DALi: A Smart Walking Assistant for Safe Navigation in Complex Indoor Environments

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Abstract Indoor navigation can be a challenging issue for people afflicted by cognitive impairments. The project Devices for Assisted Living (DALi) is a research initiative sponsored by the European Commission under the FP7 programme with the goal of developing a robotic wheeled walker assisting disabled people in indoor scenarios where crowd, obstacles and multiple points of interest may confuse or intimidate the users. The walking assistant, called *c-Walker*, is designed to monitor the environment, to detect possible hazards and to decide the best path across the space, thus guiding the user safely towards the wanted destination. In this paper, an overview of the system and some of its most important functions are described.

1 Introduction

Information and communication technologies (ICT) contribute to innovation in a variety of ways. At European level, elderly care is recognised to be one of the crucial societal challenges of the near future. With the median age in Europe projected to grow from 37.7 in 2003 to 52.3 in 2050, the population potentially afflicted by mobility problems is substantial, not only because their social lives are restricted, but also because they have a limited access to good nutrition, leisure and other activities. Several factors adversely affect mobility, the most obvious being physical impairment as well as loss or reduction of visual and auditory ability. A less recognised, but equally critical problem is the decline of cognitive abilities, which reduces confidence when a person is supposed to move in unfamiliar environments, where

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the presence of crowd and of multiple points of interest may easily cause disorientation and confusion. In such situations, the afflicted person gradually perceives public places as intimidating and starts to withdraw.

In this context, the EU project *Devices for Assisted Living* (DALi) aims at developing a smart walking assistant called *c-Walker* that supports disabled and older adults in moving in large unstructured spaces safely and with improved confidence. The main features of the walker in terms of functions and usability have been defined in cooperation with groups of potential users in England and Spain under the supervision of some psychologists. A key innovation factor of the *c-Walker* is its ability to detect and interpret human behavioural patterns in order to plan the route that minimises the level of anxiety of the user, while preserving naturalness of his/her navigation. Robotic walkers have gained an undisputed popularity in the research community on Ambient Assisted Living (AAL). Closely related to DALi is the system developed within the Assistants for Safe Mobility (ASSAM) project [1]. However, ASSAM is focused on the seamless transition from indoors to outdoors, while DALi specifically considers large indoor environments and the interaction with other people around the user. Other projects, such as iWalkActive and E-NO-FALLS [12, 6], have complementary goals, i.e. supporting physical exercise and preventing falls, respectively. Although of certain interest, these aspects are different from those faced in DALi. Thus, in the rest of this paper the main features of *c-Walker* prototype, currently under development, are shortly summarised.

2 Functional and Architectural Overview

In a typical application, the assisted person (AP) decides a destination among a list of points of interest (PoI) on a map (e.g. the restrooms, a particular shop, or a ticket office). After selecting the wanted PoI with a touch-screen, the system defines a route to reach the destination and helps the AP to follow it. The *c-Walker* is capable to estimate its position on the map while approaching the destination point. If the AP wants to move along a different trajectory, he/she is free to do so. In this case, the *c-Walker* suggests a correction, not only by showing it on the screen, but also through a pair of bracelets working as haptic interfaces. Such bracelets vibrate to inform the AP when a left or a right turn should be taken. The use of bracelets has been preferred to the integration of haptic interfaces within the *c-Walker* handles for two reasons. First of all, installing haptic handles with a suitable form factor is quite complex from the mechanical point of view. Secondly, the pressure exerted on the handles while pushing the device could reduce user's sensitivity to haptic stimulation.

The direction to follow can be indicated to the user also by a set of audio signals through Bluetooth earphones. However, while the bracelets are primarily used as a feedback for trajectory correction, the sound signals just give a suggestion about the future route.

The sensing part of the system is composed by encoders mounted on wheels, an

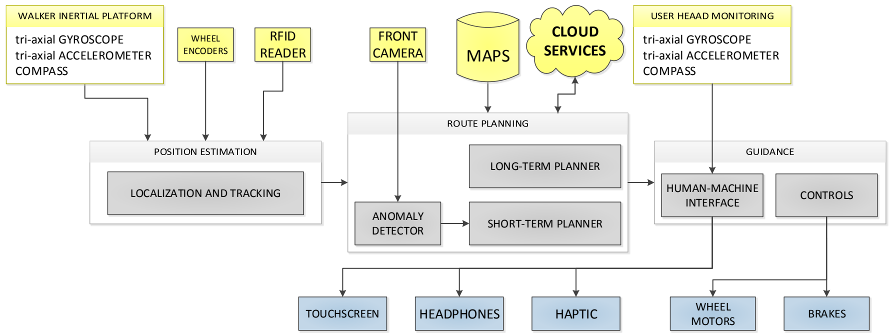

Fig. 1 Functional block diagram of the *c-Walker*.

inertial measurement unit (IMU), an RFID reader and a front Kinect. These sensors are used for localisation purposes (see Section 3). The front Kinect is used also to detect anomalies in the environment and to track people moving in the proximity of the device. A second IMU is mounted on the earphones to determine the AP's head attitude with respect to the direction of the walker (see Section 5).

A general architectural overview of the system is depicted in Fig. 1. A picture of the first *c-Walker* prototype is instead shown in Fig. 2. The higher level functions (image processing, situation assessment, trajectory planning and guidance) are implemented in a small Intel Barebone mini desktop (11.7 cm $\times$ 11.2 cm $\times$ 3.9 cm) equipped with an Intel Core i5-3427U processor running up to 2.80 GHz, 8 GB of DDR3 RAM and a 120-GB solid state drive. This platform is powered by an external rechargeable 118-Wh Li-ion battery. Communication with peripherals and subsystems relies on a USB 3.0 port, a Gigabit Ethernet link, WiFi (IEEE 802.11a/b/g/n) and Bluetooth 4.0. The USB link is used to control and to acquire images from the Kinect. The Gigabit Ethernet connection is used instead to collect the results of the low-level functions (i.e. sensor data acquisition and preprocessing or actuator control) implemented in a Beaglebone platform. This is equipped with an ARM Cortex A8 running at 720 MHz, 256 MB DDR2 RAM and a microSD memory for storage. The Beaglebone is connected to a Feig ISC.MR101-USB RFID reader through a USB link. The input data from the encoders CUI Inc. AMT10X (back wheels) and from the on-board IMU (equipped with a gyroscope Inversense IMU-3000) as well as the output commands driving the brakes Liedtke FAS21 on the back wheels and the pivoting motors M1233031 by LAM Technologies on the front caster wheels are transferred to/by the Beaglebone via CAN bus.

3 Localisation and position tracking

Walker localisation is essential to support high-level functions such as route planning and guidance. Map construction and localisation techniques play a complementary role. A map of the chosen environment is required to define the allowed

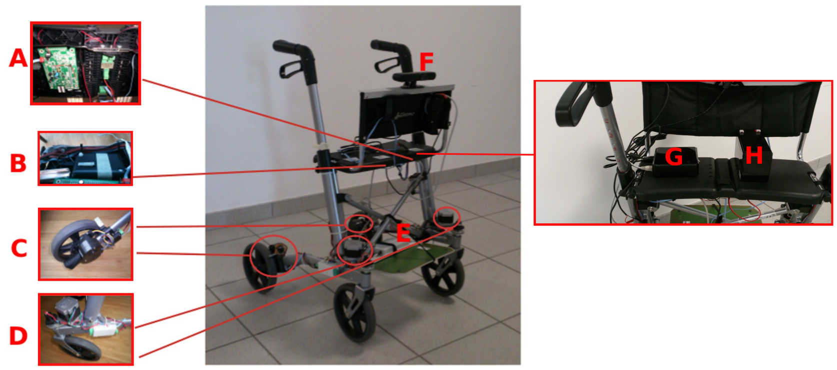

Fig. 2 The *c-Walker* prototype along with its main components, i.e. the Beaglebone platform running low-level functions (A), IMU (B), encoders (C), motors (D), RFID Reader (E), Camera (e.g. Kinect) (F), the Barebone platform running high-level functions (G) and the main battery (H).

areas (namely where the user can move freely) and the forbidden areas (e.g. due to obstacles or boundaries such as walls). Once a map is available, a Cartesian reference frame (given by the position of the origin and the direction of axes X and Y) can be defined on it. The position tracking algorithm relies on an extended Kalman filter (EKF) that processes data from:

- two fixed incremental encoders installed in the back wheels;
- a triaxial gyroscope located inside the on-board IMU;
- an RFID reader with the antenna located under the walker;
- a Kinect camera detecting predefined visual markers (e.g. arrow-shaped stickers or QR-codes [9]) on the floor.

The EKF is built upon a simple five-state unicycle-like kinematic model. A qualitative description of the localisation and position tracking algorithm is shown in Fig. 3. The state vector includes the following variables: the (x, y) Cartesian coordinates of the midpoint of the rear axle in the chosen Cartesian reference frame, the orientation angle θ with respect to the $X-$axis and, finally, the linear and angular velocity offsets (referred to as μ and δ, respectively) due to encoders nonidealities and left-side/right-side walker asymmetries. The encoders are used in the prediction step of the EKF to reconstruct the relative position and direction of the *c-Walker* with respect to the initial state. While the encoders data rate is high enough (250 Hz) to assure continuous position tracking, the open-loop estimation uncertainty tends to grow indefinitely, as customary when dead-reckoning techniques are used. In order to keep position uncertainty within wanted boundaries (e.g. ± 1 m with 90% probability), a grid of low-cost passive RFID tags stuck on the floor at known locations is used. In this way, the position estimated by the *c-Walker* on the map can be updated by simply knowing the ID of any detected tag, with uncertainty no larger than the RFID reading range (i.e. about 15-20 cm). Thanks to the fusion of odometry and

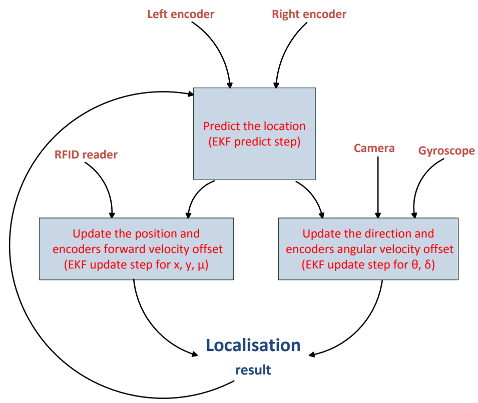

Fig. 3 Overview of the EKF-based algorithm for localisation and position tracking.

RFID data, the granularity of the grid can be coarser than other solutions found in the literature [15]. Several simulations showed that a tag distance of about 2-3 m can provide a reasonable trade-off between wanted accuracy and deployment costs [16]. Unfortunately, RFID tag detection does not provide any information about walker's direction. In order to mitigate this problem, the angular velocity values measured by a gyroscope are integrated to update the state estimated by the EKF anytime the walker turns left or right. However, also the gyroscope-based angle measurements are affected by unbounded uncertainty growth. Therefore, sporadic absolute orientation values in the chosen reference frame are needed to update the EKF state estimate. Since compasses and magnetometers proved to be unreliable indoors, such values can be obtained by measuring the angle between the direction of the walker at a given time and the $X-$axis direction pointed by the visual markers recognised by the Kinect. Again, various simulations showed that a distance of a few metres between adjacent markers is enough to assure a good trade-off between positioning accuracy and deployment complexity [16]. It is worth emphasizing that a localisation fully based on computer vision is not feasible in the case considered, as the Kinect has to be used also for trajectory planning and the available computational resources are limited. In fact, marker detection relies on low-rate image acquisition.

4 Route planning

Route planning is based on a two-level approach. The first level, called *long-term planner*, is based on a global view of the environment and computes a trajectory according to the objectives of the AP, while considering fixed obstacles, critical areas and anomalies that may occur. The second level, called *short-term planner*, exploits the available on-board sensors (particularly the Kinect camera) to detect dynamic

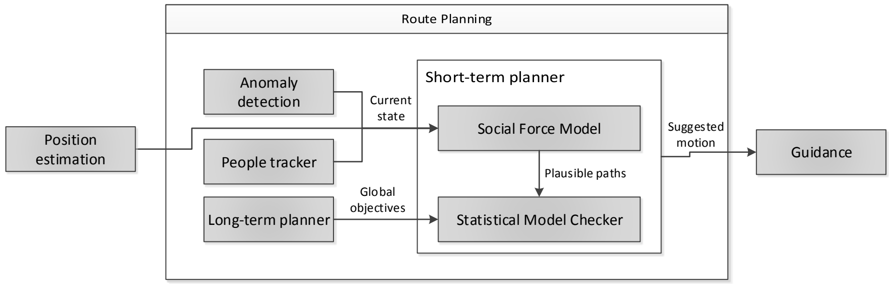

Fig. 4 Overview of the route planning algorithm.

obstacles (e.g. other people [17]) and to update the trajectory, while assuring comfort and minimising the probability of collisions [5]. Fig. 4 shows the main modules of the route planning algorithm running on the Barebone platform.

The long-term planner takes care of building a complete route between the current AP position and one or more selected PoIs. Route construction takes into consideration static obstacles (e.g., walls, pieces of furniture) and temporarily forbidden areas including, but not limited to, crowded places and critical regions identified by appropriate signs (e.g. wet-floor or out-of-order signs). Such signs are detected by a vision algorithm that uses live images recorded by the front Kinect. The algorithm relies on both optical character recognition (OCR) and geometric shape recognition and exploits the depth information associated to the images to localize the corresponding signs on the map. The core of the planner is the Dijkstra algorithm executed on a Quadtree representation of the map of the environment [7]. From the technical point of view, the vectorial map and its representation are stored in a spatial database[1]. The set and the weight of nodes and edges of the graph representing the map are periodically updated to reflect the status of the environment at a given time. For example, if a wet-floor sign is detected, the planner disables all the graph nodes within a circular area of a few squared metres centred in the position of the sign.

The short-term planner relies on a control algorithm based on a receding horizon approach, which exploits social rules driving the cohabitation of humans [4]. The algorithm uses the well-known Social Force Model (SFM) that represents people as 2D circles with attractive and repulsive forces [11]. Thus, it is possible to model the force that attracts people towards the same PoI, as well as the repulsive force that naturally prevents people from crashing into walls or other people. The control algorithm predicts the evolution of pedestrians moving in the environment and, consequently, it estimates the probability for the AP to reach safely the goal without any collision. In particular, the position of pedestrians is obtained using a people-tracker algorithm that relies on the images collected from the Kinect. The evolution of pedestrians moving in the environment is predicted by integrating the SFM over a limited time horizon. There is no upper limit to the number of pedestrians

[1] Spatialite: http://www.gaia-gis.it/gaia-sins/

that can be handled by the algorithm. However, some performance tuning might be needed if the computational resources are limited. Further details on this algorithm are reported in [5]. Pedestrians' directions can be estimated from the vectors built using pairs of consecutive position values. The control algorithm exploits Statistical Model Checking techniques to verify the evolution of the SFM against temporal-logic high-level constraints [14, 13], such as, for instance, "*reach the goal in a finite time, but no closer than 0.5 m from people and 1 m from obstacles*". In order to estimate the probability of success, at first the possible evolution of the environment around the *c-Walker* in a limited time horizon (a few seconds) is simulated many times. Then, every predicted scenario is verified against the above temporal-logic constraints and, finally, the probability of success is estimated under the assumption that the AP slightly changes its initial direction. This step is repeated till when the algorithm tests all possible directions (e.g. $0, \pm 25, \pm 50, \pm 75, \pm 90$ degrees) [5]. Finally, the direction that maximises the probability of success is suggested to the AP through the guidance mechanism (see Section 5). If the AP ignores the suggested trajectory or if an unforeseen obstacle is detected, a new route is computed.

5 Guidance Mechanism

The guidance system has the purpose of gently inviting the user to follow the planned route. In order to improve comfort during navigation, the force feedback has to be perceived as *soft* by the user and it should properly modulated while he/she approaches the boundaries of an area of interest. Guidance is implemented using various complementary techniques, i.e. mechanical, haptic and audio-based.

Mechanical guidance has been designed according to a passive robotics paradigm. Normally, the AP is free to push the *c-Walker* according to his/her needs. However, two electromechanical brakes, mounted on the rear wheels, can be selectively activated by the control system to steer the walker along the suggested path. To reduce the intrusiveness of the guidance as much as possible, the control law has been designed by solving an optimal control problem, in which the braking actions have to be minimised [8]. As long as the user moves within a safety region around the desired path, only sporadic and soft corrective actions are exerted. The control becomes more authoritative when the walker deviates significantly from the path, thus approaching potentially dangerous areas.

Although the mechanical feedback is effective, sometimes it can be perceived as annoying by older adults. This is the reason why we have also investigated vibrotactile feedback. Various studies have demonstrated that sensitivity to vibrations is particularly high on hairy skin and in bony areas [10]. Thus, two identical wearable haptic bracelets have been developed to warn the AP when to turn right or left. In each bracelet, two cylindrical vibro-motors are controlled independently using the Bluetooth communication protocol. Each vibrotactile bracelet can be fitted to the arm, just below the elbow. This configuration has proved to be very effective to discriminate the haptic stimuli from the intrinsic vibrations of the *c-Walker*.

Another way to inform the AP about the best path to follow is based on the generation of appropriate sound stimuli. In daily life, humans are able to estimate the direction of arrival of sounds because our brain is able to recognise relative differences in amplitude and phase of sound waves impinging the two ears (binaural cues). Also, the brain can identify the spectral cues that originate at a single ear (monaural cues) because of the reflections generated by the pinna folds. These cues depend on the relative position between the listener and the sound source [3]. By modeling and reproducing these phenomena, we are able to synthesise positional audio signals associating a sound source to the route suggested by the route planner. As a result, the user can be invited to move in the direction where the perceived sound comes from.

Each synthesised audio signal is obtained by means of a convolution between a monoaural sound signal and an impulse response. These impulse responses can be obtained through measurements (HRIR), or can be synthesised using models that compute the response based on anthropometric measurements. To increase the sensation of spaciousness, the sound rendering algorithm includes the Image Source Method that performs reverberation taking care of both the relative position of the virtual sound sources and the size of the environment. The sensation of distance is accentuated by introducing a proper amount of delay and attenuation into the sound signal [18]. In order to ensure a correct displacement of the spatial sound stimuli, the AP's head orientation with respect to the *c-Walker* direction of motion has to be monitored. For this reason, the headphone is equipped with an inertial platform. Moreover, the IMU allows the AP to exploit small head movements to discriminate ambiguous situations. In fact, also in real life humans take advantage of small head movements to collect more cues on the position of the auditory event [2].

6 Preliminary Experimental Results

The first experiments on the *c-Walker* prototype have been conducted in the premises of the Department of Information Engineering and Computer Science of the University of Trento. Fig. 5 shows the results of localisation and haptic-based guidance in a simple case: an L-shaped path along a corridor towards an elevator. In Fig. 5(a) the planned route (dashed line) and the estimated trajectory (solid line) are compared. Fig. 5(b) shows the differences between planned and measured direction angles along the way. Anytime such values exceed ± 0.2 rad (dash-dotted horizontal lines) the haptic bracelets are activated to correct user's trajectory. The activation signals of the right (dashed line) and of the left (solid line) haptic bracelet (c) are shown in Fig. 5(c).

Table 1 shows the mean values and the average standard deviations of the position errors along the $X-$axis and the $Y-$axis, respectively, averaged over 10 paths of different length and shape in an room of 150 m^2. In all the experiments the distance between pairs of adjacent RFID tags and visual markers on the floor is about 2 m. The individual position errors result from the differences between the coordi-

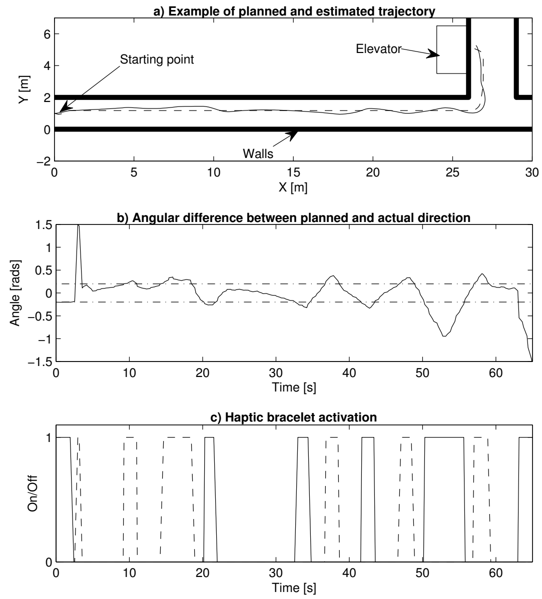

Fig. 5 Planned route to the elevator (dashed line) and corresponding estimated path (solid line) (a). Difference between planned and measured direction angles along the way (b). Activation signals of the right (dashed line) and of the left (solid line) haptic bracelet (c).

nates estimated by the EKF and the corresponding values (properly aligned in time) measured by a laser scanner SICK S300 Expert located in the origin of the chosen reference frame (i.e. one corner of the room). The results in Table 1 confirm that the positioning uncertainty is well below ± 1 m, as desired.

Table 1 Average mean values and standard deviations of $X-$axis and $Y-$axis errors over 10 different paths in a 150-m^2 room. The distance between pairs of adjacent RFID tags and visual markers is about 2 m.

	Avg. Mean Error [cm]	Avg. Std. Deviation [cm]
$X-$coordinate	16	48
$Y-$coordinate	14	58

7 Conclusions and Ongoing Work

The *c-Walker* system developed within the EU project Devices for Assisted Living (DALi) has the ambitious goal to assist people with cognitive impairments to navigate safely and with improved confidence in large and complex environments. The system consists of modules for localisation, route planning and user guidance and it is conceived to enhance the sensitive and cognitive abilities of the user, but without forcing him/her to act unwillingly. A first prototype of *c-Walker* is currently under test in the laboratories of the University of Trento, in view of performing extensive experiments on the field with potential final users.

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