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This work was supported in part by FCT/MCTES through national funds and when applicable co-funded EU funds under the Project UIDB/EEA/50008/2020; in part by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Finance Code 001; and in part by the Brazilian National Council for Scientific and Technological Development (CNPq) under Grant 309335/2017-5 and Grant 305805/2017-7.

ABSTRACT This study proposes to develop, build and implement the IoT of the mobile network robot integrated with features of mapping and location in an internal environment, to trace the best route and obtain a fast and efficient change to detect changes in the environment as an identifier of falls in the elderly. It is observed that it is applied research to aggregate several available algorithms. The robot was provided with internal mapping and location capabilities to map the best route and achieve fast and active movements in a retirement home for the elderly. The mobile robot was also set up to monitor and assist in the transport of medicines and notify the caregiver of any incident with the elderly within its environment. A mobile app controls system and robot development. The main phases are highlighted: definition and acquisition of the model and the components used (mechanical structure, microcontroller, sensors and actuators); application development of user-system interaction; development and construction of a robot, auxiliary modules (environment) and central module; and integration experiments. Monitoring and mapping of the environment are performed using Wall-Following, Simultaneous Location and Mapping (SLAM) and Sensor Fusion techniques. The precise movements of the robot are assured through a combination of navigation and control techniques. Moreover, the robot received internal mapping and location, resources to map the best route and obtain quick and active movements in Institutions of Long Stay for the Elderly (L.T.C.F.). Besides, the performance of the following algorithms was analyzed and compared: Breadth-First Search (B.F.S.), Depth First Search (D.F.S.), and Wall-Following. The B.F.S. algorithm obtained the best results for the minimum path.

INDEX TERMS Mobile robot, breadth-first search, Internet of Things, simultaneous localization and mapping, wall-following, elderly.

I. INTRODUCTION

Knowledge of the environment without human interference is one of the essential skills of an autonomous robot. This autonomy gives the robot the ability, in whole or in part, to make decisions based on the local map, built by the robot, through its navigation techniques for transport, cleaning, searching, retrieving, locating and monitoring activities. On the other hand, the ageing process includes several biological, psychological, social and cultural factors. Such a physiological condition corroborates a loss of functional reserve, due to the neuromuscular impairment that affects the loss of muscle, bone and postural balance to people with advanced age. These situations favour the incidence of falls, which is also

The associate editor coordinating the review of this manuscript and approving it for publication was Victor Hugo Albuquerque.

affected by the presence of chronic diseases, visual and auditory deficits, polypharmaceuticals and, as the leading cause, as accidents related to the physical environment [1], [37]. The loss of the elderly can affect the loss of autonomy and the ability to perform instrumental activities of daily living, caused by fractures, immobility and psychological disorder, in the face of fear of falling again and risk of death [2]. As Long-Term Care Institutions for the Elderly (L.T.C.F.) have a higher incidence of falls than the elderly who fall in the community, they send their institutionalization in favour of an accident, as the elderly changes their family environment to an L.T.C.F. or that affects their own social and reduction in physical activity [3]. Among the main reasons were imbalance, as a factor associated with ageing and slip associated with the environmental factor [4], [6]. Although the institutions have trained professionals to monitor the elderly and assistants in their food activities, there is still some difficulty in monitoring and avoiding how much risk there is. Therefore, single monitoring is recommended for the implementation of strategies, through an autonomous system of support to the caregiver, which understands the activities of the elderly and decides which services are offered in different situations and when to notify or deal with any incident in the service health, an end to control quickly and effectively as consequences of the fall and prevention or decline of post-fall functionality [1], [7]. In the context of this research, prominent applications for the elderly were presented the novel non-invasive monitoring system for fall detection in older people who live alone [38] and the design of a low-cost device that automatically detects micturition events [39].

Thus, the autonomous navigation ability of the robot is controlled by a variety of processes that develop models of the environment, based on the position of the robot in an unknown location. Therefore, the model must be able to apply practical navigation logic. Due to the conditions of an external environment, which would require purchasing costly sensors and actuators, it was decided to implement the robot indoors. The contribution of this research is linked to a control system capable of monitoring indoor environments and carrying out a path planning in real-time, with position control of mobile robot surveillance, as well as the environment mapping simultaneously, in order to identify a fall incident at an L.T.C.F. early. The adaptive Augmented Extended Kalman Filter (A.E.K.F.) algorithm has been proposed [8] to solve the accumulation of errors in the process of locating autonomous mobile robots indoors. Convergence and complexity are analyzed, and the experiments carried out proved that the A.E.K.F. algorithm performed well regarding error accumulation.

Traditional short-path route planning algorithms, such as Dijkstra [9], [10], A* [11], [12], do not calculate the shortest path in a graph with negative weights. The goal of route planning is to achieve a collision-free way for mobile robot navigation that can move from a starting point to an end-point quickly and accurately, regardless of static or dynamic environments [13]. Among the minimum path algorithms that assist in performing navigation in the environment, are the Breadth-First Search (B.F.S.) [14], [15] and Depth-first search (D.F.S.) [16], [17]. Identification of the location based on the previous estimate is incremental, that is, measurement errors are accumulated along the route and this orientation capacity in the environment inserted is limited to land, wheeled or crawler mobile robots. Thus, to reduce such biases, some strategies are used, such as Inertial Measurement Units (IMUs), Global Positioning System (G.P.S.) and LASER Odometry [13], [18].

A remote-controlled mobile explorer robot has been tried and tested in [19]. The authors used a graphical user interface (web application), and the video provides real-time environmental measurements of the location where the mobile robot is; however, thanks to IoT technologies, it can also be controlled over the Internet.

Noteworthy is important advances in multimedia communication in health on the Internet watching algorithms structured Quality of Experience (QoE) optimization by managing the mobility of wireless channel between vehicles. [42], [43]. Moreover, [40] presents algorithms that allow video stream when applied to a smart city with the support of information and communication technology (I.C.T.), sensor enabled IoT devices. Also, the Forward Central Dynamic and Available Approach (F.C.D.A.A.) by adapting the running time of sensing and transmission processes in IoT-based portable devices are presented in [41].

New research proposes to develop, build and implement the integrated network mobile robot IoT with mapping and location capabilities in an indoor environment, in order to trace the best route and get a fast and efficient shifting to detect changes in the environment. The robot was provided with internal mapping and location [20], [21], capabilities to map the best route and achieve fast and active movements in a retirement home for the elderly. The mobile robot was also set up to monitor and assist in the transport of medicines and notify the caregiver of any incident with the elderly within its environment.

The remainder of this paper is structured as follows: Section 2 provides some theoretical foundation necessary to support the research. Moreover, section 3 presents the Proposal, Development and Topology related to the subject of this paper. Also, Section 4 describes the experiences of using the proposed approach in simulations and presents the results from the analyses, as well as the evaluations and limitations of the work. Finally, Section 5 presents the conclusions and suggestions for future works.

II. TOPICS RELATED TO MOBILE ROBOTICS AND THE INTERNET OF THINGS

The main topics needed to understand the proposal developed by integrating the IoT and mobile robotics applied to internal monitoring are listed and explained below. A mobile robot can be defined as a device composed of mechanical and electronic parts, equipped with sensors and actuators, and has an autonomous or semi-autonomous system for locomotion, whose activities are limited to the task or application for which it was developed [22]. Autonomous mobile robots interact with the environment through sensors that allow them to capture and process information to choose the corresponding action to be performed by activating actuators. The performance of their tasks within its environment depends on the perception and performance of its sensors, actuators and motors, as well as the robustness of intelligence [23]. Another critical feature to consider is the space in which the robot is inserted. Its functions will consider the environment, whose area does not need to be delimited and the position of the objects around it which can be observed, and which may be static, dynamic, or susceptible to change [22]. Mobile surveillance robots can collect images and making videos, indoors or outdoors, using navigation and control techniques, such as Wall-Following and P.I.D., which were also applied in this work [24].

A. INTERNET OF THINGS (IoT)

The Internet of Things (IoT), defined by Kevin Ashton in 1999, can be considered as an extension of the Internet of today and can provide communications between electronic equipment, sensors and actuators without the need for human intervention. The central idea of IoT is related to the diffuse presence of several devices with unique addresses interacting with each other. Initially, connect the computer network to remote controls connected devices, which then allows mobile phones, sensors, and others to be accessed as service providers [25]. Such possibility is still in the process of growth, since there are still restrictions regarding processing, memory, communication and energy, besides the divergence of implementation and resources [26].

In the development and research of IoT, relevant aspects in its construction should be respected, such as 1) Identification: responsible for identifying the equipment connected to the network, for example, N.F.C. (Near Field Communication) technology and I.P. address, which are capable of carrying out proper Identification; 2) data collection or system performance: through sensors capable of detecting changes in the environment, store or forward the information to a Data Warehouse (D.W.), clouds or a Database (B.D.). In this case, the actuators manipulate the environment, according to the data obtained; 3) Communication: a certain level of security and processing is required so that the Message Queuing Telemetry Transport (MQTT) protocol can be used; 4) Computation: which corresponds to the processing unit such as microcontrollers, processors, which are responsible for running local algorithms on objects; 5) Services: IoT enables various types of services, such as Identification, data reading, and actuator manipulation; [27].

Furthermore, MQTT Publisher / Subscriber is a message transport protocol that is designed to facilitate mobile development and seeks to minimize bandwidth and device requirements, ensure message reliability and delivery. This protocol uses an intermediary in the process of communication between the media, called a broker, responsible for managing the exchange of information between devices connected to the network. The connection between the broker and the client is made via a Transmission Control Protocol (TCP) [28].

B. CONTROLLER

The proportional Integral Derivative (P.I.D.) controller is capable of: keeping the robot at a desirable distance from the wall, according to the data from the Wall-Following technique; effectively responding to sudden changes in trajectory; correcting it when dodging obstacles and going through a specific place [24]. Git accurately controls numerous variables of a system, like making it stable, so that it can calculate the corrections for disturbances, noise or variations with potential to affect the system stability [29]. Equation 1 demonstrates the sum of the three control actions: Proportional, Integral and Derivative.

$$MV = K_P.E + K_i \int_0^t E.dt + K_d \frac{dE}{dt} \tag{1}$$

where:

- MV: Manipulated variable
- Kp: Proportional gain
- Ki: Full gain
- Kd: Derivative gain
- E: Error or deviation

The proportional action gave by Equation 2, and the elimination of variable oscillations do not guarantee the desired value (set-point) but make the system stable. This deviation is called off-set. System error correction occurs by multiplying it by the proportional gain [29].

$$\text{Proportional action} = K_p.E \tag{2}$$

Furthermore, the integral action given by Equation 3, allows the control variable to remain close to the desired value even after a disturbance. It integrates the error in time, so the longer the error remains, the higher the amplitude of the integral action is [29].

$$\text{Integral Action} = K_i \int_0^t E.dt \tag{3}$$

Finally, the derivative action given by Equation 4 gives the system an early action, prevents the deviation from becoming more significant in advance when a slow correction characterizes the process compared to the deviation speed and the response proportional to the process rate of change increases the system response speed if the error is present [29].

$$\text{Derivative action} = \mathrm{K_d} = K_d \frac{dE}{dt} \tag{4}$$

C. WALL-FOLLOWING

This technique consists of autonomous mobile robots navigating environments by tracking walls and are applied to the exploration and mapping of indoor environments. The technique enables the robot to locate and follow its trajectory by following walls and enables it to contour obstacles in the environment. Thus, it can navigate intuitively and return to its starting point. A physical model with the built-in wall-following technique could have ultrasonic sensors positioned on the side of the robot to detect the distance to the wall and make any corrections necessary for its movements in the environment [24]. On the other hand, wall-following reduces the two-dimensional navigation problem to a one-way navigation problem by adding a restriction of movement so that the reference is to maintain a certain distance from an indoor wall [30]. Also, wall-following control is a critical issue in mobile robotics, especially in situations such as path tracking and parallel parking. The ability to follow the wall is essential at three distinct times: mapping of unknown and unstable environments; obstacle avoidance and walls on planned routes; position estimation improvement. Wall-following based controllers have been built and designed using different approaches such as Filter of Kalman (K.F.), Extended Filter of Kalman (E.K.F.), fuzzy, neuro-fuzzy [31].

D. SLAM TECHNIQUE

Early SLAM models, in search of excellent location mapping accuracy, required markers based on variations of the Kalman Filter, such as the Extended Kalman Filter, which is applied in this research. Moreover, accurate detection of the environment is obtained, both in terms of structural features such as walls and doors as well as the presence of objects in the middle of such environments.

Positions and range data for mobile robots are often exploited for mapping. The information necessary for autonomous navigation include the following systems: the navigation system, responsible for performing the movements; the control, for performing actions and corrections related to its navigation; and the sensory system, whose purpose is to analyze the internal states of the system and the environment, according to the orientation and speed. Thus, such systems recognize structures and create maps, which are obtained by comparing interval data with the estimation of the position in which it is located [32], [33].

The technique to build a 2D map of the environment and estimate the position of a mobile robot simultaneously and interactively is called Simultaneous Localization and Mapping (SLAM). Grid maps represent the environment and are often used in SLAM [33]. In grid maps, each grid expresses the probability of the existence of objects in it compared to the reference-based maps.

E. DEPTH-FIRST SEARCH AND BREADTH-FIRST SEARCH

There are two ways to represent a graph G = (V, E) by adjacency lists or by adjacency matrices, applied to directed and non-directed graphs. Graphs are usually employed to solve short-distance problems between two points, such as finding routes between cities or moving around an obstacle in the environment [34]. The use of a minimum path bypassing obstacles is one of the route planning needs in autonomous mobile robots. Moreover, width and depth search algorithms are used to traverse and search a node in order to find out if it is reachable from one node to another. The application of Breadth-First Search (B.F.S.) and Depth-First Search (D.F.S.) stands out, noting that they have a computational complexity of less than other algorithms, in addition to allowing work with negative weights. The applications involved in the health area of the elderly require the use of negative weights. Furthermore, the B.F.S. algorithm is commonly used to search the shortest path in environments. The purpose of which is to traverse tree or graph structures and to explore through a root node or an arbitrary node adjacent node. Before advancing to an adjacent node. This algorithm runs on directed and non-directed graphs. The B.F.S. uses a matrix and the definition of the starting and ending nodes as the input parameters [35]. On the other hand, the D.F.S. algorithm performs a search that advances by expanding the child node of the search graph, and unlike B.F.S. it goes deeper into the node until the desired node is found or the path no longer has any nodes to traverse. When implemented non-recursively, expanded nodes are added to a stack for navigation. The complexity of the B.F.S. and D.F.S. algorithms depends on the number of nodes and weights of the traversed graphs. [34]. When traversing large graphs, D.F.S. is not enough because it stores all visited nodes in memory, whereas B.F.S. stores only nodes belonging to the path where the desired node can be found [34].

F. KALMAN FILTER

The Kalman Filter (K.F.), is a set of mathematical equations that implement a recursive procedure used in state and parameter estimation problems and is a predictor-corrector estimator that minimizes error covariance from feedback control. The equations are divided into two groups: time update and measurement update. It emerged in the 1960s and is applied to various areas such as artificial intelligence, industrial plants and robotics, particularly in the field of autonomous or assisted navigation [36]. It consists of estimating in the discrete process the state $x \in R^n$ in Equation 5, $z \in R^m$ in Equation 6. Considering the absence of input data or noise: the matrix A_{nxn} is the relation between the states $k-1$ and k, B_{nxl} is the relation matrix of the input of $u \in R$ and the state x, H_{mxn} is the ratio of the measurement z_k and state x [36].

$$x_k = Ax_{k-1} + Bu_k + w_{k-1} \tag{5}$$

$$z_k = Hx_k + v_k \tag{6}$$

These matrices may vary over time, but in practical applications, they are commonly considered constant. In Equations 7 and 8 the noise variables (w_k) and measurement (v_k) are represented by the covariance matrices of the model (Q) and the noise (R). Such matrices must be independent, and their elements must have white noise characteristics and normal probability distribution [36].

$$p(w) \sim N(0, Q) \tag{7}$$

$$p(v) \sim N(0, R) \tag{8}$$

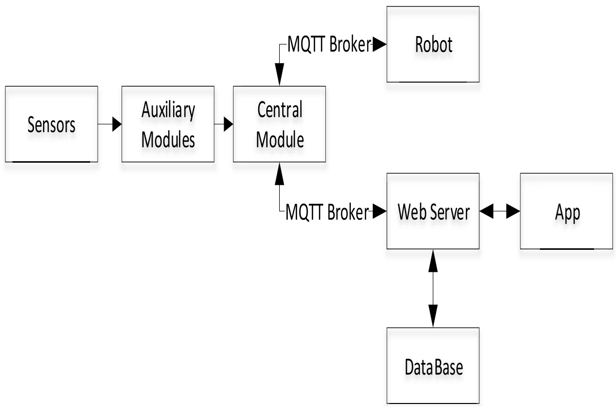

FIGURE 1. Proposed research topology.

In K.F., the time update equations (predictors), Equations 9 and 10, are responsible for projecting the state error in k + 1 and the estimation error covariance in k to obtain future estimates [36].

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k \tag{9}$$
$$P_k^- = AP_{k-1}A^t + Q \tag{10}$$

Measurement updates (brokers), Equations 11, 12, and 13, are responsible for feedback after obtaining the improved estimate [36].

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{11}$$
$$\hat{x}_k = \hat{x}_k^- + K_k \left(Z_k - H\hat{x}_k^-\right) \tag{12}$$
$$P_k = (I - K_k H)\, P_k^- \tag{13}$$

Initially, the Kalman gain (K_k) Equation 11 is calculated, then the Z_k process is calculated; after this, a state estimate is generated by including the measurements of Equation 12. Finally, the error covariance estimate is obtained from Equation 13. At the end of each prediction and correction, the process is repeated. K.F. implementations become viable by the described characteristics, since recursively the filter conditions the k estimate in all k-1 measurements [36]. The KF-based SLAM problem is common in mobile robotics in order to improve the xy position estimation, using sensors such as gyroscope, G.P.S., cameras, encoders, ultrasound, among others [36].

III. PROPOSAL, DEVELOPMENT AND TOPOLOGY

This research proposes to develop and apply a mobile robot system integrated to an IoT network, in order to monitor and identify early a fall incident at an L.T.C.F., The robotic system has mapping and location resources in order to obtain the best travel route, and through sensor readings coupled to the auxiliary modules, it can detect any possible incident or displacement of an older adult in the environment. Figure 1 shows the system topology, where the central module is responsible for mediating the communication between the robot, the server with the database and the user (caregiver) through the application, together with the auxiliary modules. These, in turn, are responsible for detecting a possible incident and sending a signal informing the central module the location of the older person and through the sensors, informing the postural state of the monitored person. Emphasize that the control panel, in turn, interprets the received signal and, through an Identity (I.D.), searches the Web server for the position of the triggered environment, thus considering sending the robot the position coordinates. The user, however, through the application, receives an incident alert and the location of the incident.

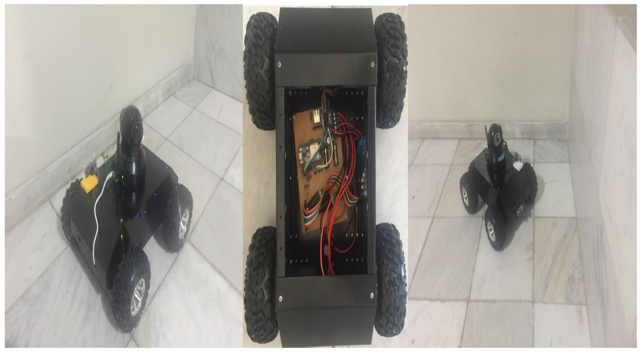

FIGURE 2. The robot developed and built.

The development and construction of the mobile robot are based on integration with the IoT network, and its primary function is to browse and monitor any incidents autonomously. For this purpose, the robot first uses the Wall-Following algorithms, P.I.D. control and the Kalman filter for location and mapping. Thus, after obtaining the mapping of the environment and being able to locate in the middle, it is possible to calculate the shortest route from its exit point to the point of the incident using the B.F.S. algorithm. For proper monitoring, an I.P. camera coupled to the robot and the system is used, as shown in figure 2.

The application (app) was developed for the user interaction system, and it has 2-way communication with the webserver. The development of the app took place in four steps: the construction of the MySQL Database, the C # Application Programming Interface (API), the Android application and the implementation of communication with Broker. The I.P. camera transmits the video streaming through which the user can follow the robot in real-time via the app.

The Wall-Following algorithm of the robot was developed with ultrasonic sensors. Two sensors were fixed on its right side, and these were responsible for maintaining its distance from the wall and guiding it along the correct path; and one sensor at the front, which was responsible for detecting any obstacles and making left turns. Each sensor controls its distance from the nearest obstacle in centimetres (cm). The algorithm uses ultrasonic data and controller correction system to navigate autonomously, and the developed logic makes it possible to move to a different location without affecting the function. The Figure 3 flowchart shows the reactive logic used in the mobile robot to navigate in the operating environment, positioned at a parameterizable reference distance of 30 cm from the wall [24].

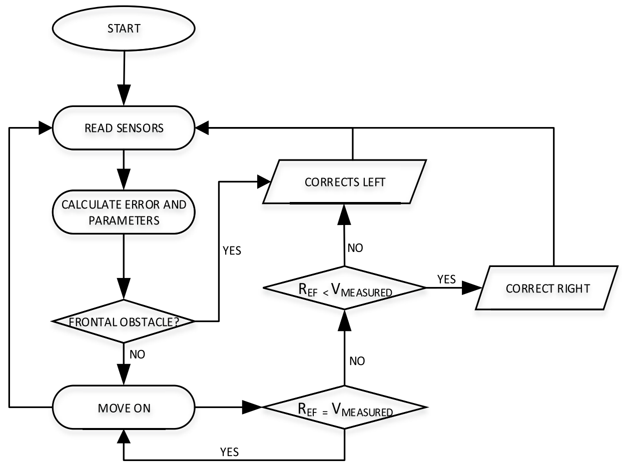

FIGURE 3. Wall-Following flowchart.

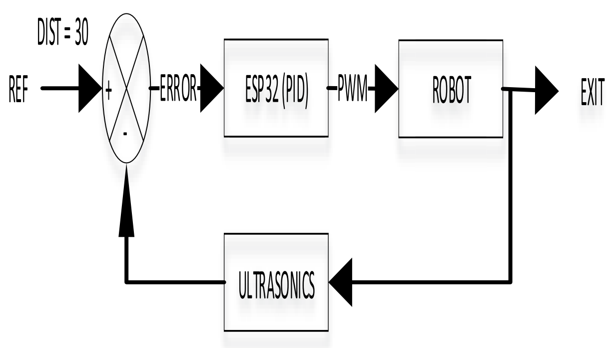

FIGURE 4. Mobile robot control diagram.

The Proportional Integrative Derivative (P.I.D.) controller was embedded for closed-loop wall distance control. Therefore, upon receiving the processed ultrasound data, the algorithm will take appropriate action and send proportional signals via Pulse Width Modulation (P.W.M.) to the motors, correcting or maintaining the position of the robot. Figure 4 shows the control diagram of the mobile robot as a whole [29].

Equation 14 represents the continuous controller, which is the starting point in the discrete-time controller derivation, where e(t) in Equation 15 is the controller error, r(t) is the reference or desired value, and y(t) is the current output of the system being controlled [29].

$$U(t) = K_P e(t) + K_i \int_0^t e(t).dt + K_d \frac{d}{dt} e(t) \quad (14)$$

$$e(t) = r(t) - y(t) \quad (15)$$

On the other hand, in Equations 16 and 17,

$$\frac{de(t_k)}{dt} \cong \frac{e(k) - e(k-1)}{T} \quad (16)$$

$$\int_0^{t_k} e(t)\,dt \cong \sum_{i=1}^{k} e(t_i)\,T \quad (17)$$

can be substituted for Equation 14, thus resulting in Equation 18, which corresponds to the digital version of the P.I.D. controller, where T is the system sampling period [24]. In this way, it can be implemented in the microcontroller [24].

$$u[k] = u[k-1] + \left(K_p + K_i \frac{T}{2} + \frac{K_d}{T}\right) e[k] + \left(-K_p + K_i \frac{T}{2} - \frac{2K_d}{T}\right) e[k-1] + \frac{K_d}{T} e[k-2] \quad (18)$$

The SLAM technique can be performed with the Kalman filter; however, this requires combining the input data of the encoders, compass, gyroscope and accelerometer. The application of this type of filter assumes the system modelling under the analysis of equations 5 and 6. In this representation it has that the current state of a given grain, x_k, can be obtained by a linear combination of the previous state, x_{k-1}, added to the control action, u_k, plus the modelling noise w_{k-1}. The measurements z_k can be modelled as the linear combination of the current state, x_k, plus a measurement noise v_k. Furthermore, the development of this work the state vector was adopted as being represented by $x = \left[\Delta d_L \ \Delta d_R \ \theta\right]^T$ and the measurement vector given by $z = x = \left[\Delta d_L \ \Delta d_R \ \theta\right]^T$. Moreover, Δd_L and Δd_R represent the displacements made by the left and right wheels, respectively, of the vehicle and $\boldsymbol{\theta}$ the angle of this with the axis 'x' in the coordinate system adopted. In the measurement vector, the displacements are provided by encoders installed on the robot wheels and the angle by an Inertial Measurement Unit (IMU). The robot kinematics modelling leads to the following equations that show the magnitudes used:

$$\Delta d_L = d_L(k) - d_L(k-1) \quad (19)$$

$$\Delta d_R = d_R(k) - d_R(k-1) \quad (20)$$

$$\theta_k = \theta_{k-1} + \frac{\Delta d_R - \Delta d_L}{l} \quad (21)$$

Moreover, component l in Equation 21 represents the distance between the robot wheels. Considering that the robot will maintain an approximately constant velocity during its movements, that is, Δd_L *and* Δd_R will vary very little from one sample to another and using the angle update θ given by Equation 21, we have the following equations:

$$\begin{bmatrix} \Delta d_L \\ \Delta d_R \\ \theta \end{bmatrix}_k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{1}{l} & \frac{-1}{l} & 1 \end{bmatrix} \begin{bmatrix} \Delta d_L \\ \Delta d_R \\ \theta \end{bmatrix}_{k-1} \quad (22)$$

$$z = [1] \begin{bmatrix} \Delta d_L \\ \Delta d_R \\ \theta \end{bmatrix}_k \quad (23)$$

By comparison of this system with the standard equations of the Kalman filter, it has:

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{1}{l} & \frac{-1}{l} & 1 \end{bmatrix}, B = [0], H = [1].$$

The quantities w and v are represented in the filter application by the matrices Q and R, respectively, and their values will be

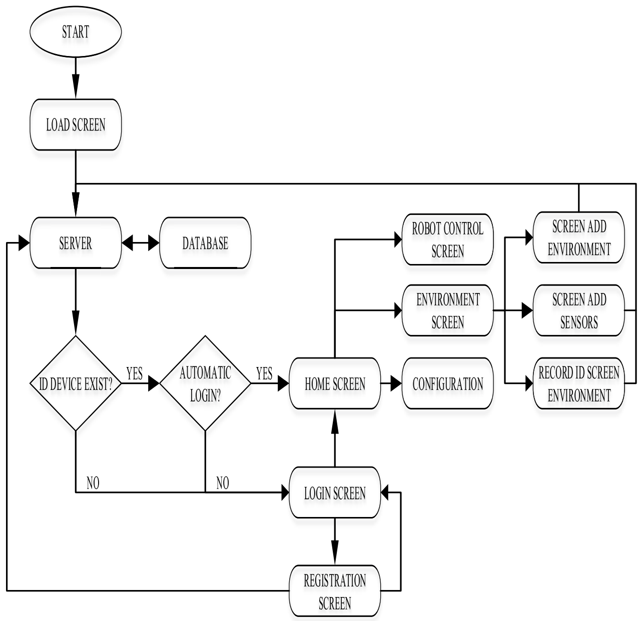

FIGURE 5. Application screen flow.

presented later. In Figure 5, the flow chart shows the operating principle of the application screens. This was developed in Java and is used to control the system fully and can access the camera robot, add settings and generate an identification ancillary E.S.P. To have access to the system, the user needs to log in or register with the settings such as the name, email, password and I.P. of the camera.

IV. SIMULATION AND RESULT ANALYSIS

Initially, the selected environment map included two bedrooms, two bathrooms and a room continuously monitored by auxiliary modules. Given this scenario, the robot developed proved to be able to navigate and dodge obstacles in order to map the proposed environment. To carry out the mapping of this environment, the wall tracking technique was performed first, and through the P.I.D. controller it was possible to keep the robot close to the desired distance from the wall, this distance is provided as a reference to the robot for autonomous navigation in the environment. It is reported that the implementation of algorithms, graphs and other computational results were performed using MATLAB 2020a. The results of the controller system for path correction in the wall following technique were relevant, and Figure 6 shows the effectiveness of the use of the control system. The following graph shows the controller acting according to the desired reference for the distances measured:

The scenario chosen for the experiments was a residential environment that, in turn, has similarities to business environments, whose map needs monitoring of various positions and environments. Experiment 1 was the first attempt to use the Wall-Following technique and shows that the ultrasonic sensors had noisy readings. In experiment 2, the noise was reduced by filtering the input data, facilitating the work of the controller.

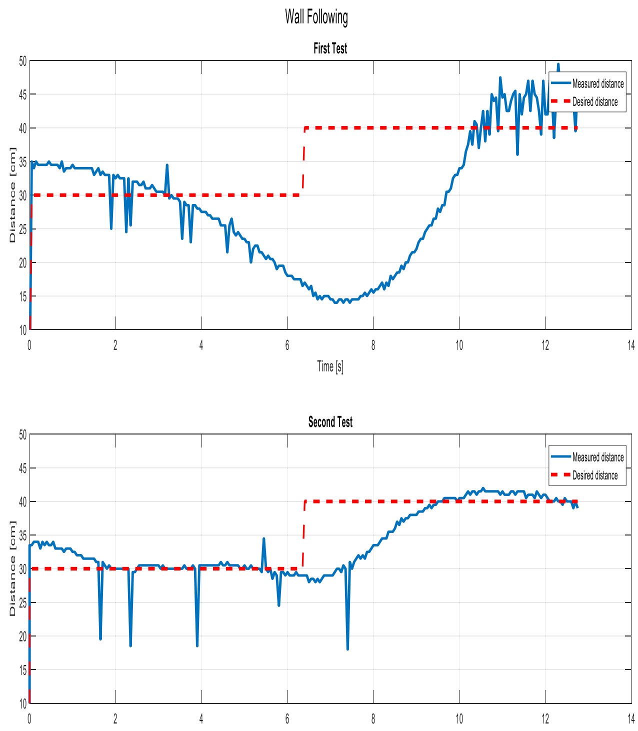

FIGURE 6. Wall-Following on experiments 1 and 2.

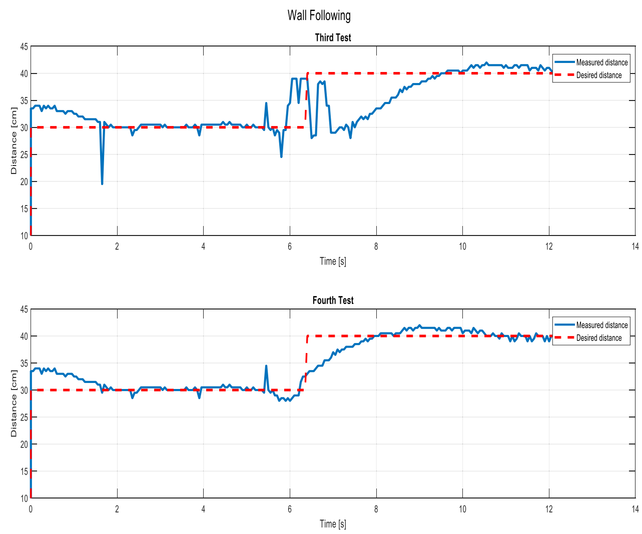

FIGURE 7. Wall-Following experiments 3 and 4.

In experiment 3 (shown in Figure 7), an attempt was made to improve the time correction by adjusting the controller, but the result was sudden movements of the robot. Finally, in experiment 4, the desired result for the wall following technique was achieved, where the sensors presented little noise, and the controller allowed the smooth and fast time correction when the robot receives a step in the reference value. The controller used is adapted from the original version mentioned in the theoretical framework. The adaptation was necessary to allow a single controller to be able to adjust the distance and angle of the robot to the wall. This control is

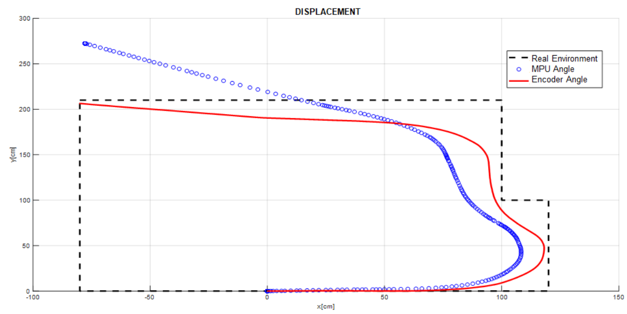

FIGURE 8. Experiments are applying the encoders and MPU9150.

calculated by equation 24:

$$U = K_D * E_D + K_\theta * \hat{\theta} \tag{24}$$

where K.D. is the adjustment constant for distance control, E.D. is the error generated between the distance the robot must keep from the wall and its current distance, K_θ is the adjustment constant for angle control, and $\hat{\boldsymbol{\theta}}$ is the angle obtained by Equation 27.

$$\hat{\theta} = Arcsen\left(\frac{S_1 - S_2}{Distance_{Whells}}\right) \tag{25}$$

The distance from the robot to the wall is given by the average of the values measured by the lateral ultrasonic sensors S1 and S2, as shown in Equation 28.

$$E_D = Ref - \left(\frac{S1 + S2}{2}\right) \tag{26}$$

Also, it is necessary to calculate the angle (θ) to generate the map. Therefore the following formulas were used while taking into account that $\Delta_{\boldsymbol{Left}}$ and $\Delta_{\boldsymbol{Right}}$ are the left and right wheel displacements, D_{Robot} the robot displacement, D_θ is the Variation of the Rotation angle, and θ is the current angle; finally, x and y are the mapping coordinates:

$$\Delta_{Left} = d_{Left}(i+1) - d_{Left}(i) \tag{27}$$

$$\Delta_{Right} = d_{Right}(i+1) - d_{Right}(i) \tag{28}$$

$$D_{Robot} = (\Delta_{Left} + \Delta_{Right})/2 \tag{29}$$

$$D_\theta = (\Delta_{Right} - \Delta_{Left})/2 \tag{30}$$

$$\theta = \theta + D_\theta \tag{31}$$

$$\theta(i) = \theta \tag{32}$$

$$x_{k+1} = x_k + D_{Robot} * \cos[\theta(i)] \tag{33}$$

$$y_{k+1} = y_k + D_{Robot} * \sin[\theta(i)] \tag{34}$$

The generated map was able to provide a matrix of zeros and ones to implement the displacement and the minimum path algorithm where 0 represents the free space that can be traversed and one the walls or obstacles. Figure 9 shows the map matrix generated from the map drawn by the robot.

The matrix is redesigned, presented as a final map of the environment, being used as input to the B.F.S. algorithm from an exit point and a destination, so it is possible to calculate the minimum path to be executed by the robot from one environment to another. Based on previous knowledge of the environment to be mapped, it was possible to modify the map obtained to make it closer to the real environment, considering the existence of only right angles and static obstacles. Figure 10 shows the final environment redrawn through the matrix obtained.

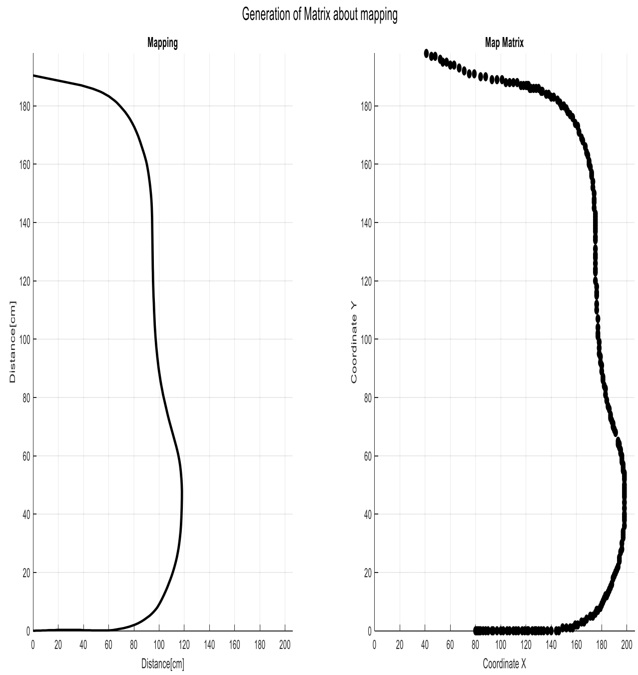

FIGURE 9. Map generation from the matrix of 0 and 1.

FIGURE 10. Redesigned map from the matrix.

Comparative performance experiments were performed between the B.F.S., D.F.S. and Wall-following algorithms. Initially, the B.F.S. and D.F.S. minimum path algorithms were implemented, where the D.F.S. aims to visit all vertices and number them in the order in which they are discovered, so that it does not solve a specific problem, but it helps to understand the graph, it is dealing with, revealing its shape and collecting information. On the other hand, B.F.S. is an algorithm that traverses a graph through the arcs from one vertex to another. After visiting the first end of an arc, the algorithm

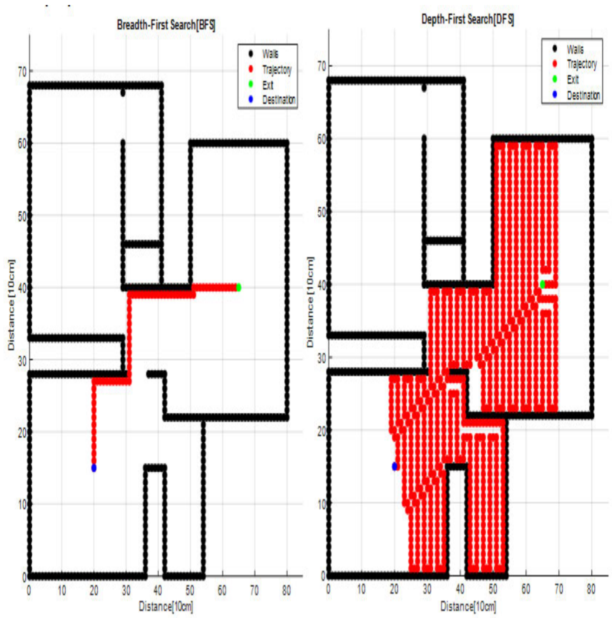

FIGURE 11. Comparison between B.F.S. and D.F.S.

TABLE 1. Comparison of current distances.

Output	DESTINY	BREADTH-FIRST SEARCH (BFS)	DEPTH-FIRST SEARCH (DFS)
Living Room: 40x65	Room 2: 15x20	7.0	91.6
Room 1: 50x15	Room 2: 15x20	6.4	96.6
Bathroom 1:55x35	Bathroom 2: 10x48	8.4	53.0
Living Room: 40x65	Bathroom 1:55x35	7.3	77.9
Average		7.275	79.775

traverses the arc and visits its end. Each arc is crossed only once. By taking two points, one exit and one destination, it is possible to carry out performance experiments and test the efficiency between B.F.S. and D.F.S. Figure 11 shows the comparison between the two algorithms using the output coordinate 40×65 and the destination coordinate 15×20, and we can see that the B.F.S. algorithm proved to be more efficient concerning D.F.S.

Then, using other coordinates, we can see in table 1 that the Breadth-First Search algorithm obtained the best result, as it presented the shortest path compared to the Depth-First Search algorithm. The distances in table 1 and 2 are in meters (m).

Additionally, the comparison between the Wall-Following algorithm and the B.F.S. was performed, when applying the 40×65 output coordinate and the 15×20 destination coordinate. Figure 12 shows the efficiency of the B.F.S. algorithm compared to Wall-Following for this minimum path case by finding a shorter path.

The comparison between the Wall-Following algorithm and D.F.S. is performed. Figure 13 shows the inefficiency of the D.F.S. algorithm compared to Wall-Following for this minimum path case, as it ran a much longer path.

TABLE 2. Comparison of current distances.

Output	DESTINY	BREADTH-FIRST SEARCH (BFS)	DEPTH-FIRST SEARCH (DFS)	Wall-Following
Living Room: 40x65	Room 2: 15x20	7.0	91.6	20.2
Room 1: 50x15	Room 2: 15x20	6.4	96.6	11.0
Bathroom 1:55x35	Bathroom 2: 10x48	8.4	53.0	29.6
Living Room: 40x65	Bathroom 1:55x35	7.3	77.9	13.9
Average		7.275	79.775	18,675

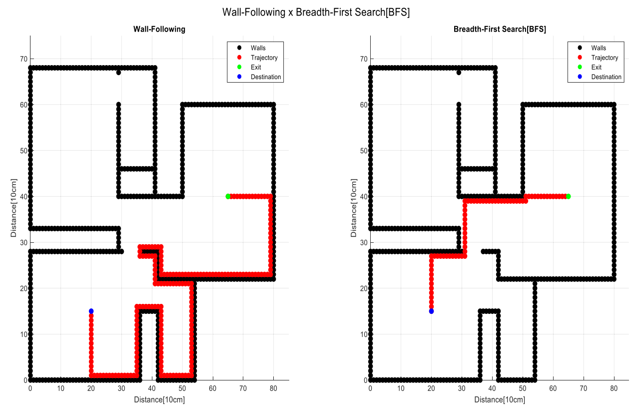

FIGURE 12. Comparison between Wall-Following and B.F.S.

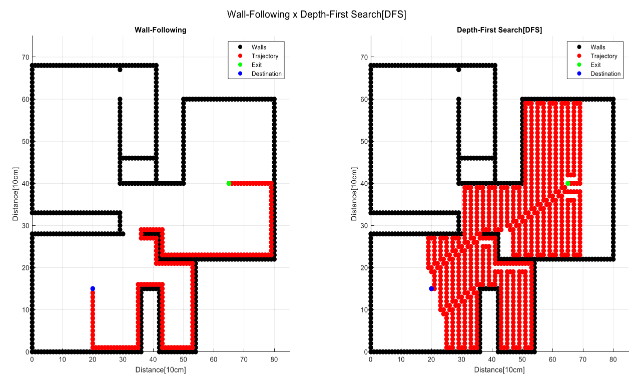

FIGURE 13. Comparison between Wall-Following and D.F.S.

Finally, for the proposed system, the Breadth-First Search (B.F.S.) algorithm had the best result as it presented the shortest path travelled compared to the Depth-First Search (D.F.S.) algorithm and the Wall-Following technique as shown in table II. This significant difference between B.F.S. and D.F.S. is due to the difference between the auxiliary data structures employed by the two strategies, B.F.S. uses a (vertex) queue. In contrast, D.F.S. uses a stack, and in general, D.F.S. has a recursive style whereas B.F.S. an iterative style.

The SLAM technique was possible as the robot gyrus angle was obtained. The purpose of the filter was to improve the rotation angle of the robot through the fusion of sensors and to use the data provided by the following sensors: Encoder, Gyroscope, Compass and accelerometer. However, considering the lack of a component that provides the absolute position indoors, the robot will accumulate position errors. Overriding numeric values that are equations of the Kalman filter, it has the following matrices:

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{1}{26.3} & \frac{-1}{26.3} & 1 \end{bmatrix}, Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.00001 \end{bmatrix}, R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.0078 \end{bmatrix}$$

, where the matrices Q and R represent the model noise and the measurement noise, respectively, and were obtained experimentally. Communication between the control unit and the auxiliary modules occurred satisfactorily, when, at a given moment, an auxiliary module detects a change in the environment that could be a fall incident detected by specific sensors through an offline reading: pre-established range or the displacement of an older person. Thus, the auxiliary module responsible for monitoring the elderly in this environment sends a message containing its identification code via MQTT to the central. The central module interprets this as an incident signal and therefore asks the server for the name and position of the triggered environment. Then the server searches the database for this information (name/position) and returns the position of the requested environment and sends the name of the environment with the disturbance notification to the application through the firebase library. Furthermore, it returns the position of the requested environment and sends the name of the environment with the disturbance notification to the application through the firebase library. Finally, the switch, via the MQTT broker, informs the robot of the following target position.

A. LITERATURE REVIEW AND CONTINUOUS IMPROVEMENT

Through a systematic mapping, a secondary study can be carried out to identify gaps in the current literature on the topic addressed in the present study.

V. CONCLUSION AND FUTURE WORK

The development of the mobile robot integrated with an IoT monitoring system played an essential role in the system, where it was able to move initially using the P.I.D. controller to maintain a predefined distance of 30 cm from the wall. When applying the Wall-Following algorithm, it was possible to generate the environment map and the input matrix for the application of the shortest Breadth-First Search path, from one environment to another. The communication between the central module, the auxiliaries and the server were carried out effectively and capable of sending and responding to momentary messages concerning the early detection of a possible fall incident by the older person. When it is possible to identify such an accident, the health professional or caregiver will be able to quickly assess probable health complications to the elderly, provide adequate assistance and request urgent medical care, in order to avoid functional decline, depressed feeling, hospitalization for the injured person, as well as the professional, can accurately assess the location in order to identify the environmental risk factors that induced the fall. It should be noted that this control of manipulation and monitoring by the user took place through a mobile application developed in order to control the system and its interactive interface. Domestic environments have a similar structure, and therefore it is believed that the computational results with their algorithms have applied equivalent results. As future works, it is suggested to carry out: experiments with other short-path algorithms, such as Dijkstra, Bellman-Ford, Floyd-Warshall, Johnson's, A $*$ for a comparative study on the search for width; experiments with control algorithms such as Adaptive, linear quadratic regulator and neural networks; development of printed circuit boards for the central and environmental modules. Conducting more computational experiments using other residential structures.

Author Contributions: All authors contributed to the design of the work, assessment of the proposed method performance and to the writing of the manuscript.

ACKNOWLEDGMENT

The authors are thankful to the National Council for Scientific and Technological Development (CNPq), Coordination for the Improvement of Higher Education Personnel (CAPES) and Foundation of Support to the Scientific and Technological Development of the State of Ceara (FUNCAP) for the support received on this project.

Conflicts of Interest: The authors declare no conflict of interest.

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