An Inertial and QR Code Landmarks-Based Navigation System for Impaired Wheelchair Users

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Abstract Personal mobility is a key factor in independent living for elderly people and people with motor disabilities, thus indoor navigation systems are of utmost concern in Ambient Assisted Living (AAL) applications. Driving an electric powered wheelchair in domestic environments becomes difficult for people with arms or hands impairments. Moreover, people affected by tetraplegia are completely unable to operate a joystick, and must rely on input interfaces, such as eye tracking and "sip and puff", which require tedious and repetitive tasks to be operated. Smart powered wheelchairs with autonomous navigation intelligence and their integration within AAL homes, may enhance independence and improve both the security and the perceived quality of life. Self-navigating systems combine different measurements provided by both absolute and relative sensors to improve localization accuracy. In this work, a low-cost localization system for autonomous wheelchairs, which takes advantage of Quick Response (QR) code landmarks information, is proposed. QR code is a low-cost pattern with fast readability and large storage capacity with respect to other landmarks solutions. The proposed wheelchair is equipped with an Inertial Measurement Unit (IMU) and a video camera: the inertial information, provided by the IMU, is fused with that provided by QR code recognition, thus reducing the error propagation caused by a Dead Reckoning (DR) approach. Autonomy and

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intelligence of the wheelchair is drastically increased by integrating within its navigation system both the knowledge about self localization and the environment (e.g. room identification). QR code landmarks are a suitable solution to store this information. This approach has been implemented and experimentally tested in an indoor scenario, demonstrating its feasibility and its good and reliable long-term performances.

1 Introduction

Assistive technology plays an important role in allowing vulnerable people (elderly or with motor disabilities) to lead and enjoy an independent lifestyle in their own homes, and thus improving their quality of life. For instance, wheeled mobility devices can significantly improve the quality of life of people who are unable to walk; however, in this case, attention must be paid also to the user's physical and mental condition since different symptoms combinations can benefit from different types of assistance and wheelchair form factors [1]. Several studies have shown that vulnerable people benefit substantially from access to independent mobility because it increases vocational and educational opportunities, reduces dependence on caregivers and family members, and promotes feelings of self-reliance. Conversely, a decrease of mobility can lead to emotional loss, isolation, stress, reduced self-esteem and fear of abandonment [2]. In order to assure a fully independent mobility, one has also to consider that many mobility impaired users are unable to operate a powered wheelchair safely, without causing harm to themselves, to others and to the environment. Thus, to fully support these users, several researchers have developed smart wheelchairs [3], employing technologies originally developed for mobile robots [4]. These devices typically consist of either a standard powered wheelchair, to which a computer and a collection of sensors have been added, or a mobile robot base to which a seat has been attached. Smart wheelchairs have been designed to help vulnerable users to navigate in a number of different ways, such as assuring collision-free movement, aiding the performance of specific tasks (e.g. passing through doorways) and autonomously transporting these users among different locations. Some smart wheelchairs operate similarly to autonomous robots: the user specifies a final destination and supervises as the smart wheelchair plans and executes a path to the target location, but they are usually unable to compensate for unplanned obstacles or travel in unknown areas. The technology developed for autonomous machines, which are capable of moving without human intervention, may offer certain multi-unable persons the needed assistance to achieve a fully freedom of mobility. A such mobility support device must be capable of working in unconstrained dynamic environments with complete regard for safety of its passenger, its surroundings and itself.

In this context, an important role concerns the indoor localization of the smart wheelchair. Moreover, a persistent navigation [5] is needed, and tags with information about absolute position, help to accomplish the indoor localization task [6]. In the literature different research works deal with this problem and different technologies are employed to solve it. Lin and Chen [7] have proposed special landmarks containing coordinates of the absolute position acquired by a camera and through a process of image segmentation. Nam [8] proposed a new approach to map-based indoor localization for walking people using Inertial Measurement Unit (IMU). Other technologies realize indoor positioning using Wireless Sensor Network (WSN) and Radio Frequency Identification (RFID), or an hybrid approach based on both, as proposed by Xiong et al. [9]. Instead of using sensors for building the navigation route map by the robotic wheelchair itself, various types of landmarks have been proposed. Courbon et al. [10], presented an indoor navigation system based on the use of a single camera and natural landmarks where the images of the environment are first sampled, stored, and than organized as a set of key images which the robot can follow as visual path to move [11].

The aim of this work is to develop a localization system which includes, at the same time, an IMU and a vision system based on Quick Response (QR) codes, used as landmarks. The proposed smart wheelchair is equipped with both an IMU and a camera: the inertial information provided by the IMU is fused with that one provided by the QR code recognition. This permits to drastically reduce the error propagation caused by the well-known dead reckoning approach. The idea is to replicate the same localization system most used in outdoor environments, i.e. the combination of an IMU and a Global Positioning System (GPS). IMUs are highly affected by both noise and disturbances, thus an exteroceptive localization sensor is required to correct the position estimation provided by the IMU. In indoor environments, however, the GPS cannot be used and an alternative exteroceptive sensor must be adopted for improving the position estimation. Localization methods based on features such as RFID (Radio Frequency IDentification) or visual systems, are often used. By using RFID technology, an RFID tag is recognized and so the location and the direction of the landmark, but in this case location accuracy is limited by the harsh propagation of the radio frequency signals caused, for instance, by the presence of obstacles among wireless nodes, multi-paths, interference, etc. These methods need dense deployments of RFID receivers, and are not able to track the mobile target [9]. An alternative is the use of visual sensors, however they can usually provide only a local estimation of the position unless the whole environment is known a priori. In this paper the IMU information is integrated with a method for indoor position and orientation based on two-dimensional barcode landmark: the QR code. QR codes are attached on the ceiling of the indoor environment and they store information about their position w.r.t. the absolute world coordinate system. By the use of image preprocessing and landmark recognition, it is possible to locate the landmark and get the information contained in the QR. The landmark shape is easily discriminated for its geometry and, by estimating the pose of it (and indirectly the pose of wheelchair w.r.t. the landmark), it is possible to calculate the absolute coordinates of the robot w.r.t. the environment. The contest in which the study has been realized is that of an autonomous wheelchair capable of driving itself in an indoor environment. This paper presents preliminary results where the considered trajectory has a “L” shape. The smart wheelchair follows the considered trajectory and, using the proposed navigation system, it is able to correct its position during the navigation.

The paper is organized as follows. Section 2 describes the system setup: the powered wheelchair, the sensors, the control unit and the adopted software. Section 3 deals with the description of the control strategy: localization, visual recognition and tracking. Section 4 presents preliminary experimental results of the proposed localization system tested on a “L” shape trajectory to be followed. Conclusive section summarizes the main results of the paper and illustrates possible improvements and future works.

2 System Setup

The proposed navigation algorithm has been developed in Robot Operating System (ROS), a framework for robotic applications which recently has been growing exponentially [12]. ROS is a thin, message-based, tool-based system designed for mobile manipulators. The system is composed of reusable libraries that are designed to work independently. The libraries are wrapped with a thin message passing layer which enables them to use and to be used by other ROS nodes. Messages are passed peer to peer and are not based on a specific programming language. ROS is based on a Unix-like philosophy of building many small tools that are designed to work together [13]. The hardware used for the experimental trials are a Microstrain 3DM-GX3-25 IMU [14] and a Logitech webcam HD C525 [15], which are connected via usb port to a laptop. An Arduino MEGA2560 board [16] has been used as an external joystick in order to set the directions and speeds motion of the wheelchair. Vision system algorithm and IMU data processing are implemented in ROS Groovy release [17]. In order to estimate the absolute pose of the considered wheelchair, two ROS nodes have been developed, one related to IMU and another one related to the camera. These nodes are capable to exchange messages between them, and thus provide the wheelchair absolute pose. The data sample rate of the IMU and the camera was set to 100–10 Hz, respectively. The camera resolution was set to 960×544 pixels. The complete system setup is presented in Fig. 1.

3 Control System

In this section the control system details are provided. In details, the algorithm for the pose estimation with IMU measurements, the QR code solution for information in the absolute reference coordinates and the visual system for recognition and tracking, are discussed.

3.1 Inertial Measurement Unit

Localization systems based on inertial measurements are capable to estimate the wheelchair position, from a known state and a previously determined location, by

Fig. 1 The smart electric-powered wheelchair with the IMU sensor

integration of internal measures. In the present paper an IMU is used to have internal measures such as angular velocity, linear acceleration and orientation. Dead reckoning system, based on a 2-D coordinate system, is described by the following mathematical model for the system at time $t_n = nT$, with sampling time T and $n \geq 0$ [18]

$$
\begin{aligned}
x_{t_n} &= x_{t_0} + \sum_{i=0}^{n-1} d_{t_i} \cos(\theta_{t_i}) \\
y_{t_n} &= y_{t_0} + \sum_{i=0}^{n-1} d_{t_i} \sin(\theta_{t_i})
\end{aligned}
\tag{1}
$$

where d_{t_i} and θ_{t_i} are the moving distance and the absolute angle at time t_i, respectively. The Cartesian coordinates at time t_n of the wheelchair are x_{t_n} and y_{t_n}. In detail, the IMU provides the linear acceleration and angular orientation, which are filtered by Kalman filter. The orientation is used to evaluate the θ parameter and the linear acceleration is doubly integrated to evaluate the d parameter. Unlike wheel encoders, an IMU is not affected by wheel slip, which is often encountered in mobile robot applications. However, there are several disadvantages on using an IMU: the errors caused by bias in the sensor readings accumulate with time, as show in Eq. (1), the misalignment of the unit's axes with respect to the local navigation frame can cause inaccurate readings. Moreover, the IMU measurements can be affected by electromagnetic interferences in the home environment such as mobile phone, laptop and wireless hotspots. An average of 100 samples acquired during system startup has been used to reduce the bias in the sensor readings.

3.2 QR Code

QR codes are barcodes that consist of black squares arranged in a square pattern on a white background. These images are capable of storing much information and handling all types of data (e.g. numeric and alphabetic characters, symbols and binary). Then any type of information can be associated and encoded in a QR code (e.g. website link, phone number, commercial content and messages). QR codes can be directly decoded by any camera and thus their information can be easily read. In the present paper, QR codes are used as landmarks, in which their absolute position is encoded. Various types of QR Code exist. For the experimental trials, the original version M2, which is able to encode up to 7,089 characters in one symbol, is chosen. The information encoded in the QR is a string of 21 characters formatted as

$$\#xx.xx\#yy.yy\#zz.zz\#rr \tag{2}$$

where $xx.xx$, $yy.yy$ and $zz.zz$ are the positions in meters of the QR code in the world coordinate system. The room, where the QR code is placed, is shown by the numeric character rr. This information is not used in the experiments but could be exploited to integrate AAL home automation technologies with the smart wheelchair. QR code detection algorithm is developed using the ZBar library [19]. This library allows to decode each QR code and thus to know the absolute position of each QR code in the environment.

3.3 Visual Recognition and Tracking

The vision system has been developed in ROS framework using different vision libraries such as ViSP, OpenCV and ZBar ([20, 21] and [19]). The algorithm is based mainly on six routines as shown in Fig. 2: camera calibration, QR code detection and decode, QR code tracking, relative pose estimation, absolute pose estimation and updating of the absolute pose. Camera calibration is a necessary step in 3D computer vision for extracting metric information from 2D images. The goal of the calibration is to estimate camera parameters that allow to make the relation between camera's natural units (pixel positions in the image) and real world units (normalized position in meters in the image plane). Furthermore, by calibration, it is possible also determinate the distortion parameters, which are intrinsic in cheap pinhole cameras, and using such parameters to reduce the distortion. The pinhole camera model is described as

$$s \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \boldsymbol{A}\,[\boldsymbol{R}|\boldsymbol{t}] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{3}$$

with

$$\boldsymbol{A} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}, \; [\boldsymbol{R}|\boldsymbol{t}] = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \quad . \tag{4}$$

In this model, a scene view is formed by projecting 3D points into the image plane using a perspective transformation. The matrix $\boldsymbol{A}$ is called intrinsic parameters matrix and the matrix $[\boldsymbol{R}|\boldsymbol{t}]$ is called the extrinsic parameters matrix which denotes the coordinate system transformations from 3D world coordinates to 3D coordinates fixed with respect to the camera. Camera calibration allows to estimate both intrinsic and extrinsic parameters. This step is carried out by the OpenCV software [20] that uses the algorithm described in [22]. In the present paper the extrinsic parameters are the position and the orientation of the origin of the QR code coordinate system expressed in coordinates of the camera coordinate system. This means that is possible to know the relative position $\boldsymbol{p_r}$ of the origin of the camera coordinate system respect to the origin of QR coordinate system as follows

$$\boldsymbol{p_r} = -\boldsymbol{R}^{-1} * \boldsymbol{t} = -\boldsymbol{R}' * \boldsymbol{t}. \tag{5}$$

After a QR code is detected, the vision system starts the tracking step using a combination of these two algorithms: the Kanade-Lucas-Tomasi (KLT) feature tracker described in [23] and the model-based edges (MBE) tracker which uses a 2D model of the QR code in which its edges are stored. These algorithms require some setting parameters that have been chosen in order to have the best tracking performance when maximum speed of wheelchair is under 1 km/s. During the tracking, the developed algorithm updates the $[\boldsymbol{R}|\boldsymbol{t}]$ matrix through two steps: in the first step the matrix is estimated using a linear approach which produces a first pose matrix that is used in the second step as initialization for the virtual visual serving non linear approach; this will converge to the solution with a lower residue than the linear approach [21]. Once the $[\boldsymbol{R}|\boldsymbol{t}]$ matrix is known, the relative pose between the QR code and the camera can be estimated using Eq. (5). Now the vision algorithm is able to estimate the absolute pose of the wheelchair by adding the relative pose between the QR code and the camera with the absolute pose decoded by QR code (Eq. 2). The absolute pose provided by the vision algorithm is fused with that carried out by the IMU in order to reduce error propagation. If the tracking routine loses the QR code (e.g. QR code is out of the camera field of view) the algorithm restarts from the detection step, otherwise it continues to perform the tracking step.

4 Experimental Results

The experiments have been performed in the hallway at the Dipartimento di Ingegneria dell'Informazione of Università Politecnica delle Marche. The wheelchair has been remoted controlled via ROS interface and the imposed trajectory reflects

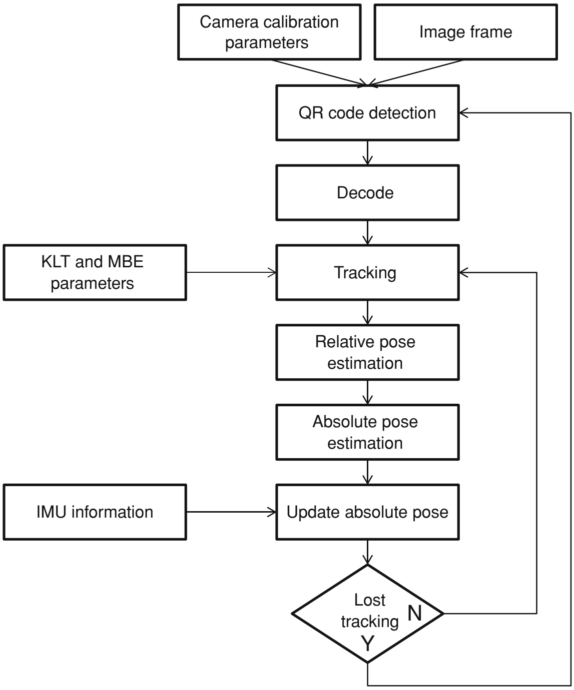

Fig. 2 Flow chart of the visual recognition and tracking system

a L shape of 8 m with 3.5 m route along x axis, a rotation of 90° at standstill and a 4.5 m route along y axis: the movements are expressed in accordance with the absolute reference system placed as in the laser scanned map in Fig. 3a. During the route the wheelchair is driven to move along the middle of the hallway which is 3 m wide. Three QR codes with $0.42 \times 0.42\ m^2$ dimension has been placed in the experimental setup and fixed to the roof of the hallway at an height of 3 m; thus the orthogonal vertical distance between the camera and the QR codes is about 2.2 m. Each QR code includes the information about its position relative to the absolute reference system, as in Eq. (2), nevertheless the room position has not been used for this experiment. The QR codes positions have been highlighted in Fig. 3b. The QR1, with coordinates (1.5; 4.5), is the first encountered during the path; the QR2, with coordinates (1.8; 1.5), has been placed near the point of 90° rotation and finally the QR3 has been placed in (4.5; 1.5) position. During the route the wheelchair has been forced to move at a constant speed of 1.16 m/s. The merge of both the IMU and the visual information gives a satisfactory pose estimation and the results can be easily evaluated in the same Fig. 3b: IMU measurements are useful in the absence of QR information, nevertheless during the periods without visual feedback, the pose error increases with time for the well known acceleration integration problem. In fact both the QR2 and the QR3 helps the algorithm to recognize the wheelchair in the absolute space as soon as they are detected.

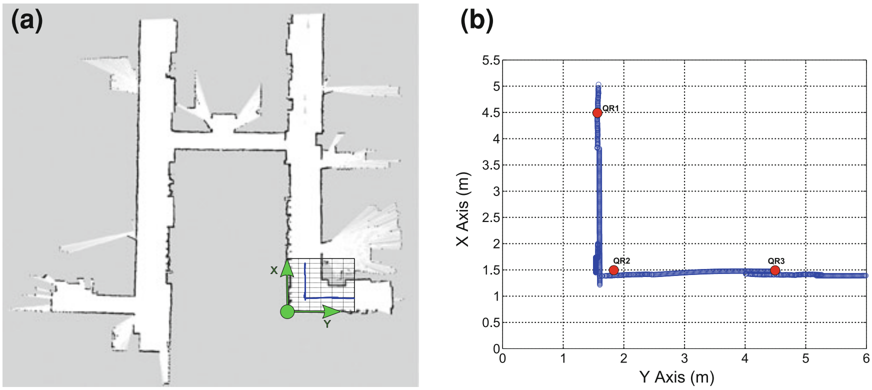

Fig. 3 Experimental Results for QR-code and IMU measurements localization algorithm. **a** Estimated pose on a setup scenario map. **b** Details for the wheelchair estimated pose

5 Conclusions

Smart powered wheelchairs with autonomous navigation intelligence and home integration ability are key points in AAL technologies as they could provide a possible sustainable solution to enhance independence, and improve quality of life for people unable to operate with classical powered wheelchairs. To ensure these aims a smart wheelchair has to be provided by a self-navigating system, which permits to localize it with good accuracy combining both absolute and relative sensors measurements. The authors main contribution is the development of an odometry and QR code landmarks-based indoor navigation system. The smart wheelchair is equipped with an IMU and a low-cost monocular camera. The vision system estimates the absolute pose of the wheelchair in the environment by adding the absolute pose decoded by the QR code with the relative pose between the wheelchair and the QR code using vision algorithms. The absolute pose provided by IMU sensor, is fused with the absolute position estimated by the vision system improving the localization accuracy. The navigation-system has been developed in ROS framework. The camera and the IMU sensor, with their relative software, have been developed as two ROS nodes that exchange messages between them in order to estimate the absolute pose of the wheelchair. According to the obtained results, the QR code localization has been proved to be a successful absolute localization method which helps to correct pose estimation algorithms based on dead-reckoning approach; as expected the improvements in the pose estimation deeply rely on the number of QR codes used. These preliminary results show that the present navigation system can be further developed and integrated with other navigation algorithms. In fact the authors are currently considering two possible future developments: the first is related to develop a voice navigation system in order to allow the users to move easily from a room to another. The system will be provided by a path planning algorithm based on the proposed QR code landmarks-based navigation system. The second is related to the integration of an home automation system which is able to take advantage of the knowledge about self localization structural information and about the environment (e.g. room identification) encoded in the QR codes in order to apply suitable and smart control actions in the environments where the user is placed.

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