GUIDANCE SYSTEM FOR ROBOTS CAPABLE OF VISION AND COMMUNICATION

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Abstract A laser system for autonomous guidance of robots is presented. This system operates with an environmental model, communicates with the robots and indicates their routes by means of light projection from a laser pointer onto the ground. Image processing and communication with the guidance system allows the robot to detect the laser light beacon on the ground and estimate its relative coordinates. The guidance system subsequently indicates target positions along a desired route. The concept of the system, its kinematic models and operation are considered. The implementation and experimental results are described.

Keywords: Mobile robots, guidance systems, control

1. INTRODUCTION

Guidance means show the way while in motion, and localization is to confine within a particular area (Hornby, 1987). Guidance is passive if no localization of the guided objects is performed (e.g. a lighthouse guiding ships), and is active when it involves localization and communication with the guided objects. This paper addresses a laser guidance system which represents an active guidance concept.

The motivation of this work originates in our experiments on teleoperation of mobile robots. The robot pose (position and orientation) obtained from dead-reckoning is transmitted to the teleoperation system in order to update the environmental model and subsequently control the robot. However, accumulation of positional and orientational errors caused by the wheels sliding on the ground and inaccurate wheel modeling results in a discrepancy between the actual robot pose in the environment and its estimation in the model. An increase of this discrepancy over time makes teleoperation impossible from some instant.

In order to solve this problem, we proposed a laser guidance system (Paromtchik and Asama, 2001). This system operates with the environmental model and comprises a computer-controlled laser pointer which directs a laser beam onto desired positions on the ground. The guidance system communicates with the robot when indicating its target position and subsequent checking if the robot has attained this position.

The key idea of this guidance system is to indicate the numerical coordinates of the target position by means of projection of a laser light onto the ground. The robot’s vision system processes the color images in order to detect the laser light beacon on the ground and evaluate its relative coordinates. This visual feedback ensures that the robot accurately follows the indicated positions.

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

The communication ability and updating the environmental model by the guidance system allow us to use this system as a mediator for multiple 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 tasks and their allocation to the robots is performed with the use of the environmental model as a part of the guidance system. One robot can also request the system to guide another robot to a specified destination.

This paper is organized as follows: the related works on laser guidance of robots are discussed in section 2; the concept of our guidance system and its kinematic models are presented in section 3; the operation of the guidance system is considered in section 4; the path computation is explained in section 5; the implementation and experimental results are presented in section 6; the conclusions are given in section 7.

2. RELATED WORKS

The robot guidance involves various topics such as: teleoperation and communication, environment modeling and motion planning, image processing and sensor fusion. This section focuses on the laser guidance of robots, while reviews of other navigation methods and sensors can be found in (Borenstein et al., 1996) and (Hebert, 2000).

The use of a laser light to indicate an area of interest has various known applications. Use of a laser pointer to indicate objects for guidance of mobile robots is discussed in (Nakamura et al., 2000). The human operator or a "manager" mobile robot directs the laser pointer onto an object of interest, and two "worker" mobile robots, each equipped with a color CCD camera, detect the laser dot. Its relative coordinates are obtained from stereo vision. This method requires that the precise poses of the "worker" robots are known. However, the precise localization of mobile robots is not a trivial task (Borenstein et al., 1996).

The robot guidance by means of information support from sensor devices distributed in an "intelligent space" is proposed in (Lee et al., 2001). The sensor devices equipped with processors watch humans and robots and guide them in a networked environment. Each mobile robot is identified by a color bar code stored in the database. The robot can be localized by one of the visual sensors by means of measuring the distance between the robot and the sensor. According to the desired path and the estimated pose, the control command is transmitted to the robot via a wireless LAN. Guidance based on localization and communication is achieved.

A system with a laser attached to one of two Canon VC-C1 communication cameras placed on a robot manipulator is described in (Redd et al., 1999). The purpose is to provide a convergence of the cameras on the viewed object. The laser is precisely aligned with the optical axis of its camera and is centered over the top of the camera lens. This system makes it possible to measure the distance to the object being viewed. The reported accuracy of the distance calculation between the camera and the laser dot is roughly the nearest tenth of an inch.

Our proposed laser guidance system is distinct from the guidance systems described above and provides the following features:

- target positions are indicated precisely in the environment by means of computer-servoing the laser pointer.
- close-loop control based on visual feedback provides better positioning accuracy of the robot.
- the path to follow is indicated as a sequence of target positions.
- communication between the guidance system and the robots allows cooperative knowledge acquisition and sharing between the robots.
- accumulation of errors caused by dead-reckoning will not influence localization of the 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 robots.

3. KINEMATIC MODELS

Our guidance system indicates target positions for the 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 an operator. The guidance system relies on communication with the control systems of the 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 (Parnomtchik and Asama, 2001).
3.1 Guidance system kinematics

Let the laser pointer be mounted onto a pan-tilt mechanism, and \( \Theta = (\theta_1, \theta_2)^T \) denote the rotation angles of this mechanism, where \( \theta_1 \) and \( \theta_2 \) are the pan and tilt angles respectively. Let an initial position be \( \theta_1 = \theta_2 = 0 \). Let the “rotation point” of the pan-tilt mechanism be situated at a height \( h_o \) and its ground coordinates be denoted \((x_o, y_o)\), as shown in Fig. 1. Let \( X = (x, y)^T \) denote the position of the laser beacon on the ground and a coordinate transformation \( F(\Theta) \) be such that

\[
X = F(\Theta) = \begin{pmatrix} x_o - h_o \cos \theta_1 \tan \theta_2 \\ y_o - h_o \sin \theta_1 \tan \theta_2 \end{pmatrix}. \tag{1}
\]

The velocity of the laser beacon on the ground \( \dot{X} = (\dot{x}, \dot{y})^T \) is

\[
\dot{X} = \frac{dF(\Theta)}{d\Theta} \dot{\Theta} = J(\Theta) \dot{\Theta}, \tag{2}
\]

where \( \dot{\Theta} = (\dot{\theta}_1, \dot{\theta}_2)^T \) is the angular velocity of the pan-tilt mechanism and \( J(\Theta) \) is the Jacobi matrix:

\[
J(\Theta) = h_o \begin{pmatrix} \sin \theta_1 \tan \theta_2 & -\cos \theta_1 / \cos^2 \theta_2 \\ -\cos \theta_1 \tan \theta_2 & -\sin \theta_1 / \cos^2 \theta_2 \end{pmatrix}. \tag{3}
\]

In order the laser beacon on the ground moves at a velocity \( \dot{X} \), the pan-tilt mechanism must provide the angular velocity \( \dot{\Theta} \) such that

\[
\dot{\Theta} = J^{-1}(\Theta) \dot{X}, \tag{4}
\]

where \( J^{-1}(\Theta) \) denotes the inverse Jacobi matrix:

\[
J^{-1}(\Theta) = \frac{1}{h_o} \begin{pmatrix} \sin \theta_1 / \tan \theta_2 - \cos \theta_1 / \tan \theta_2 \\ -\cos \theta_1 \cos^2 \theta_2 - \sin \theta_1 \cos^2 \theta_2 \end{pmatrix}. \tag{5}
\]

Note that \( J^{-1}(\Theta) \) in (5) is not defined if \( \theta_2 = 0 \).

Let the pan angle \( \theta_1 \) be counted relative to a vertical plane which involves the x-axis of the ground coordinate system:

\[
\theta_1(x, y) = \arctan \frac{y_o - y}{x_o - x}. \tag{6}
\]

Let the tilt angle \( \theta_2 \) be counted relative to a vertical line connecting the rotation point of the pan-tilt mechanism and the position \((x_o, y_o)\):
(the same angle $\beta_o$ is between the laser optical axis in the initial position $\theta_\eta = \theta_2 = 0$ and a vertical line). Let $b_o$ denote a distance between the rotation point and the laser optical axis.

The kinematic equations (1) correspond to the case of $\alpha_o = 0$, $\beta_o = 0$ and $b_o = 0$. If $\alpha_o \neq 0$, $\beta_o \neq 0$ and $b_o \neq 0$, a position of the laser light beacon on the ground is obtained as

$$X = \left( \begin{array}{c} x_o - \left( h_o \tan \theta_1' + b_o / \cos \theta_2' \right) \cos \theta_1' \\ y_o - \left( h_o \tan \theta_2' + b_o / \cos \theta_2' \right) \sin \theta_1' \end{array} \right),$$

(14)

where

$$\theta_1' = \theta_1 + \alpha_o,$$

$$\theta_2' = \theta_2 + \beta_o, \quad -\beta_o < \theta_2 < \frac{\pi}{2}, \quad 0 < \beta_o < \frac{\pi}{2}.$$  

(15)

(16)

The velocity of the laser beacon on the ground is obtained in a similar way to equation (2):

$$\dot{X} = J'(\Theta) \dot{\Theta},$$

(17)

where the corresponding Jacobi matrix is

$$J'(\Theta) = \left( \begin{array}{cc} J_{11}' & J_{12}' \\ J_{21}' & J_{22}' \end{array} \right),$$

(18)

$$J_{11}' = \frac{\left( h_o \sin \theta_2' + b_o \sin \theta_1' \right)}{\cos \theta_2'},$$

(19)

$$J_{12}' = -\frac{h_o \cos \theta_1' + b_o \sin \theta_1' \sin \theta_2'}{\cos \theta_2'},$$

(20)

$$J_{21}' = -\frac{h_o \sin \theta_1' \cos \theta_2' + b_o \cos \theta_1' \cos \theta_2'}{\cos \theta_2'},$$

(21)

$$J_{22}' = -\frac{h_o \cos \theta_1' \sin \theta_2' + b_o \sin \theta_1' \sin \theta_2'}{\cos \theta_2'}. $$

(22)

Taking into account (13) and (15), the pan angle is

$$\theta_1(x, y) = \arctan \frac{y_o - y}{x_o - x} - \alpha_o.$$ 

(23)

The tilt angle is derived from (16) while using the following equation:

$$h_o \tan \theta_2' + \frac{b_o}{\cos \theta_2'} = r.$$ 

(24)

One can obtain for the tilt angle:

$$\theta_2(x, y) = \arctan \frac{r}{h_o} - \arcsin \frac{b_o}{\sqrt{r^2 + h_o^2}} - \beta_o.$$ 

(25)

As it follows from comparing (6) and (23), the angular velocity $\dot{\theta}_1(x, y)$ is given by (9). The angular velocity $\dot{\theta}_2(x, y)$ is derived by means of differentiating the equation (25):

$$\dot{\theta}_2(x, y) = \frac{\left( \frac{x_o - x}{r^2 + h_o^2} \right) (x_o - x) \dot{x} + (y_o - y) \dot{y}}{r^2 + h_o^2} \left( \frac{h_o}{r} - \frac{b_o}{\sqrt{r^2 + h_o^2}} \right).$$

(26)

4. EVENT-BASED GUIDANCE

Let a desired path $X(t) = [x(t), y(t)]^T$ be indicated as the laser light beacons separated by a distance step $\Delta X_s > 0$, as shown in Fig. 3, where the actual path of the robot is denoted $X_r(t)$ of the robot

$$X_r(t) = [x_r(t), y_r(t)]^T.$$ Let $\tau > 0$ denote a period corresponding to robot motion over a distance $\Delta X_s$. When the robot reaches the $\Delta X_s$-proximity of its target position, a new target position is set. Tracking the desired path $X(t)$ is achieved if

$$\lim_{t \to \infty} |X_r(t) - X(t)| \leq \varepsilon,$$

(27)

where $\varepsilon > 0$ is a given constant. As illustrated in Fig. 3, a distance between the robot and its target position during the path tracking is bounded by $2 \Delta X_s$.

The diagram in Fig. 4 illustrates communication between the robot’s control system and the guidance system. Initially, the robot sends a target request to the guidance system. The request is accepted and the system orients the laser pointer appropriately in order to indicate a target posi-

![Figure 3. A desired path $X(t)$ indicated as laser light beacons at a distance step $\Delta X_s$ and the actual path $X_r(t)$ of the robot](image)

![Figure 4. Communication diagram I](image)
the guidance system along with a target request. In the case of failure to detect the beacon, the guidance system performs a failure compensation procedure (e.g., the target is set closer to the robot). The shaded areas in Fig. 4 show the time period for this event-based guidance, from requesting a target position to obtaining results of image processing.

Let \( \tau_s > 0 \) denote a motion time for a transition of the laser beacon from a position \( X^* \) to a target position \( X \). The period \( \tau_s \) is a variable delay that also includes time for oscillations in the pan-tilt mechanism to abate. When the image is captured, let the subsequent processing time period equate to \( \tau_p > 0 \) which is also variable. The periods \( \tau_s \) and \( \tau_p \) must be shortened because they represent the waiting periods for the robot and the guidance system, respectively.

For instance, the laser pointer can be re-oriented without waiting for the results of image processing – the corresponding diagram is shown in Fig. 5. However, this operation requires reliable detection of the laser light beacons.

![Diagram](image)

Figure 5. Communication diagram II

Note that target indication and detection must be fast enough to ensure the continuous motion of the robot along the path: \( \tau_s + \tau_p < \tau \) (diagram I) or \( \max(\tau_s, \tau_p) < \tau \) (diagram II). Also, the laser light beacon should appear at a distance where it can be reliably detected by the robot’s visual system.

5. PATH COMPUTATION

The path computation by the guidance system makes use of our approach described in (Paromtchik and Rembold, 1994). A cubic spline-function \( Q_3(t), t \in [T_1, T_2] \) is used:

\[
Q_3(t) = \sum_{j=0}^{3} a_{kj} \left( \frac{t-t_k}{h_k} \right)^j, \quad t \in [t_k, t_{k+1}],
\]

where \( h_k = t_{k+1} - t_k, \ k = 0, 1, \ldots, n - 1 \). The spline (28) passes through the given node points \( q(t_k) = q_k, \ k = 0, 1, \ldots, n \), while \( T_1 = t_0 < t_1 < \ldots < t_n = T_2 \). The initial and final conditions are: \( Q_3(T_1) = q_0, \ Q_3(T_1) = 0, \ Q_3(T_2) = q_n, \ Q_3(T_2) = 0 \), and an auxiliary point is introduced: \( q_{n+1} = q_{n-1} \). The coefficients of (28) are:

\[
a_{k0} = q_k,
\]

\[
a_{k1} = h_k q_k,
\]

\[
a_{k2} = h_2 \frac{h_k + h_{k+1}}{h_{k+1}} (q_{k+1} - q_k) - \frac{h_k^2}{h_{k+1} (h_k + h_{k+1})} (q_{k+2} - q_k) - 2 h_k q_k,
\]

\[
a_{k3} = -h_k + h_{k+1} (q_{k+1} - q_k) + \frac{h_k^2}{h_{k+1} (h_k + h_{k+1})} (q_{k+2} - q_k) + h_k q_k,
\]

where \( k = 0, 1, \ldots, n - 1 \), and they provide the continuity of \( Q_3(t) \) and \( Q_3(t) \) for \( t \in [T_1, T_2] \).

The equations (28)-(32) are used to compute the functions \( x(t) \) and \( y(t) \) which pass through the given points \( (x_k, y_k), \ k = 0, 1, \ldots, n \). The guidance system indicates target positions along a path \( X(t) = [x(t), y(t)]^T \) at a distance step \( \Delta X_s > 0 \) while a value of \( \Delta X_s \) is set according to a desired precision.

6. EXPERIMENTS

Our mobile robot is shown in Fig. 6. The robot is equipped with four omnidirectional wheels which allow it to perform motions in two directions and rotate simultaneously. The kinematic model of the robot is described by the following equations:

\[
\begin{align*}
\dot{x}_r &= v_x \cos \theta_r - v_y \sin \theta_r, \\
\dot{y}_r &= v_x \sin \theta_r + v_y \cos \theta_r, \\
\dot{\theta}_r &= \omega,
\end{align*}
\]

where \( v_x \) and \( v_y \) denote the robot velocities in the longitudinal and lateral directions respectively, \( \omega \) is the rotational velocity, and \( \theta_r \) - the orientation angle. Note that if the constraint \( v_y = 0 \) is set in (33), this results in a non-holonomic model.

The robot is equipped with a CCD color camera (focal length 7.5 mm) which is in the inclined position relative to the ground. The guidance
system comprises a pan-tilt mechanism of a Canon VC-C1 communication camera which is equipped with two stepping motors. The laser pointer is mounted on top of the camera, shown in Fig. 2. The laser provides a red light (wavelength 635 nm, power output 2 mW).

The accuracy obtained from localizing of the laser beacons on the ground relative to the robot’s camera is illustrated in Fig. 7, where the position reflects the total error caused by the inaccurate operation of both the robot and the laser system. Since the laser system is in a fixed position in the environment, its accurate setting is relevant. The vision-based guidance of the robot along a path which is precisely indicated by the laser light beacons allows to eliminate this discrepancy. Our experiments are illustrated by a video.

7. CONCLUSION

The concept of a laser guidance system for robots was considered. The system kinematics and event-based guidance were described. The implementation of the system and our experimental results obtained were discussed. Our future work will address the problem of path tracking in a laser guidance system.

REFERENCES


