Augmented Robotics for Electronic Wheelchair to Enhance Mobility in Domestic Environment

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Abstract. This paper focuses on the development of a novel Human Machine Interaction strategy based on Augmented Reality for the semi-autonomous navigation of a power wheelchair. The final goal is the development of a shared control, combining direct control by the user with the comfort of an autonomous navigation based on augmented reality markers. A first evaluation has been performed on the real test bed.

Keywords: Augmented Reality · Virtual reality · Eye tracking · Assistive technologies · Shared control · Autonomous navigation

1 Introduction

Mobile robotics is the discipline that studies the development of autonomous systems in order to provide support or help to human users. Applications of this kind range from industrial application to medicine. Power wheelchairs represent a good example of assistive tool that could benefit from the technological transfer from the mobile robotic field. Indeed the wheelchair has a strong impact on the quality of life of patients affected by mobility limitations, example are spinal cord injuries or degenerative diseases as Amyotrophic Lateral Sclerosis (ALS). The pathological state generates in these subjects many physical inabilities but also psychological distress. The capability of moving autonomously plays therefore an important role for their quality of daily life.

The necessity of a caregiver, common condition, does not improve the self-esteem of the disabled subjects. An assistive technology should be designed to be as much comfortable as possible and not invasive in order to improve the autonomy of the patients. For this reason, a robotic wheelchair can be of great benefits restoring the human mobility.

Common techniques to control a wheelchair are based on a physical interaction between the user and a device such as joysticks, keyboards or breath. Recently, eye tracker technologies have become a promising tool as control input for any kind of user

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[3, 4, 7]. Indeed, eye movement is one of the fastest human movement, although are mainly conceived for exploration, less for control [2]. Gaze-based control devices represent very useful tools able to guarantee a good mobility also to the more critical patients. Pathologies like ALS affect the people starting from the peripheral organs, moving progressively to the rest of the body. The last part involved are the eye muscles. On top of this, the Human Machine Interface (HMI) based on eye tracking can play a fundamental role for actual usability and manoeuvrability of a wheelchair.

Many solutions for gaze-based control are quite invasive due to the necessity to wear external devices such as glasses [3] or electrodes for Electrooculography [4]. Other solutions are based on less invasive techniques like Video Oculography (VOG) [5, 6]. Due to the delicate health condition of the patients, it would be highly desirable to have interfaces the least tiring and invasive possible.

Regarding the interaction modalities, current interfaces require a continuous control by the user. This control modality results very tiring for the patients, especially for the gaze-based control technique where the user has to keep all the time the attention on the monitor. Moreover, houses are usually characterized by small spaces and narrow passages. Unfortunately, not all the disabled people have the possibility to adapt their house to the required particular necessities. For these reasons, the exploitation of a robotic path planning control of power wheelchair would be of great benefit to relief the patient. Indeed, in this manner, he/she does not have to keep attention on the HMI. An assisted guide could be very useful and comfortable especially for the movement in narrow spaces. The solution presented in this paper aims to create a novel technology to support the control of a power wheelchair during difficult manoeuvres. Furthermore, using an autonomous wheelchair the patient does not need to keep the attention on the monitor, resulting less tiring.

In our work, we propose an integration of our previous gaze-based HMI [1] with a robotic framework able to plan and control a part of the route according to a normal HMI based on AR. With this novel technology, we aimed to guarantee the freedom of movement and at the same time the comfort of the assisted guide. We use UNITY Game Engine for the development of the HMI. Moreover, we use ArUco[1] (a library for Augmented Reality AR applications based on OpenCV) to identify the possible targets and then OpenCV[2] for image processing. The proposed AR-based application is able to recognize points of interest (POIs) visible to the camera, to plan a path and to give to the patient the possibility to eventually perform the preferred path after proper checking. From an applicative point of view, when a POI enters in the field of view of the camera the user can select it, starting in this way the autonomous navigation.

The tests on the application developed were performed evaluating the repeatability of the manoeuvres starting from different positions. In this way, the impact of the uncertainty of the camera position was evaluated, with respect to the wheelchair, on the reached position.

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1 https://www.uco.es/investiga/grupos/ava/node/26.

2 http://opencv.org/.

2 System Architecture

The project involves the integration of a hardware and software module on a commercial wheelchair. The system was designed in order to enhance the mobility of the user giving him/her the possibility to control the wheelchair through both manual and autonomous navigation via gaze-based technique.

With manual navigation, the user acts directly on the wheels by selecting the forward and the rotational speed. A continuous law, to determine the forward and the steering velocities, characterizes the control strategy as described in [1]. The velocities are calculated proportionally to the position of the gaze on the monitor.

With semi-autonomous navigation, the wheelchair is able to reach a selected target without any other input from the user. To achieve such task, it is necessary to assess the actual position of the wheelchair with respect to the surrounding environment. Given the start and the end positions and attitudes, the vehicle calculates the best path to reach the goal. Then another specific algorithm, that calculates the control parameters for the motors, realizes the tracking of the path (path-following task).

Figure 1 presents a schematic representation of the system. In the left part a commercial device (power wheelchair) where the proposed technology is integrated. In the central part, the module developed, and added on the wheelchair, represented by a Windows PC that reads the navigation camera, acquires the information about the gaze position and shows the HMI on the monitor. The surrounding environment is shown in the right part, where ArUco markers are used to define all the point of interest for the user.

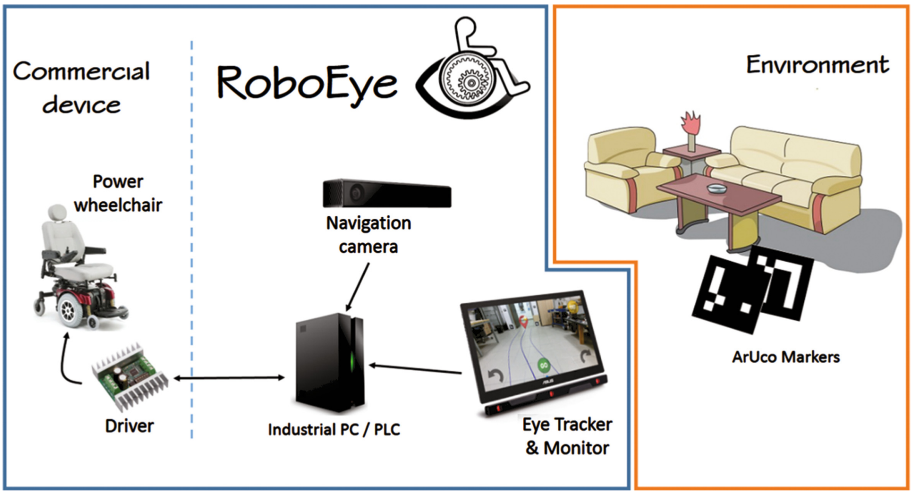

Fig. 1. Conceptual model of the project

In addition to the real wheelchair, the application was applied also on a simulator in order to perform some evaluation tests and theoretical analyses with control quantities.

2.1 Augmented Robotic Wheelchair

The system is made by a power wheelchair commercialized by Invacare[3] (model: Storm XR) integrated with some additional devices useful at including advanced robotic functionalities. From a kinematic point of view, the wheelchair corresponds to a differential drive vehicle with the traction wheels on the back part of the chassis. An industrial B&R PLC and a Windows PC perform all the logical computations. Two encoders were mounted on the wheels for the odometric localization. The motors used are the original ones of the wheelchair while a commercial driver was added for powering them.

The PLC calculates the control parameters (voltage related to forward and rotational speeds) and pilots the driver of the two motors. It also collects the data from the encoders about the rotations of the wheels, calculating in this way the position of the wheelchair. The odometric localization is performed by an incremental recursion, dead reckoning, technique that suffers of a drift in the estimation of the position and attitude. Because of that, it is necessary an absolute localization algorithm in order to compensate such effect, mainly due to the uncertainty of the vehicle parameters.

Common absolute localization systems, used in industrial application, are based on cameras or laser scanners, like NAV[4]. On the other hand, these systems are usually slower than the incremental ones and require a map of the surrounding environment. The combination (data fusion) of the two localization systems represents the optimal solution, with the update rate of the incremental and the accuracy of the absolute. In our case, the absolute localization is designed differently from the canonical ones to prevent the usage of a map of the environment. Each POI (for example doors or tables) represents a localization element, centred with respect to a couple of markers, coded and uniquely identifiable, and associated to the target position and attitude.

The identification of the markers and the localization of the wheelchair with respect to the POI is implemented with a Time Of Flight (TOF) camera, a Kinect V2.0, mounted on the frontal part of the wheelchair, few centimeters above the knees of the patient, as shown in Fig. 2. The position of the sensor was the result of the advices from a pool of tester: the presence of the knees in the field of view of the camera was defined as very useful in the depth perception of the surrounding environment and in particular for movements close to obstacles or narrow passages.

The images coming from the camera are displayed on a monitor mounted in front of the user. On that image are overlapped the HMI and the information about the POI detected in the field of view of the camera. The patient interacts with the system using an eye tracker (TOBII EyeX[5]) mounted below the monitor. A Windows PC manages the camera, the monitor and the eye tracker. It is connected to the PLC through a TCP/IP connection using PVI library from B&R[6].

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3 http://www.invacare.com.

4 https://www.sick.com/de/en/product-portfolio/detection-and-ranging-solutions/2d-laser-scanners/nav3xx/c/g91916.

5 http://tobiigaming.com/product/tobii-eyex/.

6 https://www.br-automation.com/en/perfection-in-automation/.

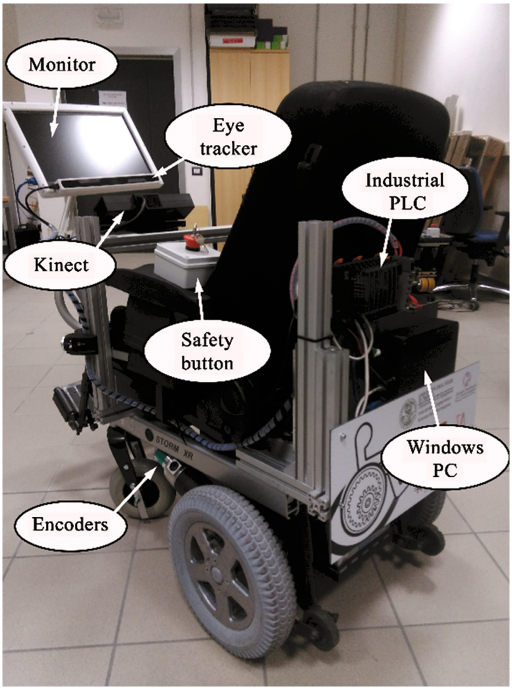

Fig. 2. Hardware architecture

A safety button, connected directly to the voltage supply of the motors, ensures the safety of the user during the learning and test phase.

2.2 Virtual Reality Architecture

The proposed HMI was developed using UNITY game engine. The aim was both to maximize the usability of the wheelchair, both to minimize the stress resulting from the intense use.

The user has in front of him/her a monitor where are shown all the commands for both the manual and autonomous navigation. On the background, the application shows the RGB frames captured by the Kinect. This video stream is useful to perceive the surrounding environment and to pilot the wheelchair but also to see the location of POIs in the Kinect field of view.

A C++ Dynamic-link library (DLL) simultaneously analyses the same images coming from Kinect to detect markers. If at least a couple of markers related to a POI are detected, the DLL performs also the relative localization with respect to the wheelchair, the planning of the path and the communication with the industrial PLC. At the end of the processing, the algorithm gives back to the UNITY application information about POI detected and associated paths planned. Such information are used by the main application to create an augmented image with a pin icon on the target point and lines that show in perspective the path planned. The described processing is performed on each new frame acquired, ensuring in this way an on-line update of the path planned.

The commands for the trig of the various actions are displayed on the foreground as the icons related to the POI detected. In order to start the semi-autonomous manoeuvre, the user must explicitly select the POI by gazing it for 3 s.

The DLL, operative core of the structure, can be conceptually divided in three levels with two parallel tasks, Fig. 3.

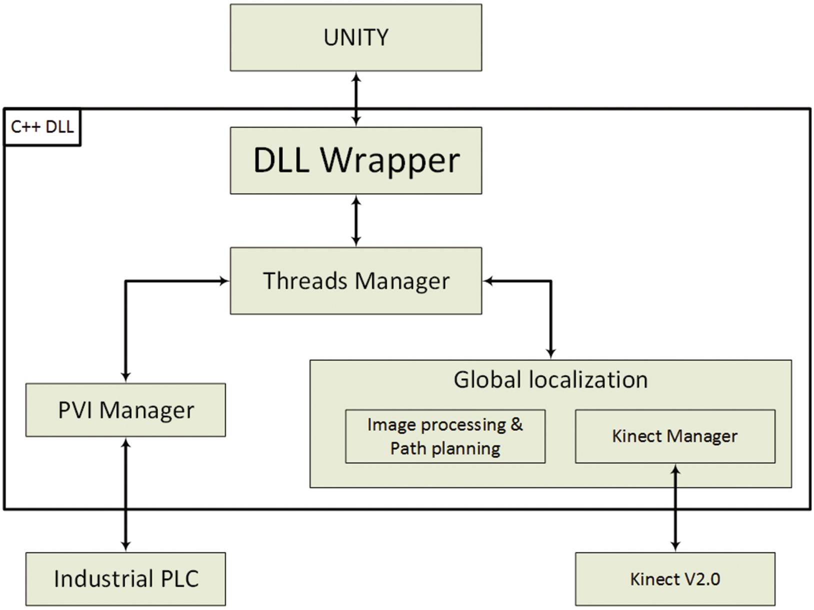

Fig. 3. Conceptual model of the C++ DLL

Starting from the lower level, two threads perform the localization and the communication with the industrial PLC. The localization includes the Kinect management, the image processing and the path planning modules.

Overall the following steps are performed at this level:

- *Data acquisition:* the algorithm acquires the information about colour and depth map from the Kinect;
- *Assessment of Kinect position:* the Kinect and the chassis are connected through a joint and so the position of the camera could be easily changed. Using RANSAC (RANdom SAmple Consensus) algorithm it is possible to calculate the height and the attitude of the Kinect with respect to the ground plane;
- *Roto-translation of the 3D points associated to the depth:* the Kinect provides the depth information in the camera reference frame. The data is then transformed to the reference system of the wheelchair;

- *Target detection:* the RGB frames retrieved from the Kinect are analysed using ArUco library to detect the markers in the field of view. The algorithm searches for couples of markers related to POIs, evaluates their 3D positions and then calculates the position and the attitude of the middle point, the POI;
- *Path calculation:* the path to reach the target is determined by using clothoids, a curve characterized by continuous third order curvature. The movement toward the target has to be as safe as possible. For this reason the paths are divided in two consecutive parts; a dynamic path that change according to the current position of the wheelchair and a fixed path for the final approach to the target;
- *Path sending:* a clothid can be expressed analytically by five parameters. The two paths, both clothoids, are sent to the PLC in this compact form by the thread that manages the PVI communication.

The classes that manage the threads are located on the second level. On the top, the wrapping class for C++ to C# conversion.

The Fig. 4 shows the HMI used to control the wheelchair with the AR information superposed to the foreground video stream. It is possible to see the pin icon related to the POI detected, in this case the door.

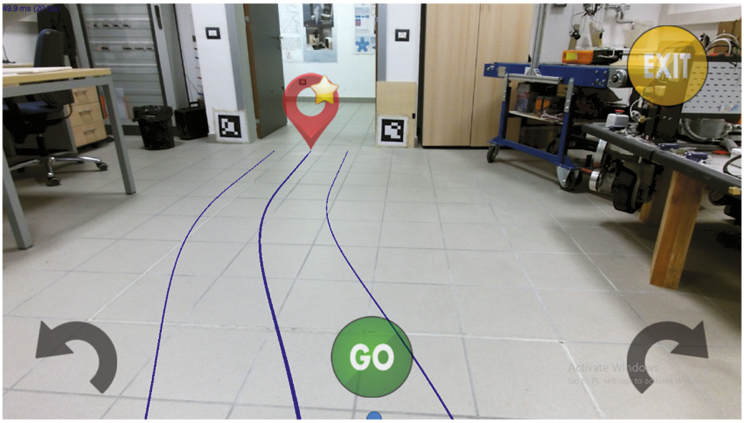

Fig. 4. HMI for the control of the wheelchair

3 Experimental Testing

The assessment of the performance of the semi-autonomous navigation was performed through a repeatability analysis on the final positions reached by the wheelchair.

Figure 5 shows the scheme considered during the test campaign. Two markers were attached on the jambs of a door, with a clearance of about 1.2 m.

Initial position and attitude of wheelchair (x', y', θ) are referred to the target reference frame (x, y), while (X_M, Y_M) define the wheelchair reference frame in (x, y). Initial conditions are the distance from target along x and y axis, respectively x' and y', and the initial wheelchair attitude θ.

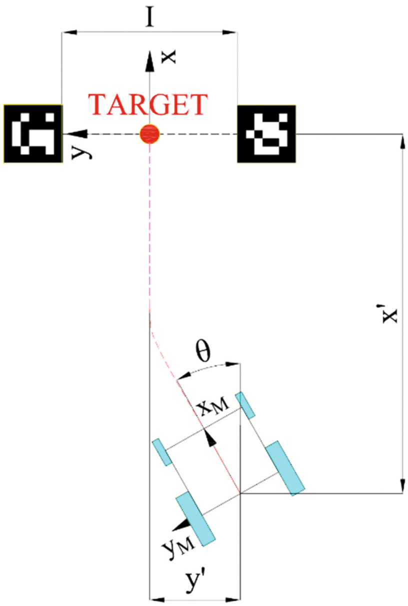

Fig. 5. Example of test scenario with the wheelchair arrangement with respect to the target position and attitude.

To evaluate the performance of the system the following tests were performed by analysing the final position and attitude repeatability. The tests are:

- The wheelchair always starts from a fixed position and attitude;
- The wheelchair initial position shifts only along the y′ direction with respect to the target. The y′ distance, related to each group of samples, was varied from −0.90 ± 0.01 m to +0.90 ± 0.01 m with steps of 0.30 ± 0.01 m;
- The wheelchair starts from a randomly generated initial condition (x′, y′ and θ).

Table 1 shows the initial conditions related to the tests. The uncertainty on the initial attitude for all tests was calculated using the uncertainty propagation law combining the information about the initial conditions (x′, y′).

Table 1. Description of the three tests performed for the repeatability analysis.

Test number	x′ distance	y′ distance	θ vehicle attitude	Number of samples
1	(4.26 ± 0.01) m	(0.61 ± 0.01) m	(0.0 ± 0.1) rad	30
2	(4.26 ± 0.01) m	Variable	(0.0 ± 0.1) rad	30
3	Variable	Variable	Variable	30

In Table 2 is reported the offset between the target position and the mean final wheelchair position, which represents the systematic error and can be compensated with a calibration, and the standard deviation which is the index of data dispersion (Figs. 6, 7 and 8).

Table 2. Results of repeatability analysis for the three types of test explained above, in terms of offset between target position and mean acquired one and principal axis of acquired data covariance.

	Offset from target in X axis [m]	Offset from target in Y axis [m]	Maximum principal std [m]	Minimum principal std [m]
1	−0.045	−0.003	0.024	0.014
2	0.034	0.028	0.049	0.013
3	−0.014	−0.054	0.064	0.026

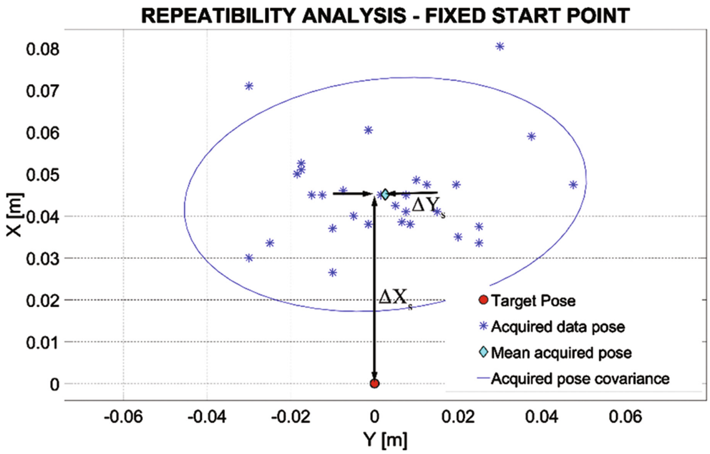

Fig. 6. Repeatability analysis results with the wheelchair starting from fixed position and attitude.

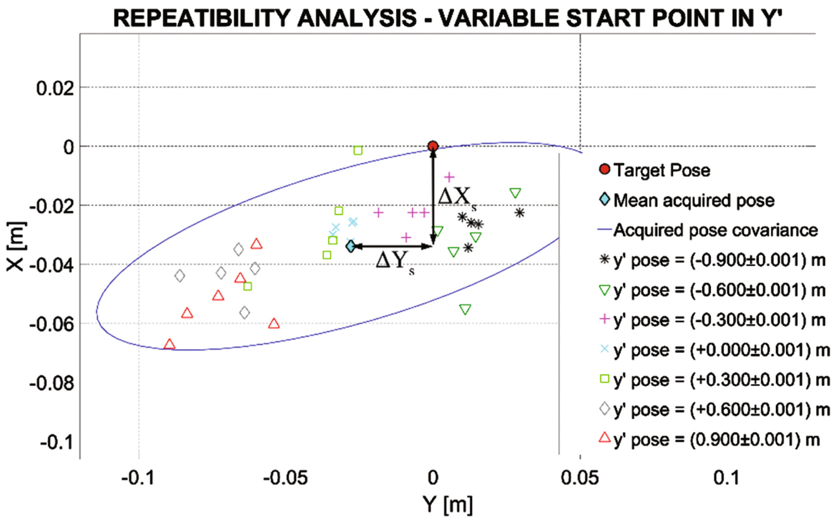

Fig. 7. Repeatability analysis results with the wheelchair starting from different y′ distances from the target position.

On the test characterized by a shift along the y′ direction, Fig. 7, it is possible to notice a correlation between the initial position of the wheelchair and the final position reached. Indeed, it can be noticed that the samples related to the same initial position are grouped close to each others.

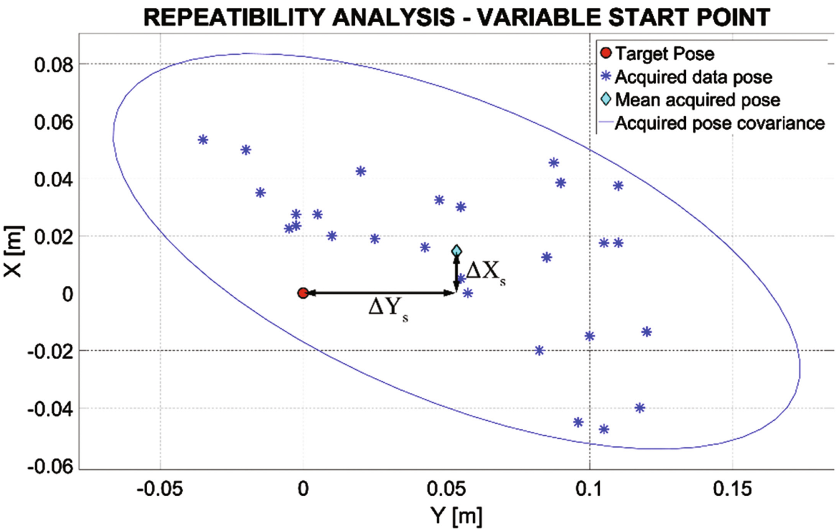

Fig. 8. Repeatability analysis results with the wheelchair starting from different positions and attitudes.

4 Conclusions

This paper focuses on the development of an Augmented Reality application based on a gaze interaction technology that is able to control semi-autonomously a wheelchair in a domestic environment. The performance of the system was evaluated by performing a repeatability analysis on the final positions reached, starting from different positions with respect to the target. In this way, it was possible to assess the influence of the starting position.

The repeatability analysis shows a maximum value (test with complete variable start point, Fig. 8) of deviation from the target position, transversal to the final desired direction of 0.18 m and 0.08 m longitudinally. From this information, we can conclude that considering a wheelchair width of 0.62 m, the minimum space actually that is required to reach autonomously a target is 0.98 m. Moreover, it is possible to notice a systematic deviation represented by the distances between the mean position of the sample and the target. This deviation can be related to the extrinsic parameters of the Kinect with respect to the vehicle that are not precisely known. As reported before, the Kinect is mounted on the chassis through a revolute joint characterized by backlashes in particular in the angle. This causes the systematic deviation highlighted in the final position reached by the wheelchair.

A future development is an on-line calibration of the Kinect extrinsic parameters by considering the changes in terms of position and attitude recorded by the odometric localization and by the Kinect absolute localization during the execution of the path. In this way, it is possible to compensate the systematic deviation and to prevent errors due to the possible variations of the position and attitude of the Kinect in the long periods.

As overall conclusion, we can say that the semi-autonomous navigation tool developed is suitable for indoor use in common houses having passages wider than 98 cm. An improvement of the performance of the overall project can be reached by the implementation of the on-line calibration tool together with an error budget analysis. Architectural house design criteria can take benefits from the error budget results in order to enhance the user mobility experience.

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