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INSPECTING INTERIOR BUILT ENVIRONMENTS USING AUGMENTED REALITY-BASED AUTONOMOUS ROBOT

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ABSTRACT

During the past several years, there has been an increasing interest in deploying mobile robots to inspect building structures. Augmented Reality (AR), which can impose digital information into the real working space, has been proved to be effective in providing most relevant information in an intuitive manner. Combining the strength of these two technologies, this paper proposed an Augmented Reality-based autonomous robotic inspection system for interior built environments. A novel path-planning optimization algorithm was also developed to improve the success of the main goal of the robot using specialized sensors when available. The algorithm can also avoid obstacles and cycles in the search, and handling errors. Experimentation on the effectiveness of this algorithm and system was conducted and the preliminary results are discussed in this paper.

KEYWORDS

Augmented Reality, Autonomous Robot, Built Environment, Inspection

1. INTRODUCTION

There has been an increasing interest in deploying robots in built environments. For example, robots have been developed to level and compact concrete [1], to set tiles [6], to finish interiors [14][15], and to detect concrete cracks [16]. Robots have also been applied as an efficient solution to explore inaccessible environments in the areas of underground sewer pipe inspection [11], removal of damages being result of disasters [2], remote assembly of planetary structures [3], etc. To this end there has been much research on how to effectively operate remote machine (e.g., navigate into an area, perform actions such as taking samples, navigating, performing manipulation, etc.). Although many robots have been developed over the past decade, very few have been used for daily operation and maintenance of existing buildings [13]. It is envisaged that autonomous robots can be employed to handle routine building operations. Such autonomous robots should be designed to move around the building without much human/objects interference. Robots should have the capacity to retrieve real-time images which are then sent back to the management centre. The key behind such robots is accurate self-identification of its own position and selection of the optimal path to maneuver around the building freely [4][9][12].

Augmented Reality (AR), which appears in the literature usually in conjunction with the term Virtual Reality (VR), is a technology or an environment where the additional information generated by a computer is inserted into the user's view of real world scene [8]. AR can create an augmented workspace by inserting the virtual space in which we store and interact with digital contents into the physical space where people work. In the area of built environment, remote control of working robots operation is necessary when there is no physical possibility for a man to be in a machine or in its neighborhood.

Augmented Reality has been investigated to be combined with robots in executing certain tasks. For instance, a setup for a mobile user employing Augmented Reality for indoor and outdoor applications has been developed at Delft University of Technology [5]. To determine the user's position and orientation in the world, it used a cognition system similar to that used by their autonomous soccer playing robots.

This paper proposed an Augmented Reality (AR)-based autonomous robotic inspection system for interior environments. The focus of the paper is the development of a novel path-planning optimization algorithm to improve the success of the main goal of the robot using specialized sensors when available. The rest of this paper is organized as follows. Section 2 presents the system architecture including hardware, software, and functionalities. Section 3 presents the proposed path-planning optimization algorithm. In Section 4, the preliminary experimental results are discussed.

2. SYSTEM ARCHITECTURE OF THE AR-INTEGRATED ROBOT

The primary goal of the system is to find a place in built environment within a minimum possible time interval. The secondary goals are avoiding obstacles, searching the area effectively, avoiding cycles in the search, turning and moving to the directions of locations in which it is believed that points of interests are located. There may be static or dynamic obstacles, other robots, and the human in the built environment. The environment structure and the map are unknown.

The mobile robot is equipped with sensing camera which collects data to reconstruct the visual image of built environment and the operator workstation has a laser scanner to locate the accurate positions of the robot. The goal of the robot is to obtain a perception of the environment from the observed scenery and to provide a map of its workspace.

The system consists of three core modules: sensing, mapping, and guiding as shown in Figure 1.

2.1 Sensing Module

The sensing module interfaces directly with actuators and sensors of the robot and is responsible for avoiding obstacles, controlling velocity, and transiting sensed information through wireless network back to the operator workstation.

2.2 Mapping Module

The mapping module retrieves sensed information from the real scene and then re-constructs a live interactive 3D virtual rendering of the robot and the environment by mapping the sensed visual image data and the robot position to a 3D world created by OpenGL. This layer also constructs the plan for the robot to implement its task in an optimal way. The strategies for avoiding cycles, forming beliefs to direct the search space, and exception handling are implemented by this layer.

2.3 Guiding Module

The guiding module uses Augmented Reality technology to overlay the virtual directions (strategies made in Augmented Reality) onto the robot's camera's real view (operator's remote view) to control the robot's navigation. The system also uses AR technology to annotate the virtual dimensions/directions onto the camera's real view (operator's remote view) to control the robot.

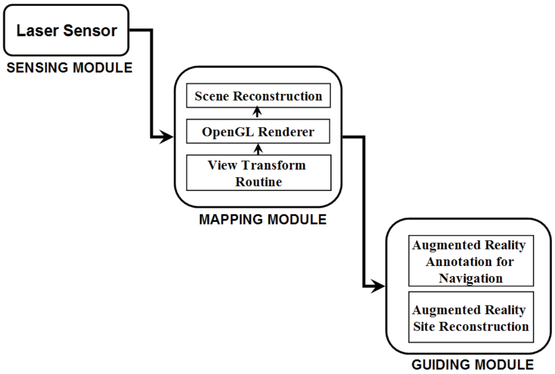

Figure 1 System Architecture

3. SEARCH STRATEGY FOR RESCUE ROBOT

In the design of the system, effective algorithms for both exploration and exploitation are important. When it is required to build an AR system, raw images captured from the camera need to be properly aligned in a common spatial domain. The location where the image is taken is determined by the location of the mobile robot. In this work, the robot position is estimated using a combination of wheel encoders and a laser scanner. The position of the robot is cast as a state vector $\mathbf{x}_k = [x_k, y_k, \phi_k]^T$, where (x_k, y_k) is the location with reference to a global coordinate, ϕ_k is the robot orientation and k is the time index. By assigning the initial robot location as the origin of the coordinate, the wheel encoder (odometry) returns the velocity and turn-rate describing the motion of the robot and infers its future positions. However, the odometry may drift and positional errors may accumulate over time. Therefore, external sensing is required to correct such induced error. A laser scanner is used and gives discrete range-bearing measurements to the fixtures in the building. The location of each scanned point is inferred from the robot position as

$$\begin{aligned} x^i &= x_k + r^i \cos(\phi_k + \theta^i) \\ y^i &= y_k + r^i \sin(\phi_k + \theta^i). \end{aligned} \tag{1}$$

Salient features, e.g., corners, are then extracted as landmarks and their corresponding range-bearings are fed to an extended Kalman filter (EKF) for estimations of the robot position. By using the EKF as a noise filter for odometry errors, the robot position accuracy is then improved.

The EKF proceeds in the following recursive steps:

Predict:

$$\begin{aligned} \mathbf{x}_{k+1|k} &= \mathbf{f}(\mathbf{x}_{k|k}, \mathbf{u}_k) \\ \mathbf{P}_{k+1|k} &= \nabla\mathbf{f}\mathbf{P}_{k|k}\nabla\mathbf{f}^T + \nabla\mathbf{u}\mathbf{Q}\nabla\mathbf{u}^T, \end{aligned} \tag{2}$$

Measure:

$$\begin{aligned} \mathbf{z}_k &= \mathbf{h}(\mathbf{x}_{k|k}, \mathbf{R}) \\ \nu &= \mathbf{z}_k - \mathbf{h}(\mathbf{x}_{k+1|k}, \mathbf{0}), \end{aligned} \tag{3}$$

Update:

$$\begin{aligned} \mathbf{x}_{k+1|k+1} &= \mathbf{x}_{k+1|k} + \mathbf{K}\nu \\ \mathbf{P}_{k+1|k+1} &= \mathbf{P}_{k+1|k} - \mathbf{KSK}^T \\ \mathbf{S} &= \nabla\mathbf{h}^T\mathbf{P}\nabla\mathbf{h} + \mathbf{R} \\ \mathbf{K} &= \nabla\mathbf{h}^T\mathbf{P}\mathbf{S}^{-1}, \end{aligned} \tag{4}$$

where the time indices *k+1* denotes a future time step, $\nabla(\cdot)$ is the jacobian of the corresponding function, for example, see the developments in [7]. Note that the location and orientation of the robot is given by the first 3 elements of the state vector $\mathbf{x}_{k+1|k+1}$ and the rest denote the locations of landmarks in a Cartesian-coordinate.

After the availability of accurate robot positions, objects such as edges in an image frame are detected, e.g., by using a segmentation algorithm [10]. These edges are spatially matched to the laser scan counterparts and a location can then be assigned to the image feature. Given the image objects and locations, the AR routine, e.g., OpenGL is used to generate aggregated scenery of the building interior.

4. EXPERIMENTAL RESULTS

The section presents preliminary experimental results, obtained from a laboratory environment, verifying the performance of the developed algorithm.

A simulation environment in C++ using OpenGL Library was implemented to measure the performance of the proposed algorithms. The environment is constructed with random locations of obstacles and objects. The dynamic objects are allowed in the environment. The results show that the proposed strategies are complete and promising for the main goal of the robot. The number of steps to find the reachable objects is smaller than that of the traditional mapping method. Typical images captured in an indoor built environment are shown in Figure 2 where vertical edges from the fixtures are noticeable and detected as inputs to the AR routine.

Figure 3 shows cases where the robot is driven in the same laboratory while moved on a circular trajectory with a number of repetitions. The figure also depicts the boundaries of the laboratory which are obtained from aligned laser scans by the EKF recursive procedure. The robot is indicated by a triangle and the uncertainties of the landmarks are illustrated by the associating ellipses.

The relative distances between the landmarks, in pairs, are shown in Fig. 4 in a mesh landscape format. The x-and-y axes denote the landmark index and the z-axis gives the distances in meters. Operators can obtain a particular separation between any two landmarks by using a user-graphic-interface. The results presented herein show that the proposed approach is complete and satisfactory for the assigned inspection task.

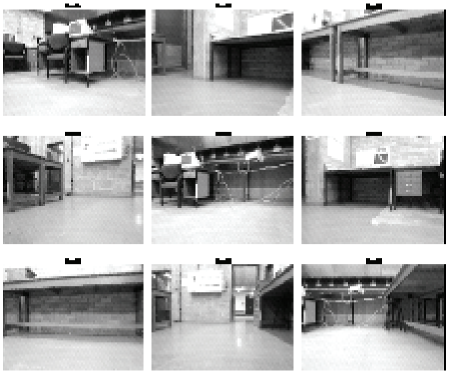

Figure 2 Typical Building Interior Scenario (images are shown in steps of 50 frames)

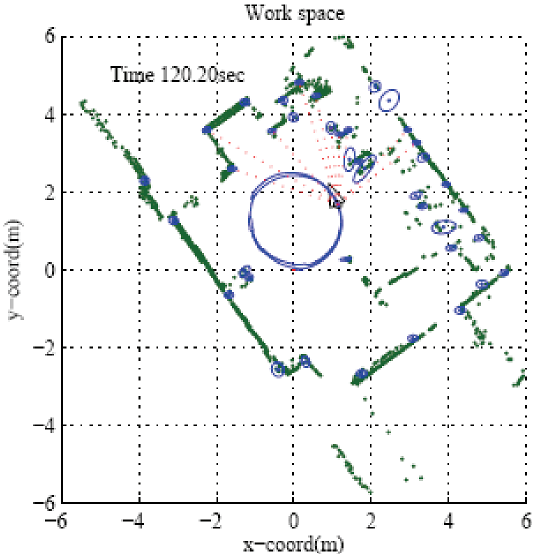

Figure 3 Typical Robot Trajectories and Potential Edge Features (the robot indicated by the triangle started at x=0,y=0)

5. CONCLUSIONS

This paper proposed an autonomous inspection system for building interiors. A mobile robot is equipped with a camera where the captured images are used to build an Augmented Reality system. Operators may tele-operate the robot and are provided with enriched information from AR for efficient inspections. A novel autonomous planning strategy suitable for intelligent robot architectures is proposed. The performance of the approach is assured by using a laser scanner and an extended Kalman filter (EKF) to provide an accurate position estimate of the robot. Preliminary results obtained from a laboratory environment are satisfactory.

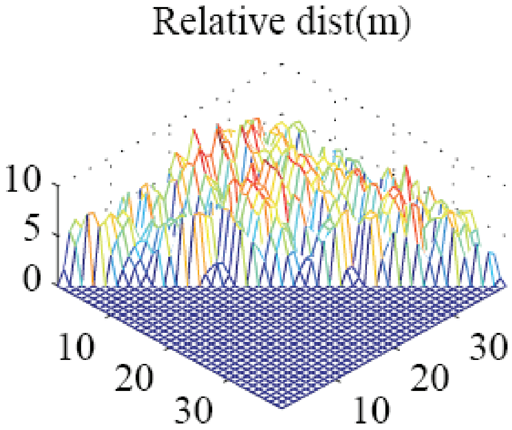

Figure 4 Relative Distance Between Landmarks

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