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Laser-activated RFID-based Indoor Localization System for Mobile Robots

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***Abstract*—Localization is a fundamental problem in autonomous mobile robot navigation. This paper introduces a new artificial landmark-based localization system for mobile robots navigating in indoor environments. Laser-activated RFID tag is designed and used as the artificial landmark in the proposed localization system. The robot localization is realized via the combination of the stereo vision and laser-activated RFID based on the principle of triangulation. The localization system functions like an indoor GPS. Preliminary research shows that the proposed system is promising to provide a robust and accurate indoor localization method for mobile robots.**

I. INTRODUCTION

Localization is a fundamental problem in autonomous mobile robot navigation. It refers to the determination of the position and orientation of a mobile robot through the analysis of sensory data. This paper introduces a laser-activated RFID-based localization system for mobile robots navigating in indoor environments.

Tremendous effort has been made to the study of the mobile robot localization. Existing localization techniques for mobile robots in indoor environments can be classified into two categories: relative localization, including odometry and inertial navigation, and absolute localization, including active beacon, landmark and map-based localization. In general, these techniques apply to not only indoor but also outdoor applications. Besides, an important technique special for outdoor robot navigation is the GPS-based localization.

The objective of our research is to create a fast and accurate absolute localization technique for mobile robots moving in indoor environments. We intend to learn from the merits of the existing localization techniques and solve the problems with the existing localization systems. The design of the proposed localization system is inspired by the GPS and RFID-based localization techniques. In this section, we review some works on these two techniques.

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A. *GPS -based localization*

Global Positioning System (GPS) is a worldwide radio-navigation system developed by the US Department of Defense. It is formed from a constellation of 24 Earth-orbiting satellites (with 3 backup satellites) and their ground stations. These satellites are used by GPS receivers as reference points. The absolute position of each satellite is maintained and updated at the satellite, which eliminates the need of a central database. By measuring the time-of-flight of the satellites' radio frequency signals which include information about the momentary locations of the satellites, a ground-based receiver can identify the satellites and compute its own position based on the principle of trilateration. With clock synchronization and error compensation, the accuracy of GPS-based positioning has been improving. Regular GPS provides an accuracy of <10m (after the removal of Selective Availability) [1]. Differential GPS, with pre-determined reference stations, can offer a positioning accuracy of 1-2m [1]. Recent technology based on phase measurement can achieve an accuracy at centimeter or lower level, and real-time-kinematic (RTK) GPS can provide high positioning accuracy in motion [1].

GPS provides a convenient and powerful tool for outdoor navigation of mobile robots. Li used a simple GPS for coarse estimation of robot position in outdoor environments [2]. Lenain et al. used RTK GPS for accurate path tracking of an agricultural robot in presence of slippage [3]. However, GPS receivers require an unobstructed view of the sky, so they are used only outdoors. They often have increased errors near trees or tall buildings due to signal blockage and multi-path interference [4,5]. In other words, accurate distance measurement depends on "line-of-sight". In addition, latency caused by data transmission, processing and communication with multiple satellites increases the difficulty in dynamic applications [6]. A well-accepted solution is to fuse GPS data with odometry or inertial measurements to improve the outdoor positioning accuracy, which combines the long-term stability of GPS and short-term stability of dead-reckoning [7-12].

It is many people's believe that GPS will become the universal standard for outdoor applications [1,4]. However, an indoor equivalent to GPS is difficult to realize. Due to signal blockage and interference, none of the currently existing RF-based trilateration systems work reliably indoors. If the line-of-sight between stationary and onboard components can be maintained, RF-based solutions may work indoors as well.

B. RFID-based localization

Radio Frequency Identification (RFID) is a technology for automatically identifying objects by assigning an ID code to an electronic tag and retrieving the ID code using a wireless transceiver operating at radio frequencies. RFID features non-contact and non-line-of-sight readability. The RFID reader can detect the existence of a tag within a certain range. RFID tags can be active, which have a power supply for sending their responses, or passive, which are powered by the RF energy transferred from the reader. In general, active tags are more reliable and more expensive, and can be read over a distance of tens of meters; while passive tags are less reliable and cheaper, and can be read over a distance from a few centimeters to a few meters [13].

Recently, some research has been conducted on RFID-based indoor mobile robot localization, where RFID tags are used as artificial landmarks. A tag is easily identified by retrieving its ID code using an RFID reader. The tag ID can be used as an index to retrieve the accurate position of a tag from a database. Alternatively, since many RFID tags have their own flash memory, the position information of each tag can be stored on the tag directly and read out by an RFID reader later, which eliminates the need of a central database. This function can be very helpful in dynamic environments where landmarks move and need to update their locations from time to time.

RFID-based localization can operate in two different ways. One way is based on the fact that a reader can detect the existence of a tag when it moves into a certain range of the tag. The main advantage is that distance measurement does not depend on the line-of-sight. However, the localization is in general coarse even with a large number of RFID tags. In the works of Tsukiyama [14,15] and Kulyukin et al. [16-18], passive RFID tags were used as landmarks to remind the mobile robot its coarse position and decide next movement based on the ID information and a map of tags. Jia et al. used passive RFID tags as landmarks with known absolute positions to help vision-based localization [19]. Chae and Han proposed a localization method for mobile robot by dividing the environment into small regions and determining the region where the robot lies by weighing each tag (active tag) based on its distance to its region boundary [20]. Yamano et al. proposed an RFID-based mobile robot localization method using Support Vector Machine Learning [21]. Hahnel et al. developed an RFID-based localization method for mobile robots by first learning a probabilistic sensor model, which describes the likelihood of detecting an RFID tag given its position relative to the antenna, and then localize the robot using Monte Carlo localization based on the model [22]. The other way is to calculate the distance between a tag and a reader based on the time-of-flight, which may suffer from the inaccuracy due to a lack of the line-of-sight. Kim et al. developed an RFID system, including three orthogonal antennae, which determines the direction of a tag by comparing the signal strength in each direction and determines the distance between the reader and the tag based on phase shift [23].

The above discussion shows that GPS and RFID-based localization techniques have a common advantage, i.e. quickly identifying and locating each reference object by retrieving the unique ID code and location information stored in the reference object using a transceiver. It also shows that the line-of-sight is important for accurate distance measurement.

Inspired by GPS and RFID-based localization, we propose a new indoor localization system for mobile robots. The proposed localization system is artificial landmark-based, with a set of artificial landmarks pre-installed in an indoor environment with known absolute positions with respect to a global frame of reference, a set of onboard sensors to detect the artificial landmarks and an onboard computer to process the sensory data and localize a mobile robot. It is less expensive than a design which uses fixed sensors to track a mobile robot. Moreover, the distance between an artificial landmark and the mobile robot is measured along the line-of-sight. The general idea of the proposed localization technique is as following:

1) Artificial landmark design: A new type of RFID tag, the laser-activated RFID (LARFID) tag, is designed on the basis of an active RFID tag and used as the artificial landmark. Each LARFID tag has a unique ID, and after installation its absolute position in an indoor environment will be written into its flash memory. The LARFID tag comes with a bright LED which makes it highly detectable from camera images. The LARFID tag will be activated by a laser beam, and then its ID and position information can be retrieved by an RFID reader. The LARFID tag will be deactivated when the laser beam is removed.

2) Landmark detection and localization: An LARFID tag is represented by its LED, and its position is defined by the position of the LED. Stereo vision is used to detect the LARFID tags. The position of an observed LARFID tag relative to the mobile robot can be calculated based on the perspective geometry. A laser beam will be shot from the mobile robot to activate the tag, and an onboard RFID reader will detect the activated tag. The tag ID will be used to retrieve the stored absolute tag position via a follow-up inquiry by the RFID reader. Each time only one tag will be activated.

3) Mobile robot localization: The position and orientation of the mobile robot in the global frame of reference can be calculated based on the principle of triangulation. The position of a LARFID tag relative to the mobile robot contains both the distance and bearing information. The absolute position of the tag is also known via RFID communication. The position and orientation of the mobile robot can be determined based on three or more tags.

This paper focuses on the design of the proposed LARFID-based indoor localization system for mobile robots. The design and function of the proposed system will be explained in details in Section II. A prototype localization system will be introduced in Section III. Some results from our feasibility study will be reported in Section IV. The conclusion and future work will be presented in Section V.

II. Design Scheme of the LARFID-based Localization System

A new type of RFID tag, the laser-activated RFID (LARFID) tag, is designed on the basis of the existing RFID technique, and used as the artificial landmark in the proposed indoor localization system for mobile robots. The LARFID tag extends an active RFID tag with a light-emitting diode (LED) and a laser-activated switch circuit (Fig. 1). A function diagram of the LARFID-based indoor localization system for mobile robots is presented in Fig. 2.

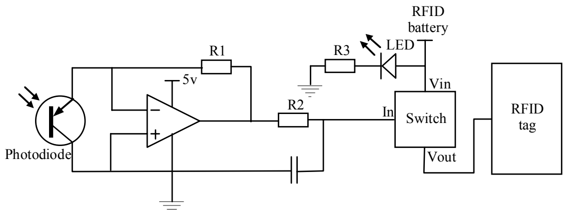

Fig. 1. Block diagram of the laser-activated RFID tag

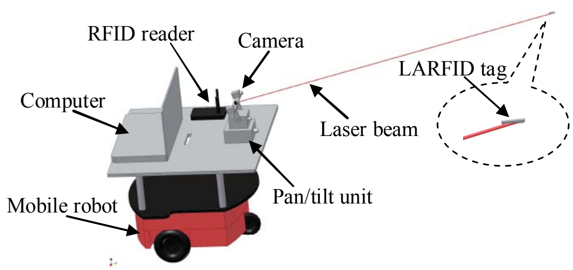

Fig. 2. Function of the LARFID-based localization system

A. *Active RFID tag as the base of the artificial landmark*

An active read/write RFID tag is used as the base of the designed artificial landmark. The main reason for using the active RFID tag is because it has its own power supply which can be easily controlled to activate and deactivate the tag. Moreover, comparing with passive RFID tags, active tags work more stable and can be detected over a longer range. As a result, a relatively small number of artificial landmarks are needed for mobile robot localization.

The unique ID of an RFID tag is used to identify the associated artificial landmark. An RFID reader is used to receive the assigned tag ID. The tag ID can be used as the index to retrieve the absolute position of the associated artificial landmark from a database. However, instead of doing this, in our design the absolute position of an artificial landmark is written into the flash memory of the underlying RFID tag and read out by the RFID reader. With this strategy, there is no need to maintain a central database for all the artificial landmarks in an environment for the purpose of mobile robot localization. More importantly, the stored position information can be updated, which makes the designed artificial landmark applicable to an indoor environment under change.

By identifying each artificial landmark using the unique ID of the underlying RFID tag, we intentionally avoid the shape-based and pattern-based artificial landmark designs. It may potentially reduce the cost of designing and fabricating a large number of uniquely-shaped or patterned artificial landmarks for applications in large indoor environments. As a result, the artificial landmarks in an environment have the same appearance.

B. *LED for landmark detection and localization*

With the understanding that the line-of-sight plays an important role in accurately locating an artificial landmark relative to the mobile robot, we choose to use a line-of-sight-based method, instead of a time-of-flight-based method, for landmark localization. An onboard stereo vision unit, consisting of two cameras with fixed transformation between them, is used to detect the artificial landmarks and measure the position of an observed artificial landmark relative to the mobile robot.

In order to make landmark detection robust and avoid substantial online image processing, a bright LED is attached to each RFID tag and kept on constantly (Fig. 1). In our design, the LED is regarded as the representative point feature of an artificial landmark, and the position of the artificial landmark is represented by the position of its LED. The apertures of the onboard cameras are intentionally minimized. As a result, with regular ambient lighting, the LEDs are shown as bright spots outstanding from the dark background in the images (Fig. 3). To find the artificial landmarks from an image, we only need to segment out the LED spots and find their centers, which does not require very complicated image processing procedure.

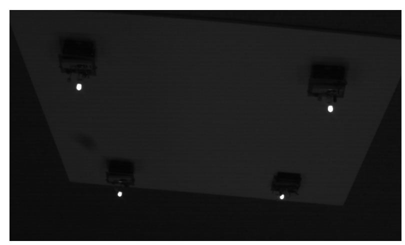

Fig. 3. Artificial landmarks as bright spots in the dark background

During each localization operation, a pair of images are taken from the stereo vision unit, one from each camera. The correspondence between the LED spots in the two images can be established by using a method such as epipolar line search [24] or combinatorial optimization [25]. In the work of this paper, we assume that a same set of artificial landmarks can be observed by both cameras, which can be realized in practice by adjusting the relative transformation between the two cameras and limiting the pan/tilt range of the stereo vision unit according to the distribution of the artificial landmarks in the environment. More complicated situations, e.g. unequal number of LED spots appearing in the two images, will be studied in our future work. With the known correspondence, the position of each observed landmark (LED) relative to the mobile robot can be calculated based on the perspective geometry.

C. Laser activation for mobile robot localization

Given the positions of some landmarks relative to the mobile robot, we also need to know the absolute positions of those landmarks in a global frame of reference in order to localize the robot in the same frame. In our design, the absolute position of an artificial landmark is stored in the flash memory of the associated RFID tag, and can be retrieved by inquiry with the tag ID using an RFID reader installed on the mobile robot.

There is a potential problem with regular RFID tags. With regular RFID tags, the RFID reader detects all the functioning RFID tags within its reading range. Meanwhile, stereo vision recovers some artificial landmarks based on their LEDs. However, the correspondence relationship between the artificial landmarks detected by the RFID reader and those observed by stereo vision is missing. Moreover, depending on how the artificial landmarks are distributed in the environment, at each moment some of them may be caught by the cameras, others may not. It may also be possible that the stereo vision unit detects some artificial landmarks which lie outside the range of the RFID reader and cannot be detected by the RFID reader.

To solve this problem, we add to each active RFID tag a photodiode-based switch circuit which stands between the battery and function part of the RFID tag (Fig. 1). In the proposed system, a laser pointer with pan/tilt capability will also be installed on the mobile robot. The modified RFID tag is called laser-activated RFID (LARFID) tag which will be activated by a laser beam sent from the mobile robot. Usually the switch circuit on an LARFID tag is off, and the tag is not powered and not functioning. When an LARFID tag is detected and its position relative to the mobile robot is calculated via stereo vision, the robot shoots a laser beam to the LARFID tag. The laser beam hits the photodiode and generates a voltage signal to open the switch circuit and turn on the power of the tag. Once the LARFID tag is activated, it will be detected by the onboard RFID reader. Then the RFID reader can retrieve the absolute position of the tag, which is stored in the tag memory, by a follow-up inquiry with the tag ID. After this operation, the mobile robot turns off the laser beam. Once the laser beam is removed from the photodiode, the switch circuit will be closed, and the tag will be deactivated. Intentionally, only one laser beam is used, and each time only one LARFID tag is activated by the laser beam. The mobile robot decides which tag to target, and the RFID reader knows which tag it detects. In this way, the correspondence between an observed LARFID tag and its ID is established successfully.

To avoid using an LARFID tag which is observed by stereo vision but lies outside the range of the RFID reader, we set a threshold value for valid distance measurement based on the capability of the RFID reader, tags and laser beam and the accuracy of distance measurement. Only those tags at a distance from the mobile robot shorter than the threshold are considered valid for robot localization.

D. Laser activation for robust landmark detection

Besides retrieving the absolute position of an LARFID tag, the laser activation operation provides an easy way to check and correct the landmark matching and reconstruction results from stereo vision. In general, if the position of an LARFID tag relative to the mobile robot is reconstructed based on the correct correspondence, then when the laser beam hits the targeted tag, it will be activated and detected by the RFID reader. Otherwise, no tag physically exists at the targeted location, and nothing will be detected by the RFID reader, which means a mismatch in stereo vision. Then the landmark matching in stereo vision can be partially redone with only those mismatches. As a result, landmark detection and localization becomes more robust. An alternative method can be also used when only a small number of tags are observed. In fact, with N tags caught by two cameras, there are totally N^2 possible tag locations in space. By shooting laser beam to every possible location, the robot can eventually figure out the N valid tag locations.

III. Prototype Localization System

An experimental system has been built for the feasibility study of the LARFID-based indoor localization technique for mobile robots. The system consists of a stationary subsystem and a mobile subsystem.

A. Stationary subsystem

The stationary subsystem of the proposed indoor localization system consists of a set of LARFID tags fixed on the ceiling of the indoor environment.

Our feasibility study took place in a lab space of 12m by 5.6m with a ceiling height of 2.5m. Four tags are fixed near the center of the ceiling (Fig. 3).

Our LARFID tag is built upon the ActiveWave CompactTag, a type of read/write active tag with a read range of 30m (Fig. 4).

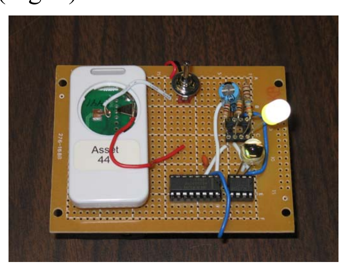

Fig. 4. Prototype LARFID tag

To assist the detection of the artificial landmark, an LED with a brightness of 11000mcd and a viewing angle of 360 degree is added to each RFID tag (Fig. 1 and Fig. 4).

To implement the laser activation, a switch circuit, mainly consisting of a photodiode and a switch IC, is added to control the power on/off of the active RFID tag (Fig. 1 and Fig. 4). With the reduced difficulty in controlling the direction of the laser beam, a slightly scattered laser beam, instead of a regular focused laser beam, is used in our experimental system. The cross-section of the laser beam has an elliptical shape, which is adjusted such that it is a 30mm by 10 mm ellipse at a distance of 2m and an 80mm by 20mm ellipse at 6m. The photodiode is placed next to the LED, which guarantees that the big laser spot also covers the photodiode when shot to the LED. The laser beam in our experimental system has a total output power of 6mw. The photodiode circuit is adjusted so that it can generate a signal of 2.4-5v which is high enough to open the switch within the valid measurement range. Once the laser beam is removed, the switch will be closed and the RFID tag will be deactivated. The photodiode is installed with a height lower than the bottom of the LED in order to minimize the voltage caused by the LED light.

B. Mobile subsystem

The mobile subsystem of the proposed indoor localization system consists of a set of sensors and a computer installed on a mobile robot.

In our experimental system, an Activmedia Pioneer3-DX mobile robot is used as the sensor carrier (Fig. 5). In the feasibility study, we did not use the original onboard sensors, such as encoders, gyroscope and sonar ring, with the purpose of testing the proposed LARFID-based localization technique.

Fig. 5. Prototype mobile subsystem

For detecting the LARFID tags and measuring their relative positions with respect to the mobile robot, a stereo vision unit, consisting of two MatrixVision BlueFox USB cameras with Kowa 12mm lenses, is installed on the mobile robot (Fig. 5). This stereo vision set is supported by a DirectedPerception PTU-D46-17 controllable pan/tilt unit which provides the stereo vision unit the landmark search capability (Fig. 5).

For identifying the tags and retrieving their absolute positions, an ActiveWave standard RFID reader is installed on the top of the mobile robot (Fig. 5). This RFID reader has a range of 85m for reading and 30m for writing.

For laser activation, in the proposed design, a laser pointer with controllable pan/tilt function will be installed on the top of the stereo vision pan/tilt unit so that a quick view-based re-orientation can be realized. This unit is still under development, and has not been integrated into the current experimental system. Instead, we operated a laser beam manually to activate the LARFID tag from various distances in our feasibility study, which mimics the function of the proposed system. An explanation of the laser beam we use was given in the previous subsection when we talked about the stationary subsystem.

A laptop computer is mounted on the top of the mobile robot, with Intel Celeron M 1.5GHz CPU and 512MB RAM. All the above-mentioned onboard devices are controlled by the computer, and the computations for stereo vision and localization are implemented by the computer.

IV. Results from Feasibility Study

Experiments have been conducted with our experimental system to test the feasibility of the proposed LARFID-based localization technique.

The laser activation function has been tested by shooting a laser beam, described in Section III, to an LARFID tag from various distances and angles. It shows that the LARFID tag can be activated and detected by the RFID reader robustly from any distance between 2m and 7m, where 2m and 7m are the shortest and longest distance between a tag and the mobile robot in our experimental environment.

The localization accuracy of the proposed system has also been tested extensively. Given the absolute positions of the tags in a global frame of reference, the localization accuracy for the mobile robot depends on the positioning accuracy of the tags relative to the robot. The positions of the tags relative to the mobile robot are obtained via stereo vision. To test the localization accuracy, we at first calibrated the cameras using a camera calibration toolbox for Matlab available at
http://www.vision.caltech.edu/bouguetj/calib_doc/.
A printed black/white checkerboard pattern was used, with different poses and at different distances from 1m to 2m, to find out the intrinsic parameters of the cameras, such as focal length, image center and distortion coefficients, and the transformation between the two cameras. Then we fixed two LARFID tags on the ceiling with a certain distance which was carefully measured by hand. We input two simultaneous images from the two cameras, corrected the distortion, segmented the bright spots and reconstructed the 3D positions of those two tags with respect to a camera frame. The distance between the two reconstructed tags was calculated and compared with the known physical distance. The difference between them reflects the error in distance measurement. This procedure was repeated many times with various distances between the tags and various distances between the tags and the cameras. The root-mean-square error was taken as the error measure (Fig. 6). The results show that with the above less accurate calibration pattern and segmentation, the distance measurement of the experimental localization system can still have an accuracy of $<$20mm from a distance of about 7m, which, as we believe, is sufficient for most of the indoor mobile robot applications. The results also show that the measurement error generally increases with respect to the distance under measurement. The underlying reason is that the resolution of the cameras decreases as the distance increases.

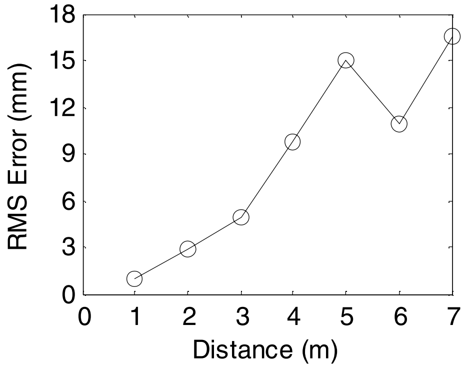

Fig. 6. Variation of root-mean-square (RMS) measurement error with respect to the distance between the camera and landmark

V. CONCLUSION

This paper introduces a new artificial landmark-based indoor localization system for mobile robots. The proposed localization technique is inspired by the existing GPS and RFID-based localization techniques. In the proposed system, a new type of RFID tag, the laser-activated RFID tag, is designed and used as the artificial landmark. The LARFID tags function like the indoor equivalent of the GPS satellites. Stereo vision and LARFID are combined, together with triangulation, to localize a mobile robot in an indoor environment. Feasibility study shows that the proposed system is promising to provide a robust and accurate indoor localization for mobile robots.

Some future research need to be conducted to complete the proposed system. A controllable laser unit is under development, and will be installed on the mobile robot. The design of the LARFID tag needs to be finely tuned to make it more compact. At the same time, a simultaneous localization and mapping algorithm is under consideration with the intention to automate the pre-installation process of the LARFID tags in an unexplored indoor environment and reduce the cost of installation and maintenance. Also under consideration is the multi-robot operation with the LARFID-based localization system.

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