Mobile robot path planning and stabilizing using static CCD camera

Bogdan Kwolek

Rzeszów University of Technology, W. Pola 2, 35-959 Rzeszów, POLAND

Abstract: *The paper presents investigations concerning an important problem of mobile robot control using visual feedback. Two main topics are considered: a collision-free path planning and posture tracking on the basis of pictures obtained from static monochromatic camera. A collision-free path is determined off-line in multiprocessor system using the artificial potential field method. Parallel algorithm has been developed and tested in several experiments. The well known method of the geometrical moments and Hough transform have been used for robot position and orientation determination. Developed system is able to track a moving object with video rate.*

Keywords: Visual feedback, collision-free path planning, trajectory stabilizing, real-time, parallel computations.

1. Introduction

Picture processing plays at present a vital role and many robot applications are connected with visual control. In this paper two topics in the trajectory generation and the control algorithm are considered: (a) how to generate a smooth and feasible collision-free path using a vision system and (b) how to make a vision based controller stabilizing the unicycle mobile robot on the trajectory.

In robot trajectory tracking applications using vision real-time systems are needed. Considerable amount of computations related to picture preprocessing and analysis is one of the reason of research in parallel computations and multiprocessor systems. Due to inherent parallelism of digital pictures it is possible to have a significant speedup specially at picture preprocessing stage. A picture analyse consists of as an instance segmentation [8], analysis of shape coefficients, position and orientation determination introduces delays which are dependent on observed scene. For instance, in Hough transform [13] for each point different from background we make additional loops responsible for generation of line in workspace of parameters.

The problems discussed in this paper are related to real-time vision based control of mobile laboratory robot. The practical application presented here concerns stabilizing the miniature mobile robot Khepera [7] on a feasible trajectory using visual feedback based on the static monochrome camera. The trajectory is planned off-line using the artificial potential field method [6]. Several modifications to algorithms proposed in [2][12] have been introduced and parallel realisations have been elaborated. During posture tracking, the robot recognition as well as position and orientation determination are realized with frequency 25 Hz. The robot occupies in determined distances of time the required positions and orientations. Image preprocessing and analysis is performed in multiprocessor real-time vision system [9].

The organization of the paper is as follows. Formulation of the collision-free path generation problem and presentation of the feedback control laws suitable for real-time systems are given in chapter 2. In chapter 3. the parallel algorithm for path planning is briefly overviewed. Vision-based posture tracking is discussed in chapter 4. Chapter 5. presents the practical experiments. Conclusions of section 6. end the paper.

2. Problem formulation

The laboratory robot Khepera was chosen as the base of experiments. The robot has a cylindrical shape with the diameter of 55 mm and the height of 30 mm. Two wheels driven by DC motors are used for locomotion. It is equipped with the on board MC 68331 microcontoller of Motorola which communicates with external computer through an RS-232/IrDA link.

The robot is observed by the static monochrome CCD camera placed on heights 85 cm and viewing a region 55x51cm. Prepared software makes possible the robot recognition and their position as well as orientation determination, collision-free path planning, system calibration and visual feedback based posture tracking.

2.1 Collision-free path planning

Having the configuration q_{init} in a robot configuration workspace A, as well as the goal point q_{goal} in this workspace, one should determine a path τ beginning at the start point and ending in the goal point, being a sequence of configuration q of robot A such that A has no contact with obstacles $b_i\,(i=1,...,K)$ that are present in the working workspace W.

It is assumed that robot A is only moving object in environment as well as the robot is a free object moving on a flat track. The real shape of robot reminds a disc and can be artificially shrinked to a point. Having the above on regard, the planner should generate a sequence of points q setting up a collision-free path between the start and the goal point.

The global path planning requires a complete specification of the robot environment. In this work, the planner works using pictures obtained from the CCD camera. Determining of the robot position is proceeded by Gaussian filtering, thresholding, morphological closing and segmentation. The method of geometrical moments is used for determination of the robot position.

After the robot recognition, its figure is removed from the processed picture and the robot workspace is discretized. This operation is based on overlapping on a picture of dimensions 256x256 a rectangular regular grid of dimensions 128x128. An artificial increasing of obstacles (and forbidden regions) about the robot radius with an extra secure reserve related to maximal calibration error and expected control errors resulting from simulation is realized in bitmap obtained in this manner.

The method of artificial potential fields has been chosen for path planning, mainly because it provides efficient and reliable planner for practical purposes. The robot is treated as an object under the influence of an artificial field. The collision-free path planning algorithm consists of building an artificial field being a source of global information about free workspace and then finding in it a collision-free path. The artificial potential function is defined in the free workspace

$$C_{free} = W - \bigcup_{i=1}^{K} B_i = \left\{ q \in W : A(q) \cap \left(\bigcup_{i=1}^{K} B_i \right) = 0 \right\} \tag{1}$$

where B_i indicates an artificially enhanced obstacle, as a sum of artificial potential independent from configuration of obstacles which pulls the robot toward the goal point and a repulsive potential coming from obstacles and independent from the goal point. In [2][12] was proposed the method for building the potential function with no or few local minima and not large areas of attraction. In present work the construction of navigation function was limited to two-dimensional case. Parallel versions for NF2 and BFP methods have been prepared and tested in a multiprocessor system communicating via message passing.

2.2 Stabilization of the robot on a trajectory

The two driving wheels robot kinematics is expressed by following equations

$$\dot{x} = u_1 \cos\varphi, \dot{y} = u_1 \sin\varphi, \dot{\varphi} = u_2 \tag{2}$$

where the state of the system $[x,\ y,\ \varphi]^T$ is the position of the wheel axis center $x,\ y$ and the robot orientation φ with respect to the x-axis. The control variables u_1, u_2 are, respectively, the tangent (driving) and angular (steering) robot velocities. They are related to the wheel velocities in the following manner

$$u_1 = \frac{1}{2}\left(u_R + u_L\right),\ u_2 = \frac{1}{2\Delta}\left(u_R - u_L\right) \tag{3}$$

where 2Δ denotes distance between wheels, the velocities $u_R,\ u_L$ are the tangent velocities of each driving wheel at its center of rotation and are interpreted as motor velocity times wheel radius. The reference trajectory is described by equations

$$\dot{x}_r = u_{1r} \cos\varphi_r,\quad \dot{y}_r = u_{1r} \sin\varphi_r,\quad \dot{\varphi}_r = u_{2r} \tag{4}$$

and states desired sequence of $x,\ y,\ \varphi$ in time. The controls $u_{1r},\ u_{2r}$ are assumed to be bound and have bounded derivatives and $\lim_{t\to\infty}\left(u_{1r}(t)^2 + u_{2r}(t)^2\right) \neq 0$. The tracking problem consists of finding of a control law such that

$$\lim_{t\to\infty}\left\{ e(t) = \begin{bmatrix} e_x(t) \\ e_y(t) \\ e_\varphi(t) \end{bmatrix} = \begin{bmatrix} x_r(t) - x(t) \\ y_r(t) - y(t) \\ \varphi_r(t) - \varphi(t) \end{bmatrix} \right\} = 0$$

In [4] the following nonlinear control law has been proposed

$$u_1 = u_{1r}\cos\varphi_r + k_1(u_{1r},\ u_{2r})\left(e_x\cos\varphi + e_y\sin\varphi\right) \tag{5}$$

$$u_2 = u_{2r} + k_2 u_{1r}\frac{\sin e_\varphi}{e_\varphi}\left(-e_x\sin\varphi + e_y\cos\varphi\right) + k_3(u_{1r}, u_{2r})e_\varphi$$

where k_2 is a positive constant and $k_1(\cdot), k_3(\cdot)$ are continuous functions strictly positive on $R\times R - (0,0)$. It has been shown in [4] that the controls (5) globally asymptotically stabilize the origin $e(t) = 0$ and has been suggested that functions of gains $k_1(\cdot)$, $k_3(\cdot)$ and parameter k_2 should be chosen as

$$k_1(u_{1r},\ u_{2r}) = k_3(u_{1r},\ u_{2r}) = 2\zeta\sqrt{u_{1r}^2 + bu_{2r}^2} = 2\zeta a\ ,\quad k_2 = b \tag{6}$$

Using the proposed control gains we obtain the poles of the linearized closed loop system equal to the root of the characteristic polynomial equation

$$(s + 2\zeta a)(s^2 + 2\zeta as + a^2) = 0\,.$$

3. The parallel algorithm for path planning

The potential function NF2 is constructed on the basis of the skeleton of the free workspace. A picture obtained from the CCD camera is filtered using the Gaussian mask, thresholded and closed. The purpose of picture segmentation following after them is to separate disconnected objects and assign unique levels of grey. Then the robot is recognized and its position is determined. An artificial increasing of obstacles about sum of robot radius and of reserve determined on the basis of simulation investigations with visual control system is executed after removing a figure of the robot from the picture. Similar operation is accomplished in reference to the edge of picture with aim to avoid the contact of the robot with the barrier restricting area of movement. The increasing of obstacles is realized using two or four processors communicating via massage passing. The idea of artificial increasing of obstacles using two processors is shown on figure 1. After realization of logical sum of both pictures we obtained the identical picture with preprocessed by one processor. In algorithm of skeleton determination is continued an artificial increasing of obstacles until filling all free discreet space C_{dfree}. The skeleton is extracted during the grey values propagation as a set of points where grey values coming from particular obstacles meet. It is also similar to the skeleton extracted using [2][12] or techniques based on mathematical morphology. The algorithm used, for example, with pictures shown at

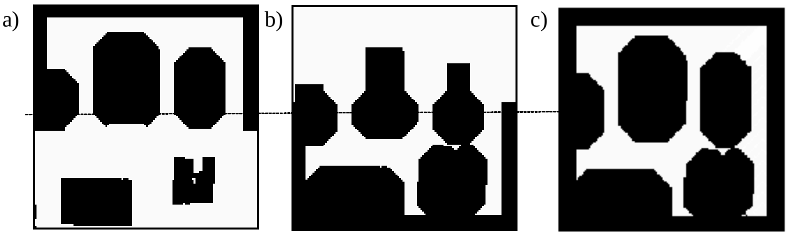

Figure 1. Artificial growing of obstacles using two processors,
a) b) processed pictures, c) resulting picture

figure 2. has been almost three times quicker in comparison to algorithm presented in [2][12]. It also makes possible the realization of parallel computations being characterized at this with high efficiency of computations. The goal point is next connected to skeleton by a path following the furthermost points to obstacles.

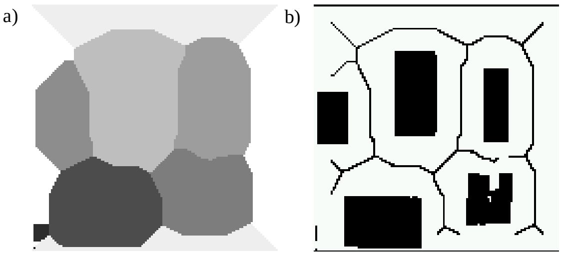

Figure 2. Illustration of skeleton extracting, a) artificially enhanced obstacles, b) skeleton

The determination of potential function NF2 is then continued with putting a potential on skeleton. The points belonging to skeleton in orders dependent from their distances to obstacles are remembered in ordered list. In first order, the unique values of potentials become the points situated at the farthest from obstacles. In algorithm used in present work, instead of ordered list, the unordered two-way list with guard is used [15]. The list constructed in such a way with remembered skeleton and potential values is then applied to complete the potential in the remaining part of the free workspace. The construction of the potential function has been realized by one processor.

The path has been generated using suggested in [2][12] best-first algorithm BFP. In best-first strategy, the most important operation, differentiating it from the classical algorithms depth-first [15], is an introduced list OPEN, ordered according to values of heuristic function. In the discussed problem of a path search it is used the list ordered according to key of potential value U in order not growing. An extension of the list is realized by expansion on neighbouring nodes $q' \in C_{dfree}$. In the applied algorithm BFP the heap sort algorithm is used [15]. The considerable shortening execution time has been obtained thanks to introduced modification. The parallel algorithm is based on adding of elements to the heap containing actually smaller number of elements.

Taking under attention computation time from moment of scene photographing until path generation ending, one reached in two-processor configuration the speedup about 30%. In four-processor configuration one reached almost twice shortening of execution time. The necessary time for robot position determination occupied about 30% of given values.

4. Realization of the visual feedback

Based on the Kalman filter predicted pose of the robot at the next sample time, the computations are realized in predicted image window location where the robot shape is expected to be found [5].

The measurement and steering, thanks to real-time system, are executed in discreet moments of time $t_k = t_o + kT$, where T is sampling period, and k accepts natural values $k = 0,\ 1,\ 2, \ldots$.

The following approximate model of movement and observation has been used

$$\begin{aligned} \xi_k &= A\xi_{k-1} + w_{k-1} \\ \eta_k &= C\xi_k + v_k \end{aligned} \tag{7}$$

where vector $\xi_k = \left[X_k, \dot{X}_k, Y_k \dot{Y}_k\right]^T$ determines system space, $\eta_k = \left[X_k, Y_k\right]^T$ denotes vector of measures, whereas X_k and Y_k represent robot center coordinates (x, y) transformed to picture coordinates, $\dot{X}_k$, $\dot{Y}_k$ denote velocity. Matrices w_k and v_k are disturbance noises assumed to be described by zero mean, Gaussian, mutually independent noises with covariances Q and R, respectively.

Matrixes of state and of measurements in the accepted model have a form resulting from assumed constant speed in sampling period.

$$A = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{8}$$

The recursive equation for the prediction of the window centre is the following

$$\hat{\xi}_{k/k-1} = A\hat{\xi}_{k-1/k-1} \tag{9}$$

where the estimate $\hat{\xi}_{k/k}$ is defined by the Kalman filter algorithm

$$\hat{\xi}_{k/k} = \hat{\xi}_{k/k-1} + K_{\zeta}\left(\eta_k - C\hat{\xi}_{k/k-1}\right) \tag{10}$$

The Kalman gain K_{ζ} is computed off-line.

Estimates $\hat{x}_{k/k-1}$ and $\hat{y}_{k/k-1}$ are determined from $\hat{\xi}_{k/k-1}$ on the basis of the camera model [14] with parameters identified using calibration procedure described in [9][11].

The prediction $\hat{\varphi}_{k/k-1}$ of robot orientation φ_k is computed on the basis of inclination angle ϑ_{k-1} of the line described by assumed analytical equation $p_{k-1} = x\cos\vartheta_{k-1} + y\sin\vartheta_{k-1}$ and detected by Hough transform. The mentioned angle φ_{k-1} was determined on the base of measurement ϑ_{k-1} and of rotation matrix used in the accepted camera model. The following Kalman filter equation has been used

$$\begin{aligned}\hat{\varphi}_{k/k-1} &= \hat{\varphi}_{k-1/k-1} + Tu_{2,k-1} \\ \hat{\varphi}_{k/k} &= \hat{\varphi}_{k/k-1} + K_{\varphi}\left(\varphi_k - \hat{\varphi}_{k/k-1}\right)\end{aligned} \tag{11}$$

The computed prediction of robot azimuth $\hat{\varphi}_{k/k-1}$ as well as position predictions $\hat{x}_{k/k-1}, \hat{y}_{k/k-1}$ have been used in control rule.

5. Practical experiments

The structure of the considered visual control system was shown in [9][10]. The system was simulated using SIMULINK software [16] having also powerful animation possibilities. Tuning of the controller (parameters ς and *b* in (6)) and of the Kalman filters (filter gains K_{ς} in (10) and K_{φ} in (11)) has been performed by simulation.

The parameters obtained by simulation are used in the T9000 transputer based control system. Appropriate task distribution among the transputers enables realization of the vision based control in real-time with the sampling period 40 ms (the full rate of 25 frames/s) [9]. The size of the moving window was set to 64x64. Sample results of experiments are presented in the figure 3. Trajectories obtained by simulation look similarly to the ones obtained in the real system.

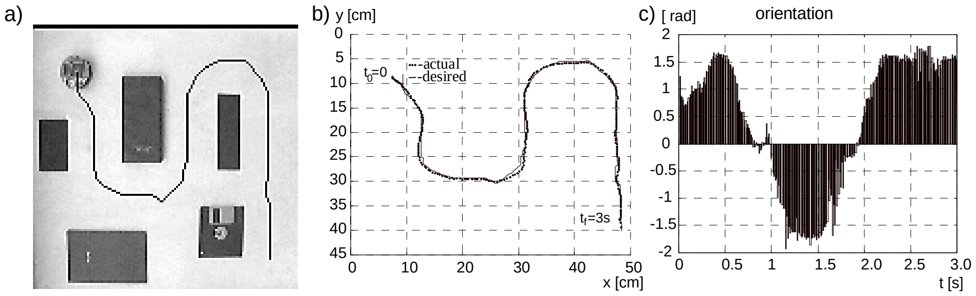

Figure 3. Trajectory stabilization using visual feedback a) sample collision-free path b) desired and real trajectory c) orientation of the robot obtained by the Hough transform

To determine the orientation a black cover with a white bar was attached on the top of the robot. Thanks to determined in first order robot position, the bar extraction as well as Hough transform were realized in window 32x32. The fast version of the Hough transform with two look-up-tables and filtering with butterfly filter have been applied [13]. The parallelization with parallel accumulator has been used [9].

Many other tests showed correct work of the system. Maximal velocity of the robot was 0.5 m/s. The collision-free path can be determined several times per second.

6. Conclusions

The vision based system for path planning and for real-time control has been designed. The static monochromatic CCD camera has been applied for posture tracking and collision-free path generation. Future research includes multirobot tracking and control.

References

1. **Baumgartner**, E.T., **Skaar**, B.S.: *An Autonomous Vision-Based Mobile Robot*, IEEE Trans. AC, **Vol. 39**, No. 3, 1994, 493-502.
2. **Barraquand**, J., **Langlois**, B., **Latombe**, J. C.: *Numerical Potential Field techniques for Robot Path Planning*, IEEE Trans. on Systems, Man and Cybernetics, **Vol. 22**, No. 2., 1992, 224-240.
3. **Bolc**, L., **Cytowski,** L.: *Search Methods for Artificial Intelligence*, Acad. Press, 1992.
4. **Canudas de Wit**, C., **Siciliano**, B., **Bastin**, G.: *Theory of Robot Control*, London, Springer, 1997.
5. **Hashimoto**, K.: Visual Servoing, *World Scientific*, London, 1993.
6. **Khatib**, O.: *Real Time Obstacle Avoidance for Manipulators and Bile Robots*, Int. J. Robotis Research, **Vol. 5**, No. 1, 1986, 90-99.
7. Khepera, User manual, version 3.0, Laboratoire de microinformatique, Swiss Federal Institute of Technology, Lausanne, 1994.
8. **Klette,** R., **Zamperoni**, P.: *Handbuch der Operatoren für die Bildbearbeitung*, Vieweg Verlag, Wiesbaden, 1995.
9. **Kwolek**, B.: *Methods and Tools of Transputer Engineering and their Application in Vision-Based Control*, PhD Thesis, University of Mining and Metallurgy, Cracov, 1998 (in Polish).
10. **Kwolek**, B., **Kapuściński**, T., **Wysocki**, M.: *Vision-based implementation of feedback control of unicycle robots*, First Workshop on Robot Motion and Control RoMoCo'99, Poznań, 1999.
11. **Kwolek**, B., **Wysocki**, M.: *Trajectory Planning and Stabilizing Using Visual Feedback and Transputer Network*, Proceedings of the Fourth Int. Symp. on Methods and Models in Automation and Robotics, **Vol. 3**, 1997, 921-926.
12. **Latombe**, J.C.: *Robot Motion Planning*, Kluwer Acad. Press, 1991.
13. **Leavers**, V.F.: *Shape Detection in Computer Vision Using the Hough Transform*, Berlin, Springer, 1992.
14. **Lenz**, R. K., **Tsai**, R. Y.: *Techniques for Calibration of the Scale Factor and Image Center for High Accuracy 3-D Machine Vision Metrology*, IEEE Trans. on Pattern Analysis and Machine Intelligence, **Vol. 10**, No. 5, 1988, 713-720.
15. **Sedgewick**, R.: *Algorithms in C,* Addison-Wesley Publ., 1990.
16. Simulink, Dynamic System Simulation Software User's Guide, The MATH WORKS Inc. 1994.