The i-Walk Assistive Robot: a Multimodal Intelligent Robotic Rollator Providing Cognitive and Mobility Assistance to the Elderly and Motor-Impaired

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A multimodal intelligent robotic rollator providing cognitive and mobility assistance to the elderly and motor-impaired

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Abstract. Robotic rollators can play a significant role as assistive devices for people with impaired movement and mild cognitive deficit. This paper presents an overview of the i-Walk concept; an intelligent robotic rollator offering cognitive and ambulatory assistance to people with light to moderate movement impairment, such as the elderly. We discuss the two robotic prototypes being developed, their various novel functionalities, system architecture, modules and function scope, and present preliminary experimental results with actual users.

Keywords: Assistive Robotics, Intelligent System, Robotic Rollator, Multimodal System, Elderly, Movement disorders

1 Introduction

Mobility problems, particularly concerning the elderly population, constitute a major issue in our society. According to recent reports, approximately 20% of people aged 70 years or older, and 50% of people aged 85 and over, report difficulties in basic activities of daily living. Mobility disabilities are common and impede many activities important to independent living. A significant proportion of older people have serious mobility problems. About 8% of people aged 75 years are not able to move outdoors without help, and the percentage increases to 28% at the age of 85. The corresponding percentages in relation to the ability to move indoors are about 5% and 14%, respectively [21]. Furthermore, current demographics show that the elderly population (aged over 65) in industrialized countries shows a constant increase. In EU, the rising life expectancy is calculated to bring about an increase of 40% of the population aged 80 and over, in the period 1995-2015, meaning that the aforementioned problems are expected to assume an even greater significance in our society for the years to come

Mobility is an important activity of the elderly since it promotes physical exercise, independence and self-esteem. Assistive robots can play a significant role since they can incorporate features such as posture support and stability, walking assistance, navigation in indoor and outdoor environments, health monitoring and others.

In this paper we present an overview and current results of the i-Walk project, regarding the research and development of two intelligent robotic rollators incorporating multimodal human-robot interaction functionalities, providing ambulatory and cognitive assistance to the elderly, as well as to people with moderate motor impairment. The key motivation for this project originates from our aspiration to devise intelligent mobile robotic mechanisms which can monitor and understand specific forms of human activity in their workspace, in order to deduce their needs, particularly regarding to mobility and ambulation, while also providing context-adapted support and intuitive assistance in domestic environments.

Fig. 1. View of the i-Walk lightweight version during an experiment with a patient

i-Walk incorporates methodologies employing multimodal signal acquisition and processing through appropriate sensors, recognition-monitoring-analysis and prediction of user actions, real-time gait analysis, user-adaptive motion control providing docking and front-following behaviors, navigation in dynamic environments, cognitive assistance, human-computer interaction based on verbal and non-verbal communication, a virtual avatar for more natural interfacing, speech synthesis and recognition, and others. The overarching goal of this effort is to provide mature prototypes, aiming at a high technology readiness level (TRL 7: system prototype demonstration in operational environment), which would require less R&D investment from the industrial partners of the project to capitalize on them and bring them to the market. Having the commercial viability of the platform as a guide, the i-Walk project offers two solutions; a lightweight one, using a commercially available design, retrofitting it with the appropriate sensors and electronics to provide a subset of the functionalities, and a heavier robotic rollator incorporating all the envisaged functionalities. The former is intended for home use, having no actuation at all while the latter is a fully-fledged motorized robotic rollator, mainly for clinical environments.

2 Related Work

In recent years, there has been an increased interest in mass production of autonomous walking assistants. Despite the small number of robotic rollators registered, approved and licensed as commercial products, there are some implementations that constitute interesting approaches, e.g. the smart walker described in [37] which is especially suitable for people who suffer from neurological disorders that affect movement, like Parkinson's disease, and is generally recommended for patients who present an increased risk of falling due to an unsafe walking pattern. It is equipped with various distance sensors, including lasers and sonars, which provide enhanced features to the user, such as the ability to navigate autonomously in order to reach the patient's location in an indoor environment. When the walking assistant mode is turned on, the platform performs basic gait analysis, adjusting the walking speed, while an obstacle detection algorithm ensures a safe navigation. It also provides cognitive support by actively notifying the user about the agenda, either using voice commands, or through a touch screen interface. In the same category, [31, 40] is a therapy device controlled by a therapist which is used for learning to walk and for balance training during standing. The two independent motorized wheels on each side provide the necessary actuation to exercise essential movement maneuvers, with adjustable linear and angular velocity. Similar products have been developed for use in outdoor environments [4, 16, 36], where in most cases an auxiliary torque plays a major role when the patient walks on inclined ground. In particular, an assistive torque is applied in order to facilitate walking uphill, whereas downhill, the electric motor brakes automatically, and independently, preventing a rolling away.

Interesting features however, are not confined only to commercial robotic walking assistants. During the last decade, an increased interest has been observed in studying, investigating and developing smart robotic rollators in the research community. A typical example is the robot described in [39] where a shared control strategy provides natural response based on the user's intention, after leveraging the interaction forces between the user and the walker, which are interpreted as navigation commands. The implementation of a robust autonomous navigation system, including mapping, localization and path planning, ensures an effective robot-environment interaction, while the adaptation of walker's behavior to each patient's gait pattern is taken after estimating and analyzing the gait parameters. Finally, the rollator is equipped with an emergency braking system that stops the walker, providing an additional safety level. In the same spirit, the idea behind [9] is to augment the manual control by observing the patient and adapting the control strategy accordingly. A similar implementation [38] provides the possibility of choosing between autonomous and assistive modes. In the first case, the robot navigates, after receiving user commands through its real-time gesture-based interface using an RGB-D camera, while in the last one the platform controls its speed according to the user's gait pattern and the ground inclination. In another approach described in [2] the walker detects the force applied by the user on the handles, and adjusts the level of assistance of each motorized wheel.

In other cases, a robotic walking rollator [32] combines the use of both passive (visual, acoustic and haptic) and active interfaces (electromagnetic brakes and motorized turning wheels) in order to guide the user during the path following process. A similar implementation that focuses on providing assistance to blind people in outdoor operation is presented in [43], where the robot keeps the user informed about the vicinity through a vibro-tactile belt, in order to avoid obstacles, while it guides them through the said interface to reach a designated target location using autonomous navigation. Several works have also been presented in the literature e.g. [7, 26] which are mostly used by therapists and aim at examining patients' mobility, stability and strength, and eventually training and exercising their skills to recover control of their gait velocity as well as their balance. Other platforms focus on estimating the features of the gait pattern, e.g. in [33] where a leap motion sensor is used for gait classification, or in [19] where force and sonar sensors are used to observe the human-robot interaction regarding the patient's upper body.

The i-Walk platform incorporates many technologies and functionalities present in related systems, and aims at combining them in a user-friendly and clinically effective manner.

3 Design & Overall Architecture

The two proposed rollator solutions share the same pool of hardware and software, with the lightweight one using a subset of the heavy rollator.

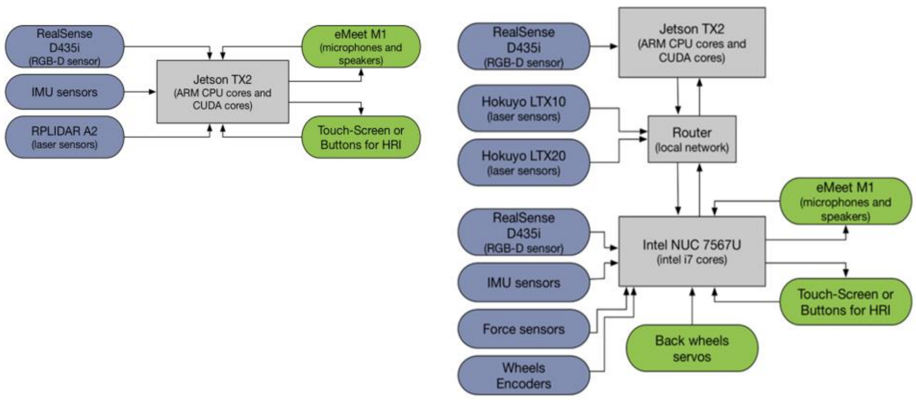

Fig. 2. i-Walk hardware architecture. Lightweight version (LEFT) and heavy version (RIGHT)

The utilized h/w of the lightweight version is listed below:

1. RealSense camera 435i
2. 360° RPLidar-A2
3. UM7 Orientation Sensor
4. eMeet M1 Black Conference Speakerphone
5. NVIDIA Jetson TX2
6. 10.1” Display

The hardware architecture and connectivity layout is presented in **Fig. 2**-LEFT. The RealSense camera is intended for pose estimation, while the IMU sensor and the laser are used in navigation. The Laser is also employed for gait tracking. All components connect to the TX2 Jetson which serves as the central processing unit of the platform.

The heavy robotic rollator incorporates hardware and software that covers all the envisaged functionalities. The additional modules include servos and encoders for the wheels, force sensors on the handles, LIDARs, localization software and a NUC mini pc additional to the Jetson. Thus, on top of the h/w in the previous list, there is also:

1. Hokuyo lidar UST-10LX for gait tracking
2. Hokuyo lidar UST-20LX for navigation
3. Mini-PC (NUC)
4. Force sensors on the handles
5. 2 Servomotors on the rear wheels
6. Differential Encoders on all wheels
7. Decawave positioning system

The advanced architecture of this version is seen in **Fig. 2**-RIGHT. The software architecture of both platforms is based on the widely used Robot Operating System (ROS), running on Ubuntu Linux. For the lightweight version (**Fig. 3**-UP), input from the various sensors reaches the necessary ROS libraries which perform signals conditioning and the communication between the different programming nodes. The first data processing leads to a first representation (yellow boxes) that is the input for the upper level processing, which recognizes the user’s state in terms of actions, movement and communication (Orange boxes). This upper level leads to assistance decision making (purple boxes).

The heavy version includes enhanced processing, like Scene Understanding and Mapping, Mobility and Cognitive Assistance and a Real Time Location System for the execution of the robotic movement and user assistance (**Fig. 3**-DOWN).

4 User needs & Clinical use-cases

The definition of user needs followed standard procedures, which were developed in two stages. In the first stage, user needs were collected by means of organizing workshops with the users and rehabilitation experts which involved interviews as well as collection of questionnaires. The second stage, involved the use of well validated evaluation scales for the classification of ambulation and balance [3, 5, 6, 14] and cognitive capacity [17] of the users who would form the group of data providers for the specification of user needs as well as the pool of users to perform the platform evaluation tasks.

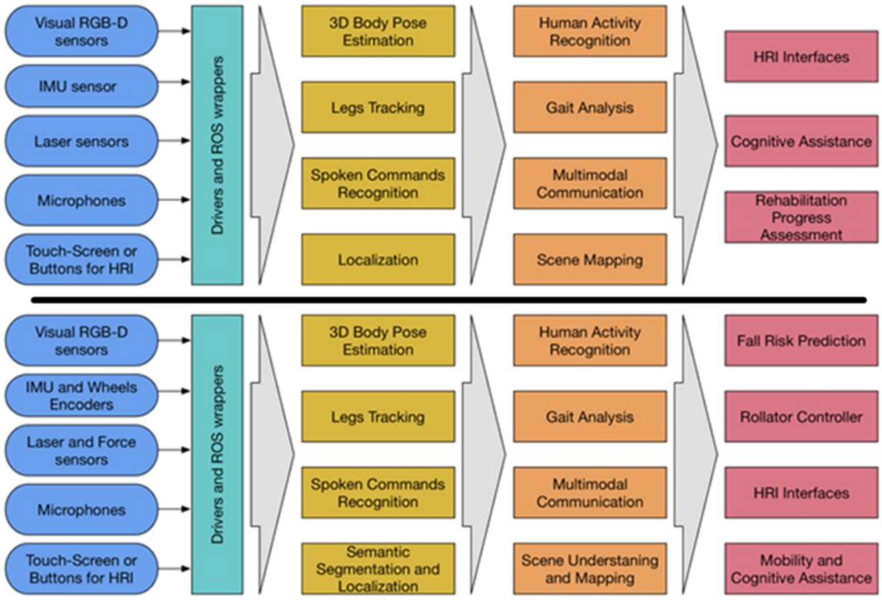

Fig. 3. i-Walk software architecture. Lightweight version (UP) and heavy version (DOWN).

This work also resulted in the definition of use case scenarios which form the testbed for the platform functionality and interaction characteristics. The adopted scenarios involve:

- Walking with a rollator. This scenario covers basic rehabilitation needs of supporting patients with ambulation problems.
- Rehabilitation Exercises. The users are instructed to perform a suite of rehabilitation exercises in seated and standing position including hand raises, torso turns, sit-to-stand transfers, etc.
- Use of the elevator. This scenario targets the support of patients' independent living.
- Transfer to bathroom. This scenario covers needs of patients with mobility problems in basic activities of daily life.

5 User-Machine Interface

The user (patient)-machine interface was designed based on user-centered principles [42]. This approach includes a cyclic design procedure of multiple phases, each of which has users and user-needs at its core. Users are involved in a series of needs analysis and design techniques so that high usability and accessibility products can be developed for the specific user group.

First, in order to design the original patient-machine interface, there was extensive analysis of user needs based on material which had been collected during on-site user observations in DIAPLASIS rehabilitation center [15]. The next step in the process was the development of a pilot patient-robot interface on the IrisTK platform [23]. IrisTK is a framework which facilitates the development of dialogue systems based on spoken interaction; it is designed to also manage multi-modal situations such as human-robot interaction.

The implemented interface helps users in terms both of cognitive and mobility issues through appropriate voice messages and visual signals which provide instructions, encouragement and cognitive support during the execution of walking and gym exercising rehabilitation tasks. Users are able to communicate via their own voice messages through which they express their preferences or give orders to the platform. These voice messages are produced in a completely natural manner and result to specific types of system reactions.

The design of the i-Walk interaction environment was the result of extensive interchange between the engineering team and the clinical team of the DIAPLASIS rehabilitation center. In the original i-Walk interaction environment, the clinical personnel may choose any of the following button options (**Fig. 4** in Greek): "***Patient Information***", "***Walking Information***" and "***Exercise Information***"

Fig. 4. Expert Interface: View of patient's performance of rehabilitation exercising

6 Multimodal Signal Acquisition & Processing

Essential to the development of an intelligent, user-aware assistive robot is the ability to interact with the user in an intuitive, multi-modal way. Towards this goal, we have designed and implemented a robotic perception system which consists of three submodules: (a) Visual Action and Gesture Recognition, (b) Speech Understanding and (c) Mobility Analysis, which are depicted in **Fig. 5**.

6.1 Visual Action and Gesture Recognition

Our activity and gesture recognition module consists of two different subsystems: the first one performs 3D human pose estimation using the RGB-D sensor mounted on the robotic rollator, while the second one recognizes human activity by employing a LSTM-based network architecture. Gestures and rehabilitation exercises are treated as special types of actions: in case the recognized activity is an exercise, the exercise monitoring module presents the corresponding recognition scores, while in case a gesture is detected, the gesture recognition module is triggered.

3D Pose Estimation: For the detection of the 2D body keypoints on the image plane we employ Open Pose Library [10] with the accompanied models trained on large annotated datasets [1, 25]. The third dimension of the 3D body keypoints is obtained by the corresponding depth maps. Subsequently, given a pair of pixel coordinates for a body joint and the depth value at this pixel, we calculate the corresponding 3D joint's coordinates through the inverse perspective mapping using the calibration matrix of the camera. For the final human skeleton we discard the keypoints of the face, hands and feet either because in many cases they are not detected, or the corresponding depth values unreliable. For activity recognition, the 3D locations of the human joints are used as features. We transform the 3D body joint locations which are provided in the camera coordinate system to the body coordinate system with the middle-hip joint as origin. We also normalize them by the length between the left- and right-hip joints (BNORM scheme). In addition, we enhance the pose feature vector with the 3D velocity and acceleration of each joint, computed from the sequence of the normalized 3D joints' positions.

LSTM-based Network for Activity Recognition: In our deep learning based module for human activity recognition we employ a Neural Network architecture based on LSTM units [22]. LSTM constitutes a special kind of recurrent neural networks that can effectively learn long-term dependencies that exist in sequential data, such as human joint trajectories. Our network architecture consists of two LSTM layers stacked on top of each other and a fully connected (FC) layer, followed by softmax activation, to obtain per-class scores. The sequence of the pose features in a temporal window is used as input to the above network. To classify the whole sequence in one of the pre-defined classes, we apply max pooling on the hidden states of the LSTM network, which, by our in-house experiments, has been shown to yield the best results compared to several other pooling schemes.

6.2 Speech Understanding

Our Speech Understanding module includes three submodules, as depicted in **Fig. 5**: An Automatic Speech Recognition (ASR) module, a Natural Language Understanding (NLU) and a dialog management and text-to-speech one. For ASR, speech recorded through a 4-channel microphone array serves as input to the state-of-the-art speech recognition Google speech-to-text API [20], and is transformed into text, thus requiring an active internet connection. Subsequently, the transcribed text serves as input to the NLU module, in order to be translated into a human intention. The integrated NLU system has been built with RASA [8, 34, 35]: A set of pre-defined intentions, both general purpose and specific to the current application has been designed. The former category includes 7 general intents, namely greeting, saying my name, saying goodbye, thanking, affirming, denying, asking to repeat, while the latter one includes 7 intents designed for the Human-Robot Interaction: standing up, sitting down, walking, stopping, ending interaction, going to the bathroom, doing exercises. Each intention is associated with various phrases to express this particular intention. For example, a user can express his/her will to stand up by saying "I want to stand up", "Can you please help me stand up", or any other variation. A RASA NLU pipeline called tensorflow embeddings [34] is then employed to predict the current intention based on the speech transcription. For the dialog part, in order to manage the several intentions and perform the specific actions required or just define what should be played back to the user, RASA Core has been used. Finally, for the actual speech feedback, Google text-to-speech (TTS) in Greek has been employed. All the above mentioned components have been integrated into ROS platform and communicate among them or with other system components, if needed, via ROS messages.

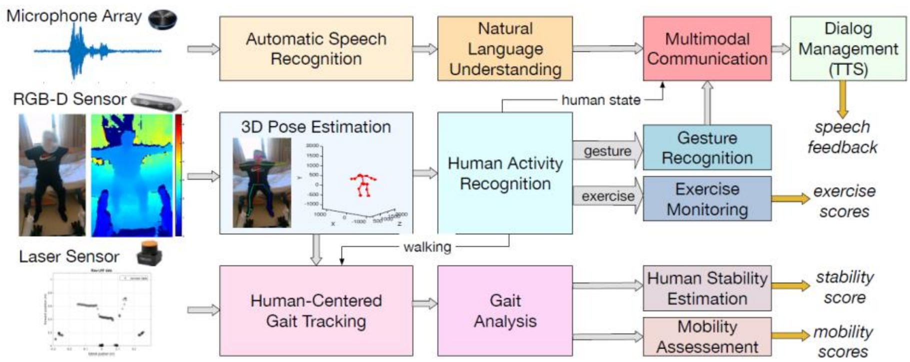

Fig. 5. Overview of the i-Walk perception system

6.3 Mobility Analysis

Gait stability and mobility assessment are important for evaluating the rehabilitation progress. The Mobility Analysis module, triggered when activity ''Walking" is recognized, consists of the following sub-systems (**Fig. 5**):

Human-centered Gait Tracking & Gait Analysis: The tracking module exploits the RGB-D data capturing the upper-body and the laser data detecting the legs. An hierarchical tracking filter based on an Unscented Kalman Filter estimates the positions and velocities of the human Center-of-Mass (CoM), which is computed by the estimated 3D human pose, while an Interacting Multiple Model Particle Filter performs the gait tracking and the recognition of the gait phases at each time frame [11, 12]. Considering gait analysis literature [45], the walking periods are segmented into distinct strides given the gait phases recognition and certain gait parameters are computed [13, 30].

Gait Stability Assessment: A deep neural network was designed and evaluated in [12], as an encoder-decoder sequence to sequence model based on LSTMs. The input features are the estimated positions of the CoM and the legs along with the respective gait phase at each time frame, while the output predicts the gait stability state considering two classes: stable walking and risk-of-fall state. In particular, the stability score used here is the probability of performing stable walking.

Mobility Assessment: For assessing the patient's mobility status, we compute gait parameters, such as stride length, gait speed, etc., which serve as a feature vector for an SVM classifier [13]. The classes are associated with the Performance Oriented Mobility Assessment (POMA) [41].

7 Navigation & Control

The navigation task has been decomposed into three main subtasks: (a) path planning, (b) localization, and (c) path following. Complementary to these, there are two further modules which provide assistive functionality; the "audial assistance" and the "user following" module. Details are presented in the sequel.

7.1 Path planning & following

The planning module consists of two layers; a local planner and a global planner. These are provided by the functionality given in ROS' navigation stack. The global planner provides a fast interpolated navigation function which can be used to create plans for a mobile base [24]. The module employs Dijkstra's algorithm to search through the available working area and find the best path. It also uses a global obstacle costmap, created using a prior known map, in order to calculate a safe global plan taking into account the distance from the obstacles. Following, given the global plan, the local planner creates a short-term plan and the appropriate velocity commands for the robot. The local planner provides implementations of the Trajectory Rollout and Dynamic Window Approach [18]. It continuously tests local motion paths in the environment, by forward-simulating the robot motion in time. Based on a score, it outputs the desired movement command to the robot. The local planner also creates a local obstacle costmap which follows the robot, in order to calculate a safe local motion plan. This functionality is included in the motorized version of the i-Walk platform.

7.2 Localization

Robot localization is performed using an Adaptive Monte Carlo Localization approach, implemented in ROS as part of the *navigation* package and provides an estimate of the robot's pose against a known map. Essentially, it registers continuously the robot pose on the map and corrects the odometry errors. In the lightweight version, the localizer uses the lidar and IMU signals in order to provide the pose estimate, while in the motorized version, the odometry is also used.

7.3 User following

This module implements a functionality that enables the robot to follow the user from the front. The goal is to have the Rollator follow the user while walking (i.e. comply with the motion of the user without any physical interaction, that is. without any force being applied on the Rollator handles), and to remain in close vicinity to the patient in case of need, e.g. for postural support, cognitive assistance, etc. This means that the user goal point is not known a priori, as the human can suddenly turn and flank the robot or move to the other direction.

The module has been based on the work presented in a string of papers [27–29], incorporating further functionality such as such as real-time crossing detection, user intent identification, and shared control. Specifically, a modified Dynamic Window Approach was devised that tests for Arc-Line paths in a robot-centered rolling cost-map. Using this technique, distinct routes are detected signifying different directions of motion (**Fig. 6**). Furthermore, it enables the on-line detection of undecidable areas, which demand user input to resolve.

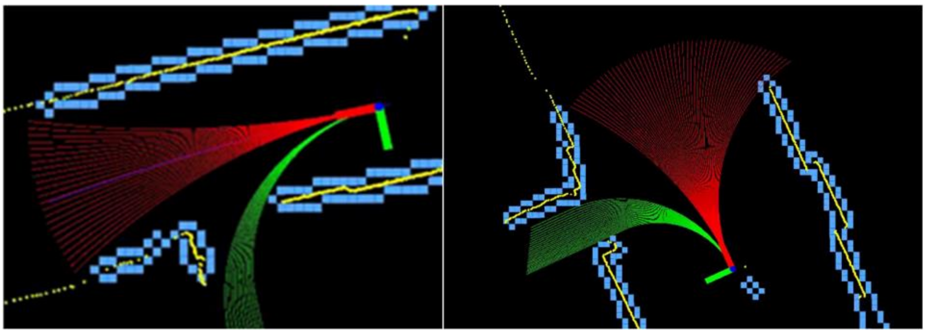

Fig. 6. Detection of distinct routes of motion in two different cases. First direction (cluster) is red while the second cluster is green. Robot is depicted as a 2D frame (red-green).

7.4 Audial Assistance

The audial cognitive assistance module provides audio cues to the user while walking with the rollator. The module assumes a known map along with a set of nodes that have audio tokens associated with them. The nodes comprise a directed graph, meaning there is a traversal order. Each node is a circle with two predefined radii R_{in} and R_{out}. When the robot enters the R_{in} circle, an audio token is heard. Conversely when exiting the R_{out} circle, another audio is played. Exiting a node makes this node obsolete and only forward nodes are considered. Work presented in [44] has shown that this navigational assistance can help cognitive impaired people to navigate easier through indoor environments, and guide them to places they want to go, for example, go from their room to the dining area, when in a rehabilitation center.

8 Preliminary Experimental Results

This section presents preliminary results from an audial assistance experiment with a patient in the Diaplasis Rehabilitation Centre. The aim was to perform functional and user acceptance testing of the assistive module, in order to assess its real-life performance and deploy it later in a more structured and systematic validation testing of the entire platform. In the experiment, the patient was placed at a starting position, and was asked to follow the audio commands of the robot, which guided him through a manually prescribed path. This path consisted of a loop around the Centre's reception area, and comprised two segments. This first segment consisted of six nodes (*0:0* to *0:5* in **Fig. 7**), and the second of three (*1:0* to *1:2*).

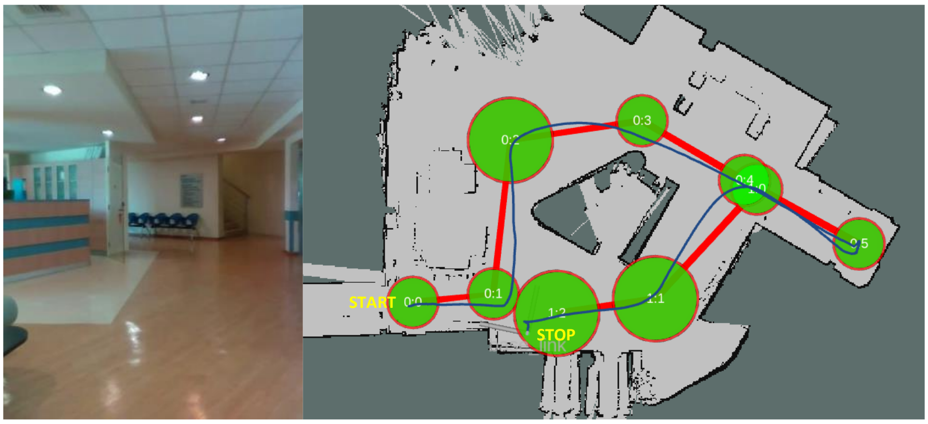

Fig. 7. View of the audial assistance experiment. The path is defined by nodes (green), and seen in the thick red line. The actual path traversed by the user is seen in blue. The user started from node 0:0 and stopped at 1:2. On the left is seen an image from the front-facing camera, mounted on the rollator, taken from the stating position.

The patient managed to follow all the audio commands of the robot, and went through all the prescribed nodes, thus traversing the desired path. The entire experiment lasted for *152 seconds* in total, where the patient traveled *49 meters* with an average velocity of *0.3 m/s.* Overall, the experiment was conducted without any adverse events, such as the patient missing a node, not hearing the audio commands or not comprehending them, and was considered successful. The patient did not report any problems with the module, and had no trouble following the commands.

9 Conclusion & Future Work

In this paper we have presented an overview of the i-Walk project, pertaining to a platform providing ambulatory and cognitive assistance to the elderly and the motor-impaired. The platform offers two solutions, one lightweight and a second heavier motorized one, aiming at home users and clinical environments respectively. This paper briefly covered the various modules developed, mainly in the lightweight version, while also presenting much of the intended functionality of the heavy platform. Further developments on both rollators, especially regarding user acceptance and clinical validation are scheduled for the months to come, and the results will be presented in appropriate venues.

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