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Optical Guidance System for Multiple Mobile Robots

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Abstract

This paper describes our research work towards the development of an optical guidance system for multiple mobile robots in an indoor environment. The guidance system operates with an environmental model, communicates with mobile robots and indicates their target positions by means of a light projection from a laser pointer onto the ground. Processing the image data from a CCD color camera mounted on the mobile robot allows it to detect the laser light beacon on the ground and estimate its relative coordinates. The robot's control system ensures the accurate motion of the robot to the indicated target position. The guidance system subsequently indicates target positions corresponding to a desired route for a specified mobile robot in the fleet. The concept of the optical guidance system, its implementation and experimental results obtained are discussed.

1 Introduction

Guidance of a mobile robot involves its *localization* in the environment [1]. The precise localization becomes especially relevant in the case of multiple mobile robots sharing a common environment. Various localization methods are known, from simple and widely used odometry and other dead reckoning methods to active and passive range sensing approaches; see a recent survey on laser range finders, triangulation range finders and passive stereo for mobile robots [2].

The on-board sensors (odometry, sonar, gyroscope, laser, vision) along with external means (landmarks, beacons) and *fusion* of sensor data are necessary in order to obtain the precise position and orientation of the robot in the environment and update the environmental model. An increase in discrepancy between the actual robot position and its estimate (e.g. if localization relies on a dead-reckoning method) can lead to inadequate motion planning and control, resulting in collisions with objects or other robots.

In order to deal with the localization problem, various optical guidance methods have been developed such as using reflective beacons, tracking stationary light sources, tracking a guidance line on the floor or ceiling, or using a scanning laser on the mobile robot in order to measure distances to surrounding objects [1].

We propose an *optical guidance system* for mobile robots that makes use of a projected laser light. The guidance system operates with the environmental model and comprises a computer-controlled *laser pointer* with at least two degrees-of-freedom in order to direct a laser beam onto the desired positions on the ground. The guidance system communicates with the mobile robot when indicating its target position and subsequent checking if the robot has attained this position.

The *key idea* of the optical guidance system is to indicate the numerical coordinates of the target position for the mobile robot by means of projection of a laser light onto the ground. The on-board vision system of the robot processes the color images in order to detect the laser light beacon on the ground and evaluate its relative coordinates. This visual feedback ensures the accurate following of the indicated positions by the robot.

The main advantage of the proposed guidance system is the improved accuracy. The system also allows *implicit localization* of the mobile robot within the environment: when the robot has reached its indicated target position, an estimate of its coordinates in the environmental model is known. Since the robot's control system operates with the relative coordinates of target positions obtained from image processing, the transformation between the coordinate systems of the environmental model ("world" coordinate system) and that of the mobile robot becomes less relevant for guidance.

Our paper focuses on the concept of the optical guidance system integrated into an environment with multiple mobile robots. The paper is organized as follows. The concept of the proposed optical guidance system is described in section 2. The mobile robot and its control architecture are presented in section 3. The operation of the guidance system is discussed in section 4. The implementation and our experimental results are presented in section 5. The conclusions are given in section 6.

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2 The Optical Guidance System

The proposed optical guidance system indicates target positions for the mobile robot by means of a laser light projected onto the ground. The guidance system is sketched in Fig. 1. The system comprises a teleoperation board connected to a laser pointer which has at least two degrees-of-freedom in order to direct the optical axis of the laser to any position on the ground. The coordinates of the target positions are computed from the environmental model according to the motion task, or they are set by a human operator from the teleoperation board. The guidance system relies on a TCP/IP client-server wireless communication with the control systems of the mobile robots. The robot's vision system processes color images in order to detect the laser light beacon on the ground and evaluate its relative coordinates.

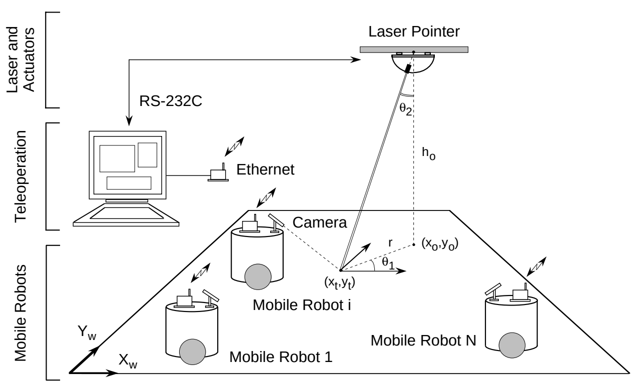

Figure 1: A sketch of the optical guidance system

Let (X_w, Y_w) denote a common coordinate system in Fig. 1, where (x_t, y_t) are coordinates of a target position for a mobile robot, and (x_0, y_0) are coordinates of the laser pointer. Let the laser pointer be situated at a hight h_0 from the ground and have two degrees-of-freedom (θ_1, θ_2). The light beam from the laser pointer will indicate the coordinates (x_t, y_t) on the ground, if an orientation (θ_1, θ_2) of the laser pointer is obtained from the following expressions:

$$\tan\theta_1 = (y_0 - y_t)/(x_0 - x_t), \quad (1)$$

$$\tan\theta_2 = \sqrt{(x_0 - x_t)^2 + (y_0 - y_t)^2}/h_0. \quad (2)$$

The features of the proposed optical guidance system are summarized as follows:

- target positions can be indicated precisely in the environment by means of a laser pointer connected to a computer.
- close-loop control based on visual feedback provides better positioning accuracy of the mobile robot.
- the path to follow can be indicated as a sequence of target positions.
- TCP/IP and wireless Ethernet are used for communication based on a client-server model between the guidance system and the mobile robots.
- accumulation of positioning errors will not influence localization of the mobile robot in the environment because the localization is performed when the robot has attained its indicated target position.
- one guidance system can indicate target positions for multiple mobile robots in the environment.

The communication ability and updating the environmental model in the guidance system allow us to use this system as a mediator for multiple mobile robots. For instance, the sensor data gathered by the robots and stored in the environmental model is available to all robots in the fleet, i.e. cooperative knowledge acquisition and sharing is achieved. The distribution of the motion tasks and their allocation to the mobile robots are performed with the use of the environmental model as a part of the guidance system. One mobile robot is also able to request the system to guide another robot to a specified destination.

To the best of our knowledge, such an optical guidance system is new and it presents an alternative approach to the robot guidance. This system is especially intended for an indoor environment where the global positioning system (GPS) can not be used.

3 The Robot's Control Architecture

The overall control architecture of the developed mobile robot which is capable of operating with the optical guidance system, is shown in Fig. 2. It involves three main parts: the vehicle with its actuators and sensors, the on-board real-time control system, and the remote control interface (teleoperation).

The mobile robot is equipped with four omnidirectional wheels which allow it to perform motions in two directions and rotate simultaneously. Three DC motors and a transmission mechanism provide the omnidirectional motion [3]. Three servo-systems execute the motion control commands issued by the control system of the robot and ensure attaining the commanded position, orientation and velocity.

The sensor system of the robot involves a CCD color camera and eight infrared and sonar range sensors. These sensors gather data about the local environment in order to evaluate relative distances between the robot's frame and environmental objects. Processing of the color data about

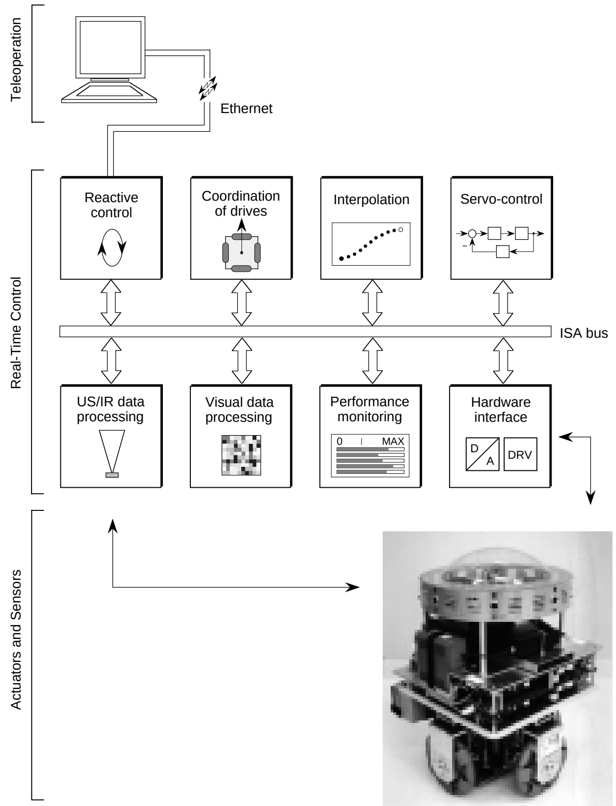

Figure 2: The overall control architecture

the local environment allows the robot to detect and localize a specified object, e.g. another mobile robot or a projected laser light. The sensor system also involves three encoders used in the feedback loop of the servo-systems.

The control system processes the data obtained from the sensor system and the servo-systems and issues the motion control commands which are subsequently executed by the servo-systems. The robot is able to follow a specified object (e.g. a mobile robot) while keeping a safe distance from the object as a function of the motion velocity. The target positions for the mobile robot can also be set by a remote computer or an operator from a graphical user interface [4].

The reactive control ensures an autonomous operation of the robot in a dynamic environment [5]. The collision avoidance algorithm operates with a rule matrix obtained from an adaptive behavior acquisition scheme which is based on reinforcement learning. The reactive control processes data gathered by the ultrasonic and infrared sensors as well as the CCD color camera. Based on the sensors configuration, eight possible directions of motion are considered [5, 6]. The reactive control algorithm ensures a collision-free motion to a given target position.

The motion controller provides coordinated translation and rotation of the omnidirectional vehicle when moving to a target position, as well as to attain a desired velocity [7]. Omnidirectional motion (holonomic case) or constrained motion (non-holonomic case) can be performed according to the assigned task. For instance, vision-based tracking of a dynamic object requires the object to be kept in the view field of the on-board camera and is achieved by the coordinated control of the translational and rotational coordinates of the mobile robot.

The performance monitoring aims to increase the reliability and safety of the robot operation. Monitoring of measurable signals allows for fault detection and diagnosis in a closed-loop during operation [8], e.g. measuring the capacity level of the electric batteries of the robot and, if needed, requesting the control system to interrupt execution of the on-going task and direct the robot to a location where the electric batteries can be replaced.

4 The Robot Guidance

The optical guidance system proposed in section 2 indicates the target position as a laser light beacon on the ground. The robot's control system detects this beacon from image processing and generates a smooth trajectory $\mathbf{x}(t)$ to the detected target position $\mathbf{x}_d$ (the target position can also be set numerically in teleoperation mode). The guidance system operates according to the following basic algorithm in order to indicate a target position for a mobile robot:

1. Establish a client-server connection between the teleoperation board and control system of the mobile robot.

2. Transmit a request whether the robot's control system is ready to process a new target position.

3. If the mobile robot is ready to receive a new target position, then set the laser pointer in the appropriate orientation (θ_1, θ_2). Otherwise, go to step 2.

4. Turn on the laser pointer light in order to indicate the target position on the ground.

5. If the robot's control system confirms detection of the indicated position, then turn off the laser light. Otherwise, wait until the confirmation or failure response is received from the robot's control system.

6. If the indicated target position could not be detected (failure response), then proceed to failure analysis and its compensation, e.g. by means of setting a target position closer to the mobile robot.

7. If another target position must be set, then go to step 2, otherwise stop.

The light of a laser pointer is specified by its brightness (power output), wavelength (color) and focus. The laser light projected on the ground is seen as a small, bright dot of red light (we use a laser with a wavelength of 635 *nm* and a power output of 2 *mW*). The size of such a beacon is within the known range of a given laser (e.g. a spot of 8-10 *mm* in diameter at a 10 *m* distance). The detection of the beacon can be performed either by means of comparing two images obtained when the laser is “off” and “on” [9], or by means of a search for an area of specified brightness, color and size in the captured image.

Since the brightness at the laser beacon changes abruptly in magnitude, an edge detection technique is applied [10]. We have tested a discrete *differencing* (horizontal and vertical) of the RGB image and a subsequent search for pixels where the intensity change of the red color is maximal. When such pixels are found, an image segmentation by means of a global *thresholding* technique is performed: the neighboring pixels in the original image are evaluated relative to a given color threshold in order to estimate the size of detected areas. The *selection* of pixels which correspond to the red laser light makes use of a CIE chromaticity diagram where the chromaticity values of the given laser are within a known range. The selected area is centered, and the coordinate transformation from pixels into meters results in obtaining the target position $\mathbf{x}_d$.

The subsequent generation of the smooth trajectory $\mathbf{x}(t)$ to the target position $\mathbf{x}_d$ is based on our motion generation approach [7]. This approach represents a modified cubic spline-interpolation which involves a recomputation of the spline between the actual position of the mobile robot and a *virtual running point* situated at a distance Δx_T ahead of the robot in the target direction x_d, as it is illustrated by Fig. 3.

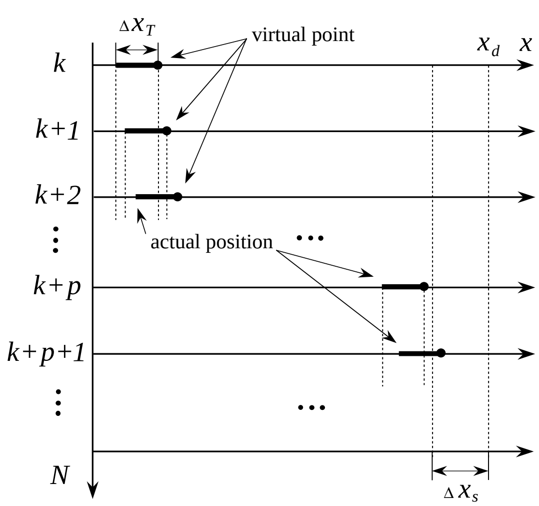

Figure 3: A virtual running point

The virtual point is shifted with a sampling period $T^\star$ in the direction x_d in order to lead the robot to the target. The recomputation of the spline terms in the proximity Δx_s of x_d. This motion generation approach is effectively used for various tasks where trajectory generation in real time is needed to control the mobile robots, e.g. collision avoidance, tracking an object or a laser light beacon on the ground as it is performed in the optical guidance system.

5 Experiments

The mobile robot is equipped with a CCD color Toshiba camera (focal length is 7.5 *mm*) that acquires images about the local environment. At present, we use a LP-310 Plus laser pointer (wavelength is 635 *nm*, power output is 2 *mW*) that provides a red light. In order to direct the laser beam onto the the desired positions on the floor, this laser is mounted onto a pan-tilt mechanism equipped with two step motors of a Canon communication camera VC-C1, as it is shown in Fig. 4.

Figure 4: A laser pointer mounted onto a camera with a pan-tilt mechanism

The experimental setup is sketched in Fig. 5, where the robot’s camera is in the inclined position relative to the ground. The laser light beacon is seen in the image as a bright spot of the size of a few pixels, as illustrated in Fig. 6 and Fig. 7. The projected laser light on the ground has a blur contour and the shape of the beacon is elliptical, shown in Fig. 7. The central part of the beacon in the image is white-colored that shows saturation of the camera. The pixels indicated by bold contours in Fig. 7 illustrate the horizontal and vertical differencing applied in order to find the pixels where the intensity change of the red color is maximal.

One should note that detection of a laser light beacon depends strongly on the lighting conditions and the surface material. For instance, our experiments on a grey con-

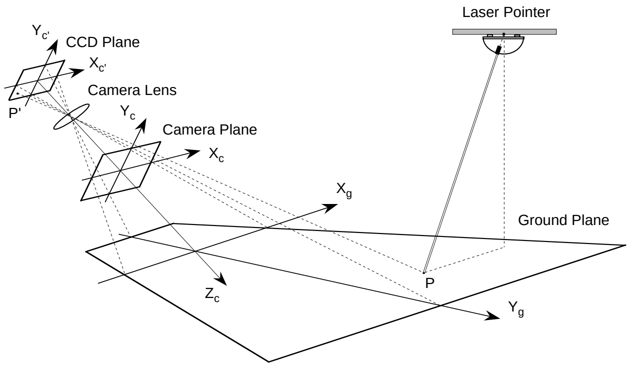

Figure 5: A sketch of the experimental setup

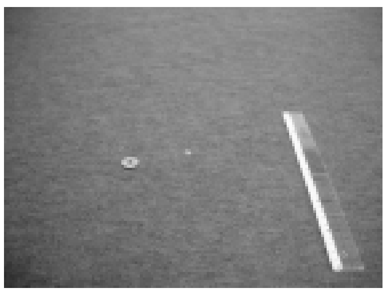

Figure 6: An example of a camera snapshot of the ground: a laser light beacon (center), a 5 Yen coin (left) and a 30 cm ruler (right)

crete surface or a green synthetic carpet have shown reliable detection. The maximal detection distance depends on the laser power output and the camera sensitivity. The precision of the position estimation of the detected laser light beacon is influenced by various factors such as quantization errors due to the small size of the beacon, camera displacement from the calibrated setting as well as camera constraints [11].

In order to transform the obtained coordinates of the beacon from pixels into meters, a non-linear transformation table was experimentally obtained for a rectangular area in front of the robot's camera. The measurement results for an area of 1.0 *m* in width and 1.4 *m* in length (the size of the graph paper used) are depicted in Fig. 8. The curves of the longitudinal distance are plotted for the lateral distance range from -0.4 *m* to 0.4 *m*. The functions of the lateral distance are plotted for the longitudinal distance range from 0.25 *m* (the shortest line in Fig. 8,b) to 1.3 *m*.

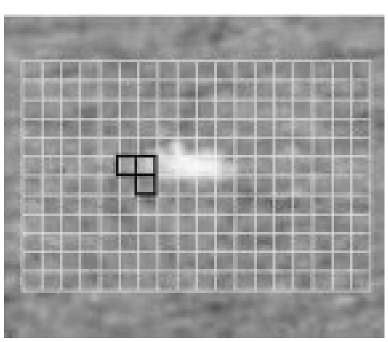

Figure 7: A laser light beacon (zoomed)

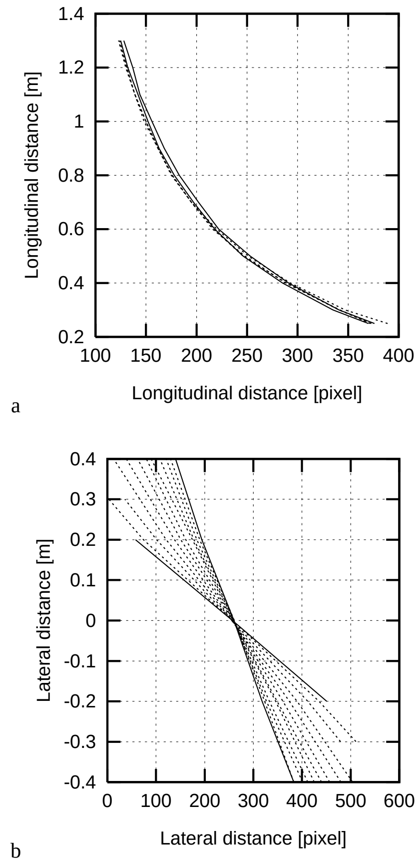

Figure 8: Coordinate transformation from pixel to meter: a - longitudinal distance, b - lateral distance

The estimation of the coordinates of the laser light beacon on the ground relative to the robot's camera is illustrated in Fig. 9. The camera position corresponds to the origin of the coordinate system in this figure, and the actual positions where the laser light is projected are depicted as points. The plus signs in Fig. 9 show the corresponding coordinates estimated by image processing. The localization accuracy is lower at the borders of the camera view field (upper and lower point sequences in Fig. 9) while the accuracy along the optical axis of the camera (central points in Fig. 9) is sufficient for tracking the projected laser light (the maximal dispersion was less than 10 *mm*, and the average dispersion was about 3 *mm*).

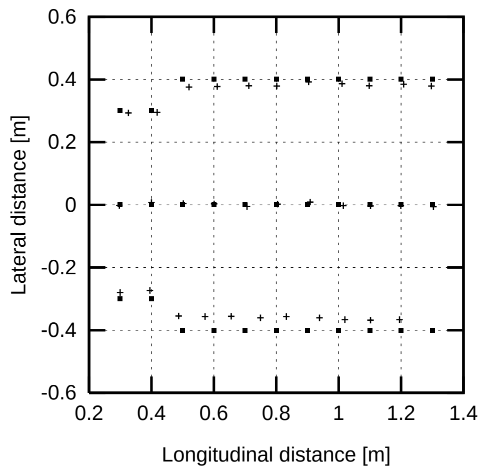

Figure 9: Localization of projected laser light

The software for the teleoperation and optical guidance system is developed in JAVA language. The software of the robot's control system is implemented in C language and runs under VxWorks real-time operating system on a Pentium 200 MHz processor. The client-server communication between the teleoperation and optical guidance system ("client") and the mobile robots ("servers") is performed via a wireless Ethernet. Our video illustrates the experiments performed.

6 Conclusion

The concept of the optical guidance system that makes use of a laser pointer was introduced. The features of the optical guidance system and its use for multiple mobile robots were discussed. The control architecture of the mobile robot and the vision-based robot guidance were considered. The implementation and experimental results on the operation of the optical guidance system were presented. Our future work will deal with the improvement of the image processing algorithm, system integration and conducting experiments with multiple mobile robots.

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