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Indoor Localization System based on Artificial Landmarks and Monocular Vision

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Abstrak

Makalah ini menyajikan pendekatan lokalisasi visual yang cocok untuk lingkungan rumah tangga dan industri karena akurat, handal dan estimasi pandangan yang baik. Robot mobile dilengkapi dengan kamera tunggal yang meng-update pandangan kapanpun ketika terdapat landmark. Inovasiyang disajikan dalam penelitian ini difokuskan pada sistem landmark buatan yang memiliki kemampuan untuk mendeteksi keberadaan robot karena kedua entitas berkomunikasi satu sama lain menggunakan protokol sinyal infra merah termodulasi frekuensi. Selain ini kemampuan komunikasi, setiap landmark memiliki beberapa LED intensitas tinggi yang bersinar hanya untuk beberapa kasus sesuai dengan komunikasi, yang memungkinkan bekerjanya alat pengatur cahaya kamera dan berkedipnya LED untuk sinkronisasi. Sinkronisasi ini meningkatkan toleransi sistem tentang perubahan kecerahan pada lampu ambien dari waktu ke waktu, secara independen dari lokasi landmark. Oleh karena itu, langit-langit lingkungan yang dihuni dengan beberapa landmark dan Extended Kalman Filter digunakan untuk menggabungkan perhitungan mati dan informasi landmark. Hal ini meningkatkan fleksibilitas sistem dengan mengurangi jumlah landmark yang diperlukan. Evaluasi eksperimental dilakukan dalam lingkungan indoor nyata dengan purwarupa kursi roda otonom.

Kata kunci: beacon aktif, landmark buatan, lokalisasi visual, navigasi robot

Abstract

This paper presents a visual localization approach that is suitable for domestic and industrial environments as it enables accurate, reliable and robust pose estimation. The mobile robot is equipped with a single camera which update sits pose whenever a landmark is available on the field of view. The innovation presented by this research focuses on the artificial landmark system which has the ability to detect the presence of the robot, since both entities communicate with each other using an infrared signal protocol modulated in frequency. Besides this communication capability, each landmark has several high intensity light-emitting diodes (LEDs) that shine only for some instances according to the communication, which makes it possible for the camera shutter and the blinking of the LEDs to synchronize. This synchronization increases the system tolerance concerning changes in brightness in the ambient lights over time, independently of the landmarks location. Therefore, the environment's ceiling is populated with several landmarks and an Extended Kalman Filter is used to combine the dead-reckoning and landmark information. This increases the flexibility of the system by reducing the number of landmarks required. The experimental evaluation was conducted in a real indoor environment with an autonomous wheelchair prototype.

Keywords: active beacons, artificial landmark, robot navigation, visual localization

1. Introduction

In the near future, mobile robotic systems will become an integral part of our daily lives. To make some of these systems completely autonomous, mobile robots require a practical and reliable localization system as this is fundamental for them to correct the execution of their tasks. In addition to the localization system, incorporating computer vision in a mobile robot allows it to perform other activities related to navigation (collision avoidance [1] , path planning and control decisions [2]) or even surveillance (person recognition). However, there is a major drawback related to the light variation in the environment, which normally compromises the applicability and performance of computer vision techniques. For that reason, the task of detecting the artificial landmarks based on color extraction is very conditioned, requiring an automatic color compensation method.

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This article addresses the problem of a generic, robust and accurate indoor localization system based on artificial landmarks and a single camera. Similarly to the explorers who used the stars to navigate their boats between continents, the approach presented here is based on a constellation of landmarks placed on the ceiling. This will allow several robots to simultaneously locate themselves. The presented method includes two phases: mapping and localization. This article focuses on the localization process since it represents what is new and what is different from the approaches presently described in the literature. The mapping creates the *prior knowledge* on the position of each landmark in the environment, for example, a common simultaneous localization and mapping (SLAM) technique can be used in this step in order to automatically generate relations between landmark positions. After the mapping stage, the robot can move freely in the environment, using the current visual information to determine position and orientation. The core of this localization method is the "intelligent" landmark, which is called *Synchronized Color Landmark* (SCL) in this paper as this is composed of a cluster of RGB LEDs (with different colors) which shine synchronized with the camera shutter, using a communication protocol that resorts to a frequency modulated infrared signal whenever the robot is close. The high intensity RGB LEDs and the synchronization made the system highly immune to external light sources, which represents an enormous advantage comparatively to other similar methods. This concept, called *SincroVision* (patented),is under development at the Faculty of Engineering of the University of Porto. The aim is to automatically teach robotic manipulators [1] .

The system is evaluated considering its robustness and accuracy in a robot platform-autonomous wheelchair, *IntelWheels* [4-6], and in realistic testing scenarios. The results were obtained with a real person sitting on the wheelchair, which represents a drawback for the localization accuracy due to the unbalanced weight distribution and movements made by the person. Given the intermittent availability of the landmarks, an Extended Kalman Filter (EKF)is used to update the dead-reckoning estimation. One major contribution of this research is the remarkable accuracy and robustness of the localization system, even in a presence of illumination instabilities.

This paper is organized as follows: the next section introduces a brief presentation about some related works. Section 3 provides a detailed explanation about the localization concept. Section 4 analyzes the robustness and accuracy performances, and finally, Section 5presents the main conclusions and topics for future research.

2. Related Work

The literature on mobile robots localization in indoor environments is long and rich, with many different sensor approaches and methods. Focusing only on localization systems based on landmarks, it is possible to find two methodologies: natural and artificial landmarks.

Natural landmarks have become increasingly popular because they do not require external infrastructures for localization as they usually resort to laser range finders (LRF) and cameras to extract features from the environment. A feature extraction algorithm based on Curvature Scale Space and laser range finder data are presented in [7] . In this approach the extract curvature extreme obtained using a laser scan data corresponds to a landmark at different scales (invariant to rotation and translation). Other approach can be found in [8] , which uses an Iterative Endpoint Fit with weighting as segment extraction of the LRF data. According to this work, the 2D environment can be described using vertex and line segments. The uncertainty of the line feature was estimated based on the Hough Transformation and incorporated in an EKF-SLAM. The research presented in [9] shows a SLAM method based on feature extraction (landmarks) using a charge-coupled device camera. The extracted SIFT (scale-invariant feature) features are used with the dead-reckoning information to allow an incremental map building of the indoor environment without *a priori* knowledge. The research in [10] presents an interesting performance analysis of several localization methods: SURF (speeded up robust feature), WIFI, color histogram and HoG (histogram of oriented gradients) based on low cost sensors that can easily be found on smartphones. This work revealed that the SURF is a good landmark extraction. Most visual methods extract the landmarks based on SIFT. For instance, [11] uses a stereoscopic camera and [12] uses a monocular camera to generate features and EKF-SLAM. Others similar approaches can be found in [14] .

Nowadays, methods based on natural landmarks still present some restrictions and for that reason some researchers prefer artificial landmarks. Perhaps the most used technology to identify landmarks is the RFID (radio-frequency identification)tag. In particular, the researches in [17] present method that resorts to the read-time of the RFID antenna and to the relation between the previous and current passive RFID in order to estimate the robot's pose. This method uses 34cm tag spacing, leading to a tremendous number of RFID tags in a small environment. The performance registered in these experiments revealed an 8cm error, which is acceptable for indoor environments. A passive RFID method (with 50cm of tag spacing), where each tag is placed on the ceiling with 260cm of height, is presented in [19] .The robot uses the UHF (ultra high frequency) RFID reader which detects the tags and transmits this information to a server containing the tag position. After computing the position of the robot, the server sends the information back to the robot. This method is very interesting; however, it does not rely on self-localization and the localization error obtained was more than 50cm.

An approach which combines stereo vision and RFID can be seen in [20] . The artificial landmarks based on RFID (each containing their identification and global position) and the LEDs are activated by a laser beam. The identification and position are retrieved by the RFID reader and the stereo vision detects the LEDs and computes the pose of the robot using the principle of triangulation. The root-square error for this method was less than 2cm. Another interesting study can be found in [21] where coded infra light is used as an artificial landmark on the ceiling. A fusing method to update the dead-reckoning using the landmark information is also presented which decreases the uncertainty of the robot's configuration. The work presented in [22] focuses on an industrial environment, where the global localization of one AGV equipped with an LRF is accomplished by measuring the range and bearing of the robot to a set of indistinguishable reflective landmarks.

Artificial landmark methods are commonly used in industrial and domestic fields because it is quite simple to populate the environment with the landmarks. Subsequently, it is possible to use a mapping method to retrieve the global position of each landmark, in a reliable and easy way. In [23] a mapping method is proposed for artificial landmarks based on dead-reckoning and laser range finder. The grid SLAM detects the landmark based on a landmark detector, extracting and saving their position on the grid map which can later be used for the localization process.

The research presented in this article focuses on some important features that every visual localization method should comprise: reliability, robustness to light changes and accuracy (less than 5cm). To accomplish these features, an innovative localization system based on a single camera is proposed to detect visual artificial landmarks placed on the ceiling. The technique resorts to high-intensity RGB LEDs synchronized with the camera shutter, which makes the overall system very tolerant to environment lighting. Most of the localization methods that use cameras are subjected to the influence of light. In contrast, the performance of the technique presented here does not depend on the illumination factor. As a result, excellent localization estimation is possible regardless of the type of indoor environment.

3. The proposed system

The system is based on artificial landmarks (SCL) placed on the ceiling, and monocular vision. A single landmark is formed by a communication mechanism based on an infrared communication protocol modulated in frequency and several high intensity LEDs that blink only at some instances. Whenever a robot is detected, that is, when the landmark receives the correct infrared signals from the environment (meaning that a robot is in range), the blinking of the LEDs and camera shutter are synchronized. High intensity LEDs in sync with the camera decreases the influence of ambient lighting, making detection more robust and immune to changes in brightness. These LEDs emit a high intensity light overshadowing most of the other light sources. Therefore, they are more suitable for the localization method proposed here. Another advantage with synchronization is related to human comfort as they will have to share the environment with the proposed localization system. The advantage is that the LEDs are switched-on during a very short time period which does not affect people's vision [1] energy consumption is reduced and the longevity of the LEDs is increased.

This visual approach made it possible to perform a pose estimation that is accurate and reliable regardless of the environment and task. Therefore, by placing the landmarks on the ceiling, it is possible to reduce the obtrusive level of the original environment. This system can be used by different robots simultaneously as they do not experience any occlusion (such as RFID solutions for instance).

3.1. Overall Architecture

The proposed system is based on two components: the Robot and SCL. The robot resorts to a camera with external trigger for the synchronization with the SCL, which must have a unique and distinctive color sequence.

The synchronization between image acquisition and the SCL is accomplished by an infrared signal modulated in frequency. This signal is sent by the robot's *trigger controller* to the SCL present in the environment. Whenever a landmark is in range, it receives the infrared signal from the robot and triggers their visual RGB LEDs. At the same time, the landmark sends the infrared signal back to the robot and the camera shutter is triggered. The cluster of LEDs is detected and the landmark is identified by the algorithm based on *a priori* knowledge, see Figure 1. This way the landmark is able to respond to several robots using a FIFO (first-in, first-out) approach. Since the environment is populated by several SCL, an artificial *constellation* is created on the ceiling and the distance between each landmark is directly related to the accuracy required by the robot to perform its tasks.

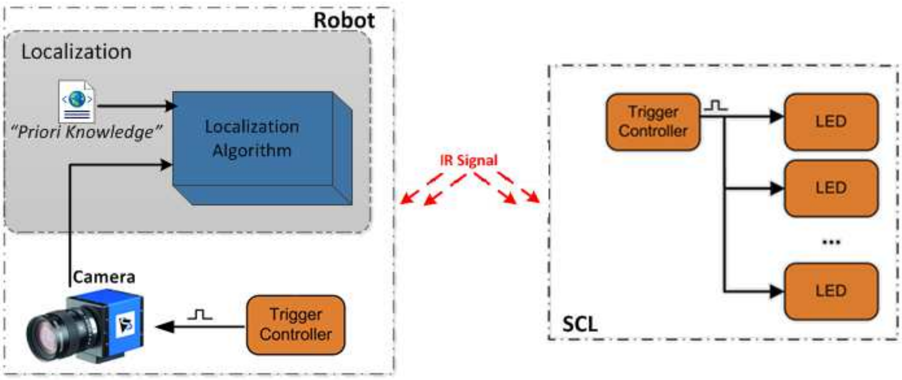

Figure 1. System architecture: The robot's localization module and the SCL landmarks that are placed on the ceiling.

3.2. Localization procedure

The localization algorithm presented in this paper is based on five steps. The first should be performed before the localization process since it retrieves the "*priori* knowledge" on the current position of landmarks in the environment. This means that each SCL is identified, for instance, using a conventional EKF-SLAM approach. Each SCL consists of a number of LEDs that must be adjusted based on the size of the environment where the robots move. There is no limit to the number of LEDs used by each SCL and they should increase as the size of the environment increases or when higher localization accuracy is required. Obviously, the color combination of LEDs in each SCL must be unique in order to allow a more complete identification.

The second step focuses on "cluster detection", which is a pre-processing stage and implements the *SincroVision* concept. Briefly, this step calibrates the camera, the landmark's height (that will be further computed based on the distance between the LEDs captured in the image), defines the navigation axes of the robot, and finally, the color calibration. This way, it is possible to obtain the required color palette.

After this, during the "cluster filter stage" all clusters of pixels whose size is not within the range defined in relation to a typical size of a LED are eliminated. The SCL at shorter distance are considered more reliable and, therefore, the localization phase will only consider the LEDs that are closer to the robot (a large distance between one LED and a set of other LEDs means that the LED belongs to another cluster).

Furthermore, each cluster (set of LEDs with closer distances) is identified in the "LEDs Identification" step. Since the SCL can be distinguished by their unique color combination, it is possible to identify the LEDs based on the *a priori* knowledge and, therefore, knowing the position of each LED at the global coordinate reference belonging to a detected landmark; it is possible to estimate the robot’s pose. Thus, the "LEDs Identification" stage aims at identifying every landmark that will be used in the localization step. The identification is achieved by the color combination of detected LED sand; therefore, it will be possible to provide information on the position of each LED in the world reference frame. The identification is performed by searching all previously imported artificial landmarks.

The following and final stage is the "localization" stage. Given the positions of LEDs of one SCL described in the global reference and the position of the same LEDs described in the navigation reference, it is possible to determine the position and orientation of the robot. Figure 2depicts the localization concept based on a cluster formed by one green (L1) and one yellow (L2) LED. It is important to highlight thatX_i^j is the value for the Cartesian component X, is the value of the LED "i" and described in the frame "j", and vice-versa for Y_i^j.

The first step to compute the robot's pose (X_R^0, Y_R^0, Θ_R) is finding the angle between the global (X^0 , Y^0) and the navigation frame (X^1 , Y^1), that is, the robot's orientation.

$$\Theta_R = \alpha - \beta \quad (1)$$

$$X_R^0 = X_1^0 - X_1^1 \cos\Theta_R + Y_1^1 \sin\Theta_R \quad (2)$$

$$Y_R^0 = Y_1^0 - X_1^1 \sin\Theta_R - Y_1^1 \cos\Theta_R \quad (3)$$

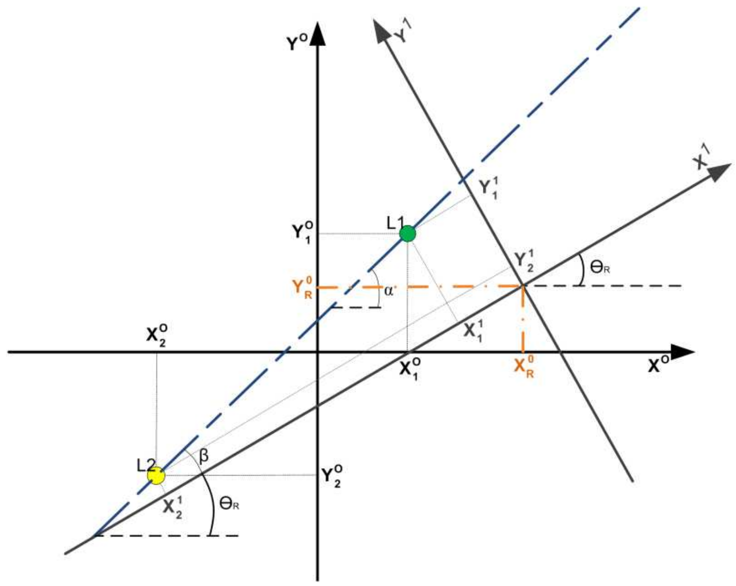

Figure 2. Localization based on a single landmark formed by 2 LEDs (green and yellow).

Given the virtual line (dashed blue), see Figure 2, which passes by the two LEDs (L1 and L2) and computing their slope (α- the angle described in the global reference and β- the same angle but described in the frame of the robot), it is possible to determine the orientation of the robot (Θ_R). Equations (1), (2) and (3) are used to compute the localization of the robot and define the minimum number of LEDs in each cluster (SCL) as two. In these equations, the L1 position is used in order to compute the robot's position, however, it is also possible to use L2.

The algorithm presented is cyclically executed over time, with the exception of the first step "*a priori* knowledge", which can be performed only at the beginning or even in the SLAM architecture.

4. Results and Discussion

Several experiments were conducted in order to evaluate the performance achieved by the localization system. The tests were made over a large periods of time, different navigation circumstances and different environment conditions.

4.1. Robustness

The first step to analyze the performance is confirming robustness against factors that may compromise the integrity of the visual detection. The impact and influence of ambient brightness on the accuracy of the localization system were tested. This way, it was possible to compare two cases: the detection of the SCL with and without the presence of intense artificial lighting. The results below provide the image obtained by the camera (Figure 3a) and the resulting images of the pre-processing stage (Figures 3b and 3c), where only the colors that were previously defined are represented, that is, pixels that have colors of the LEDs that are necessary to identify in the original image.

To reduce the influence of the environment light sources, the aperture of the onboard CCD camera is intentionally minimized. This way it is possible to reduce the amount of light that enters the camera (this is why Figure 3a is darker).

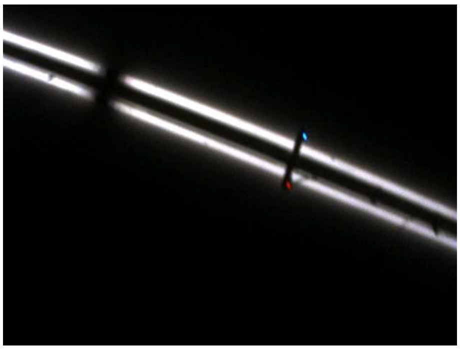

Figure 3a. Original camera image with external illumination.

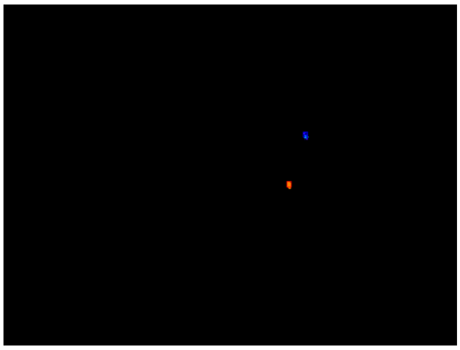

Figure 3b. Pre-processed image with color identification of the image with external illumination (Fig. 3a).

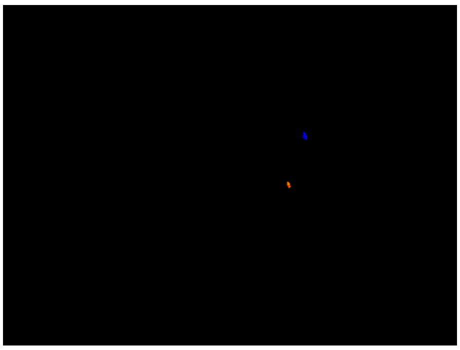

Figure 3c. Pre-processed image with color identification of the image without external illumination (the original camera image was not presented because it is quite similar to this one. This happens because every the environment light sources were turned off).

These Figures show the detection of the artificial landmark with color identification of each LED, with and without external illumination. It is possible to confirm that even with the SCL directly in front of the environment light sources the LEDs are correctly detected and identified, which means thatthe localization system is not affected by external light. During the tests, there was no problem related to an erroneous identification of the SCL, since the algorithm defines the typical size of a LED. Therefore, detected clusters of pixels without proper size are neglected.

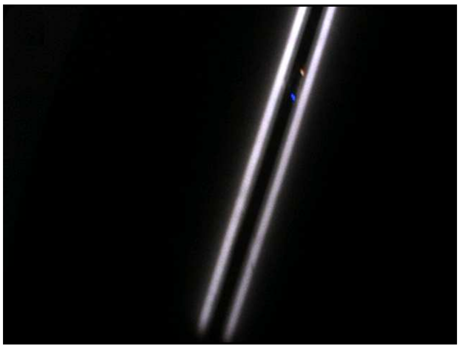

Figure 4a. Original camera image with external illumination. Similar color between a LED and the environment light sources.

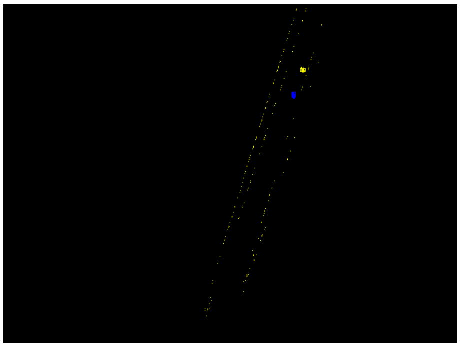

Figure 4b. Pre-processed image based on color identification of the image with external illumination and similar color between a LED and the environment light sources.

LEDs with a color identical to the environment source lights are not very recommended for the system (see Figures4a and 4b). Nevertheless, (see Figure 4b) the yellow LED was completely detected since the proposed algorithm has several steps that make it possible to verify consistency (such as LED size, distance between adjacent LEDs, valid color sequence) of the captured information in order to retrieve a reliable extraction of the landmark.

In these experiments we show that the SCL can be placed on the ceiling, even near to an external illumination which is an advantage because we can use the power supply of these illuminations to power up each SCL. This turns the system flexible and more practical in indoor environments since the tests did not produce any erroneous localization for the robot.

4.2. Error characterization

This section describes the localization accuracy achieved by this system. The results with direct measurements are compared in order to characterize the error obtained by this innovative localization system. In the experiments, 50observations were made per series (a total of 25 series) on the real robot’s pose. The influence of the illumination factor in the system is also characterized in these tests as the accuracy of the system with and without environment light sources is evaluated.

Table 1. Error characterization with and without light sources (fluorescent lamp).

	Position Error (m)	OrientationError (º)
With	0.0283	0.645
Without	0.0248	0.705

Table 1 presents the error of the proposed system. Although in the absence of the artificial light the mean error lower obtained was lower, the gap is so small that it is possible to infer that the environment’s light sources do not have an influence on this system, considering this scale of accuracy. This minor gap is caused by the size of each LED which is different in both conditions as the centroid position of the LEDs is used to compute the pose estimation.

4.3. Comparison with the Stargazer

The performance of the proposed method is compared with a commercial landmark-based localization system –the StarGazer [24] .The StarGazerwas evaluated under several environment light conditions and different ceiling heights.

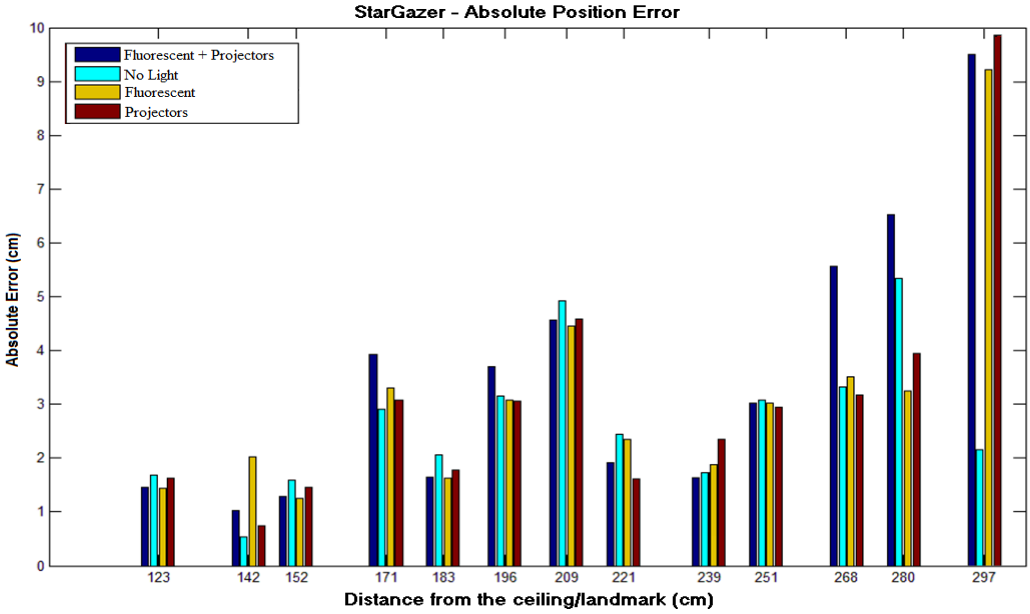

Figure 5. Stargazer-Error evolution at different ceiling distances and under several environment light sources. The error increases with the distance to the ceiling. Excluding the distance of 3 meters, the performance did not reveal significant variations with the light condition.

Even though the system is based on infra-redland marks, the performance of the StarGazer remains significantly the same for different lighting conditions (See Table 2). Nevertheless, the performance is highly influenced by the distance to the ceiling (see Figure 5). This is an important disadvantage since it compromises the reliability of the localization in ceilings with different heights; and therefore reduces the system's flexibility as it cannot be used in every type of environment.

Table 2. StarGazer-Error characterization with and without light sources (fluorescent lamp).

	Position Error (m)	OrientationError (º)
With	0.0295	0.853
Without	0.0248	0.812

Therefore, the system proposed in this article reveals higher accuracy (less absolute errors) and is not influenced by the ceiling's height. However, the system is based on active landmarks, which is a disadvantage because it requires a power supply.

4.4. EKF in a Real Robot

Finally, the performance achieved by the robot (intelligent wheelchair) was studied in a real environment and under a realistic scenario. The EKF is used to estimate the location based on dead-reckoning and artificial landmarks. The tests were performed using only three SCL with two LEDs each. The main purpose was to analyze the robot's capability to execute transportation tasks without getting lost in an environment with fewer landmarks. The landmarks on the ceiling originate areas where the robot can update its pose estimation-in Figure 6 this area is represented in green and the desired robot's path is represented in blue. As it is possible to see, there are three SCLs in the environment with spacing of more than 3m.

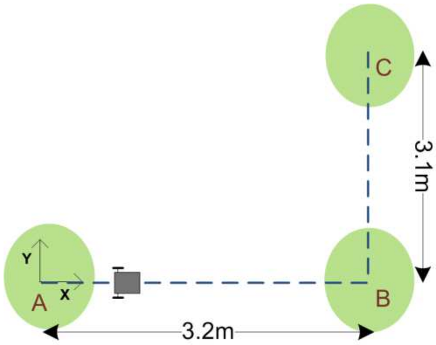

Figure 6. The setting of 3 SCL in the environment.

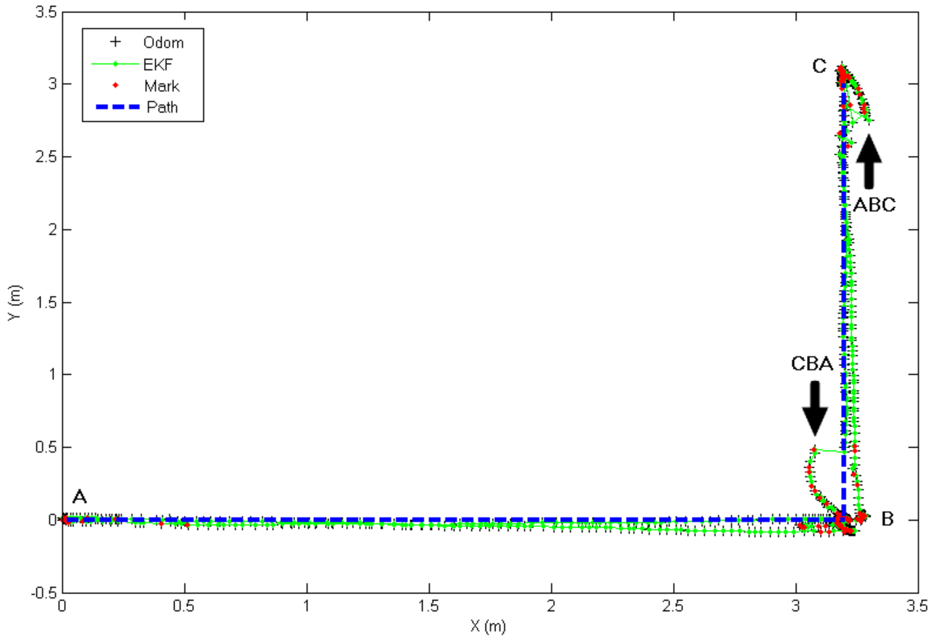

Figure 7. Pose estimation duringthe path: estimation based on odometry, landmark and EKF.

The desired path starts in point A and goes to C passing by B. At point C the robot picks the human person and then it returns to point A in the same manner. Therefore, the path is A-B-C-B-A. This path makes it possible to compare the performance of the robot's localization while moving in a realistic test scenario.

Figure 7 presents the desired and executed (green) trajectory during the path. The robot uses odometry to estimate its pose when no SCL is available (red dot). As a consequence, during this period the state of the robot is only provided by the encoders and there is an accumulation of errors proportional to the displacement. However, when a SCL is available the state of the robot is updated and the movement corrected in order to accomplish the navigation task (see the arrows in Figure 7).

Figure 8 shows the pose evolution during the execution of the A-B-C-B-A path. The top graph represents the X coordinates, the middle graph represents the Y coordinates and the one on the bottom represents Orientation (-180º to 180º) (see Figure 6 for global reference position). It is important to highlight that it is not possible to obtain the localization error during the entire path because there is no indoor localization system capable of providing a reliable ground truth with more accuracy better than the localization system proposed by this research. However, the important result that this works intends to demonstrate is the robot's ability to navigate in an indoor environment with the proposed localization system, even with only a few landmarks to update pose estimation. All the tests were conducted in a realistic scenario where the autonomous wheelchair navigates with a human at an indoor environment. The robotic platform is highly conditioned by odometry because its wheels are from an ordinary wheelchair, which causes large odometry errors resulting from the lack of balance in human weight. Therefore, better results are expected to occur with other type of robots (such as AGVs, for instance).

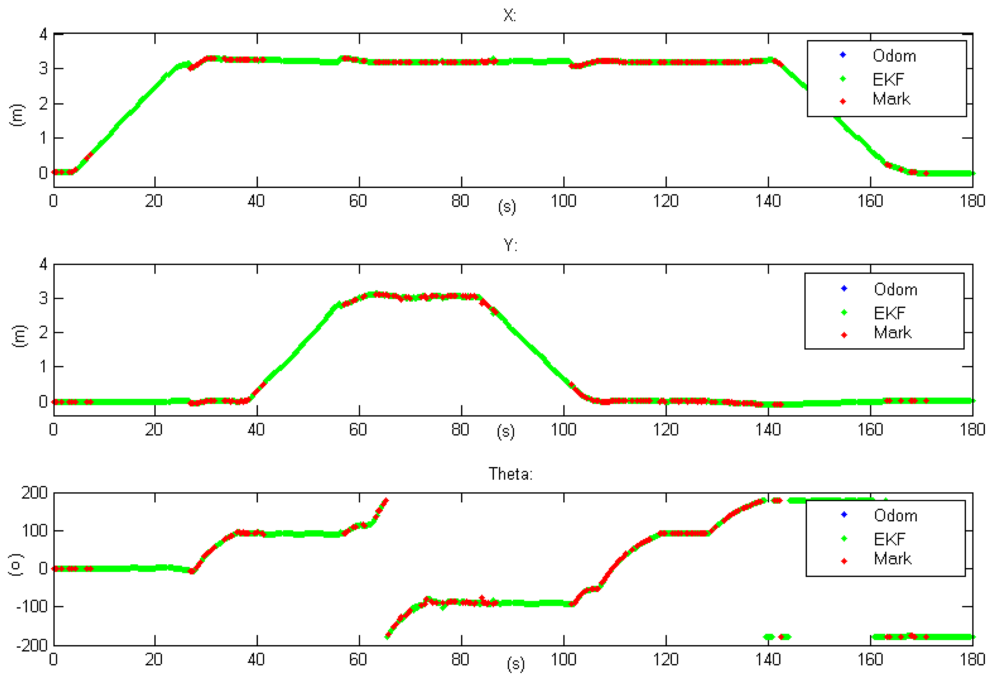

Figure 8. Temporal evolution of the robot's localization using EKF.

5. Conclusion

This paper presents a precise and reliable indoor localization system that can be used in both industrial and domestic environments. This method uses innovative artificial landmarks (clusters of high intensity RGB LEDs) on the ceiling which create a *constellation*. The landmarks use infrared signals modulated in frequency to synchronize the blinking of their LEDs with the robot's camera shutter. This synchronization reduces the influence of the environment light sources on the localization system. It also prevents any inconvenience for the human that cohabitates in the environment where the system is installed because the high intensity RGB LEDs do not affect human vision (the light of the SCL is very soft for humans).

The localization method was rigorously tested using a real robotic platform, that is, an autonomous and intelligent wheelchair. The results obtained by the method make it possible to conclude that the robot localization achieved was very accurate and a greater accuracy is expected using other robotic platforms (rigid structure which leads to a more stable camera support).Usually the biggest disadvantage of using an artificial landmark approach is changes in the original environment. However in environments where this change is somewhat simple, the technique is a robust and realistic approach to be used, for instance by a massive production of mobile robots.

In addition, the landmark proposed by this research leads to a very accurate and reliable localization and it increases the flexibility of the system because it is easy to install and to maintain. This happens because the system uses the infrastructures that are already present in almost every indoor environment.

6. Acknowledgments

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