APPROACH TO GLOBAL AND LOCAL GUIDANCE OF MULTIPLE MOBILE ROBOTS

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Abstract This paper addresses the development of optical and information assisted guidance for multiple mobile robots. The optical 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. The distributed knowledge acquisition and sharing for local guidance in a structured unknown environment is achieved by means of our "information assistants" which provide data storage about the environment and local communication with mobile robots. The implementation and experimental results obtained are described.

Keywords: Optical guidance, mobile robots, knowledge acquisition and sharing.

1. INTRODUCTION

Guidance of a mobile robot involves its *localization* in the environment (Borenstein *et al.*, 1996). The precise localization becomes especially relevant in the case of multiple mobile robots sharing the 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 the mobile robots (Hebert, 2000).

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 map. An increase in discrepancy between the actual robot's position and its estimate 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 (Borenstein *et al.*, 1996).

We propose an *optical guidance system* for the mobile robots that makes use of a projected laser light (Paromtchik and Asama, 2001). 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 performs image processing 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 optical guidance system is the improved accuracy. The system also allows *implicit localization* of the mobile robot in the environment: when the robot has reached its indicated position, an estimate of the robot's coordinates in the environmental model is known. Since the robot's control system operates with the relative coordinates of the target positions obtained from image processing, the transformation between the coordinate systems of the environmental model ("world" coordinate system) and that of the robot becomes less relevant for guidance.

The robot guidance in a structured unknown environment is performed with the use of *information assistants* which allow distributed knowledge acquisition and sharing among mobile robots. The information assistant is a device that provides data storage and local communication with the robots. Such devices are placed in various spots of the environment, e.g. at a crossing or a junction. The robots communicate gathered sensor data about the local environment to the information assistants. They also retrieve information about the local environment from the information assistants while moving to the specified destinations.

Our paper is organized as follows. The concept of the optical (global) guidance system is described in section 2. The robot guidance by means of information assistance (local guidance) is considered in section 3 where an autonomous knowledge acquisition and sharing among mobile robots in a structured unknown environment is explained. The implementation of our optical guidance system and information assistants as well as our experiments and simulation results are discussed in section 4. The conclusions are given in section 5.

2. THE OPTICAL GUIDANCE SYSTEM

The 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 and 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 or they are set by a human operator. The guidance system relies on a wireless communication with the control systems of the mobile robots. The robot's vision system processes images in order to detect the laser light beacon on the ground and evaluate its relative coordinates.

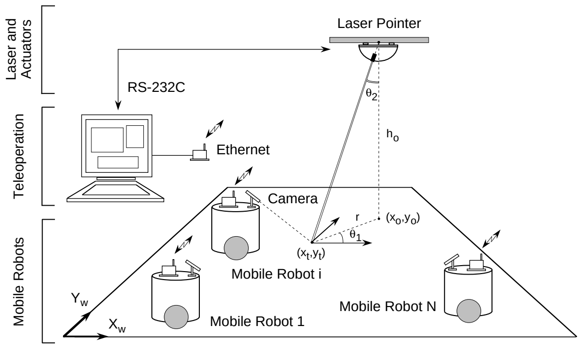


Figure 1. A sketch of the optical guidance system

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. The laser pointer is situated at a hight h_0 from the floor surface, and (θ_1, θ_2) denote its two degrees-of-freedom. The guidance system operates according to the following basic algorithm:

(1) Establish a communication between the teleoperation board and a 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 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 the laser light can be turned off. 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 features of the 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.
- wireless communication is used 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.

3. INFORMATION ASSISTED GUIDANCE

Information assistance is relevant for robot guidance in an unknown environment. It provides data storage about the local environment and communication of this information to mobile robots. The information assisted robot guidance is biologically inspired, e.g. ants forage by pheromone trails that is reported to be very effective for completion of the iterative transportation tasks performed by autonomous agents (Drogoul and Feber, 1992).

We have developed a device called an *information assistant* which provides cooperative knowledge acquisition and sharing among mobile robots (Kurabayashi and Asama, 2000). A sketch of an environment with the information assistants is shown in Fig. 2 where IA denotes "information assistant". A mobile robot is capable to operate without a global map of the environment because it retrieves information about the local environment from the nearest information assistant. It also communicates its own gathered sensor data about the local environment to the information assistant.

We consider the information assisted robot guidance on an example of iterative transportation (Yoshimura *et al.*, 1996). The mobile robot delivers objects to the specified destinations in

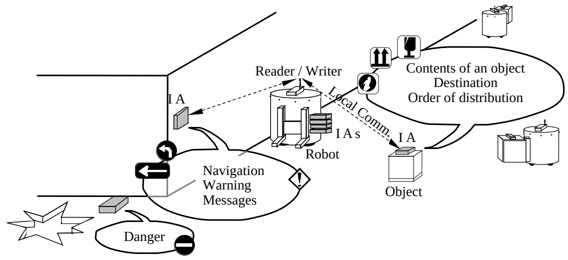


Figure 2. A sketch of an environment with information assistants

a structured environment. When the robot has reached its destination, it receives a new one. The following assumptions are made for the mobile robot and its environment:

- The robot does not operate with a global map of the environment and it does not estimate its global position.
- The robot estimates its position locally in the environment by means of sensor data processing and communication with the nearest information assistant.
- The robot operates in a maze-like structured environment which consists of square cells and walls, as it is shown in Fig. 3, and the information assistants are situated at the junctions in this environment.
- The robot detects walls and distinguishes paths, junctions and destinations as well as branches at the junctions.
- The robot moves to its neighboring cell by one step at a time.
- The destinations are numbered in the environment. When the robot arrives to its specified destination, a new destination number is commanded at random to the robot.
- The robot remembers its last visited destination and counts, in steps, a duration of running time.
- Collision avoidance is not discussed in this paper.

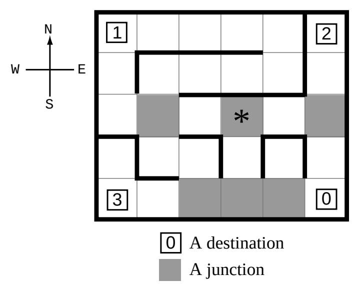


Figure 3. An example of a structured environment

The last visited destination and the current branch and junction are processed. For example, if the robot is moving from a destination 1 and enters a junction marked by a star sign in Fig. 3 through a Western branch, then, the Western branch is assumed to lead to a destination 1. The shortest route to the specified destination is selected from a set of branches which connect the current junction to the specified robot's destination. For example, if the robot's next destination is numbered 2 in Fig. 3 and the robot is at a junction marked by a star sign, an Estern branch leading to the destination 2 is selected.

The corresponding data structure of the information assistant is shown in Fig. 4 where IA denotes "information assistant". At the initial state, no guidance data is available from the information assistant. When the robot enters a communication area, it reports to the information assistant an entry branch, a number of the most recently visited destination and a step number from this destination to the current position. If the information assistant has already received data about the same destination and the same branch, a route of the shortest step number is recorded. The recorded routes in Fig. 4 illustrate a level of the acquired knowledge about the environment.

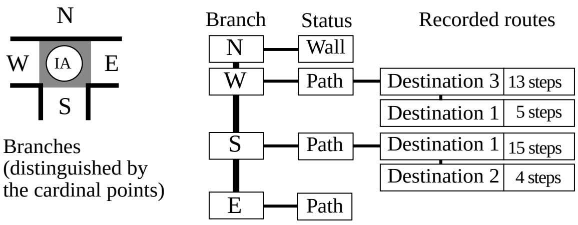


Figure 4. A junction and a data structure in its information assistant

The route selection at a junction of $N \geq 3$ branches to a destination k is based on the following procedure:

(1) A number of steps $t_{ik} \geq 1$ for a recorded route to a destination k through a branch i is retrieved for $i = 1, 2, \ldots, N$.
(2) A weight of a branch i toward a destination k is obtained as $s_{ik} = 1/t_{ik}$ for $i = 1, 2, \ldots, N$ if a route through a branch i was recorded in the information assistant, otherwise $s_{ik} = 0$.
(3) A probability of selecting a branch i at a junction toward a destination k is:

$$p_{ik} = (1 - p_0)\frac{s_{ik}}{\sum_{j=1}^{N} s_{jk}} + \frac{p_0}{N},$$

where $0 \leq p_0 \leq 1$ is a probability of selecting a branch at random and $\sum_{j=1}^{N} s_{jk} \neq 0$.
(4) If the information assistant has no record about a destination k, i.e. $\sum_{j=1}^{N} s_{jk} = 0$, or the robot is unable to communicate with the information assistant at a junction, a branch is selected at random.

4. EXPERIMENTS

The optical guidance is tested on our mobile robot shown in Fig. 5. The robot is equipped with a CCD color Toshiba camera (focal length is 7.5 mm) that acquires images about the local environment. A laser light is projected onto the ground where it forms a bright colored dot. 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 ground, 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. 6. Our experimental setup for the optical

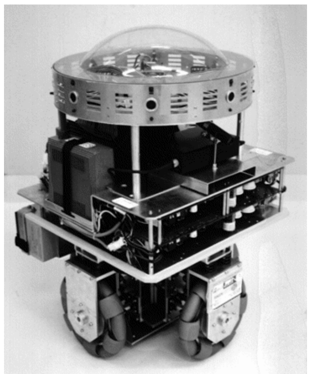


Figure 5. Our mobile robot equipped with a camera

Figure 6. A laser pointer mounted onto a camera with a pan-tilt mechanism

guidance is sketched in Fig. 7, where the robot's camera is in the inclined position relative to the ground.

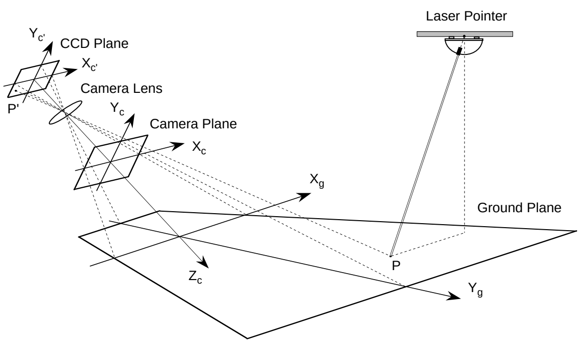


Figure 7. A sketch of the experimental setup for optical guidance

Since the brightness at the spot changes abruptly in magnitude, an edge detection technique is applied (Ritter and Wilson, 1996). 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 a size of the 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.

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 concrete 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 (Yang and Ciarallo, 2001).

The estimation of the coordinates of the laser light beacon on the ground relative to the robot's camera is illustrated in Fig. 8. The camera position corresponds to the origin of the coordinate system in this figure. The actual positions where the laser light is projected are depicted as points in Fig. 8. The plus signs 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. 8) while the accuracy along the optical axis of the camera (central points in Fig. 8) is sufficient for tracking the projected laser light (the maximal dispersion was less than 10 mm, and the average dispersion was about 3 mm).

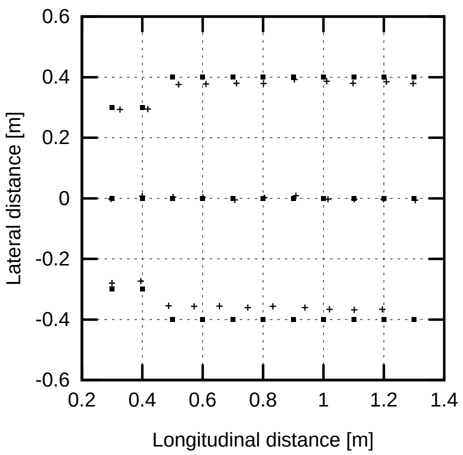


Figure 8. Localization of projected laser light

Table 1. Specifications of an information assistant

Media	Electromagnetic wave
Frequency	290 or 310 MHz
Memory	32 $Bytes$
Modulation	on/off keying
Data rate	1200 bps
Power source	Li-ON battery (3.6 V)
Dimensions	Information beacon: 110x65x25 mm Reader/writer: 195x130x50 mm
Communication range	3 m

The information assistant comprises: (1) – an information beacon equipped with a microprocessor, a memory and a battery, and (2) – a reader/writer, as it is shown in Fig. 9. The specifications of our information assistant are given in Table 1. An information beacon is mounted

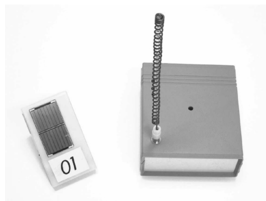
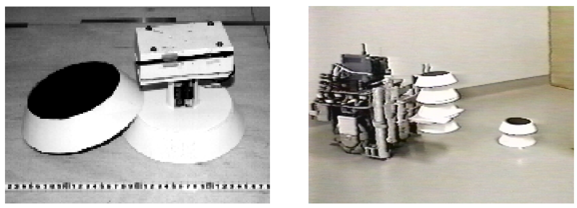


Figure 9. A prototype of an information assistant: an information beacon (left) and a reader/writer (right)

into a portable frame designed to be carried by a robot, as it is illustrated in Fig. 10a (Fujii *et al.*, 1996; Kurabayashi and Asama, 2000). The mobile robot operating with the frames is depicted in Fig. 10b. The information beacons are placed in the environment, and the robot equipped with the reader/writer communicates with them.



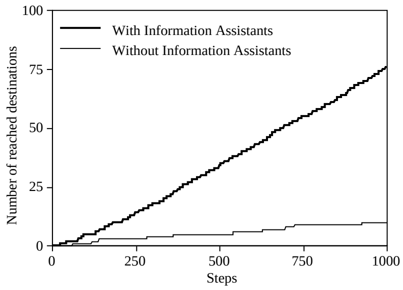
a: A portable frame b: Operating with frames

Figure 10. Information beacons in an environment

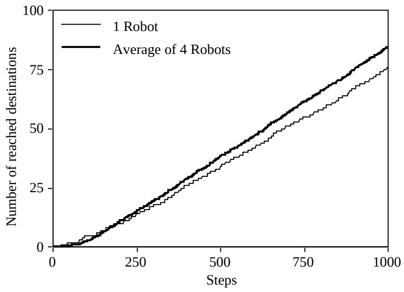
The effectiveness of the robot guidance by means of information assistance is verified by a simulation which results in a number of destinations reached by the mobile robot. The simulation is performed for 1000 steps while $p_0 = 0.1$, and the information assistants are present at all junctions of the environment shown in Fig. 3. Then, the obtained results are compared with the case when there are no information assistants in the same environment.

In the case of one mobile robot, the information assisted guidance increases a total number of reached destinations by approximately 600%

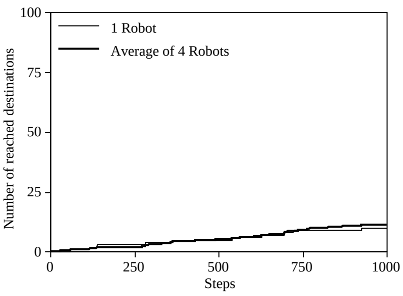
in the initially unknown environment, as it is illustrated in Fig. 11a. The simulation results for a group of four mobile robots in the environment with the information assistants situated at all junctions are shown in Fig. 11b. The results for a group of four mobile robots without information assistance are depicted in Fig. 11c. The thin lines in Fig. 11b and Fig. 11c denote a total number of destinations which were reached by one robot, and the thick lines – a total average number of destinations reached by a group of four robots.



a: One robot



b: Four robots, with information assistants



c: Four robots, without information assistants

Figure 11. Comparison of task execution

Comparing the simulation results depicted in Fig. 11a and Fig. 11c, one can conclude that operation of a group of four mobile robots is similar to those of one robot if there are no information assistants in the environment: average number of reached destinations is approximately the same. If the guidance information is provided by the information assistants, a group of four mobile robots operates by approximately 10% more efficiently than one robot, as it is seen in Fig. 11b (a group of four robots acquires guidance knowledge faster than one robot). These results show that guidance by information assistance provides *implicit cooperation* among mobile robots even without direct inter-robot communication nor a priori knowledge about the environment.

5. CONCLUSION

The concept of an optical guidance system that makes use of a laser light was considered. The operation algorithm and features of the optical guidance system were presented. The robot guidance by means of information assistance was proposed. Cooperative knowledge acquisition and sharing among mobile robots was considered. The implementation of the optical guidance system and information assistants was illustrated by the experimental results and simulation which have shown the effectiveness of the approach.

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