수정된 비용함수를 이용한 비선형 최적화 방법 기반의 이동로봇의 장애물 회피 비주얼 서보잉

논 문
58-12-32

Visual Servoing of a Wheeled Mobile Robot with the Obstacle Avoidance based on the Nonlinear Optimization using the Modified Cost Function

김 곤 우*
(Gon-Woo Kim)

Abstract – The fundamental research for the mobile robot navigation using the numerical optimization method is presented. We propose an image-based visual servo navigation algorithm for a wheeled mobile robot utilizing a ceiling mounted camera. For the image-based visual servoing, we define the composite image Jacobian which represents the relationship between the speed of wheels of a mobile robot and the robot's overall speed in the image plane. The rotational speed of wheels of a mobile robot can be directly related to the overall speed of a mobile robot in the image plane using the composite image Jacobian. We define the mobile robot navigation problem as an unconstrained optimization problem to minimize the cost function with the image error between the goal position and the position of a mobile robot. In order to avoid the obstacle, the modified cost function is proposed which is composed of the image error between the position of a mobile robot and the goal position and the distance between the position of a mobile robot and the position of the obstacle. The performance was evaluated using the simulation.

Key Words : Visual servoing, Mobile robot navigation, Nonlinear least squares, Obstacle avoidance

1. Introduction

Recently, research in navigation of mobile robots has been dramatically increased in various environments as the demand increases for service robots. For the accurate navigation, the accurate localization is needed. However, it is difficult to obtain the accurate position of mobile robots in various environments. In order to overcome this localization problem, many approaches has been researched such as sensor-based localization, indoor GPS, the intelligent space, the vision system, etc. A ceiling mounted camera system is the one of the efficient solutions which can be used to determine the position and the orientation of mobile robots. In addition, mobile robots can be also controlled using visual information from the ceiling mounted camera system.

Visual feedback control is generally referred to as visual servoing which is the control method using visual information. The image-based visual servoing is visual feedback control to use the image error directly to control the robot in the image plane with the image Jacobian. A number of visual servoing algorithms for robotic manipulators have been proposed [1][2]. Piepmeier et al. in [2] demonstrated the target tracking and obstacle avoidance of a robot manipulator for uncalibrated visual servoing. For visual servoing of mobile robots, many researchers have been focused on on-board camera [3-10]. Zhang et al. in [7] proposed a visual motion planning algorithm which can make motion plans directly in the image plane. For eye-to-hand configuration, some research in navigation of a mobile robot in the image plane has been proposed [11-13]. Dixon et al. in [13] proposed an asymptotic pose tracking controller which is developed for a wheeled mobile robot with an uncalibrated ceiling mounted camera system. For the visual servo navigation of a mobile robot with obstacle avoidance, the architecture for the navigation of a mobile robot with the obstacle avoidance was proposed by Defoort et al. in [8]. Han and Lee in [10] proposed the navigation algorithm of a mobile robot using circular path planning algorithm.

In this paper, we are focused on the image-based visual servo navigation with obstacle avoidance using the modified cost function of the numerical optimization method. We define the mobile robot navigation problem as an unconstrained optimization problem to minimize the image error between the goal position and the position of a mobile robot in the image plane [12]. Nonlinear least squares algorithm has been adopted for solving this unconstrained optimization problem. In order to avoid the obstacle, the combined cost function is proposed which is

---

* 정 회 원 : 원광대학교 전자및제어공학부 조교수
E-mail : kgw0510@wku.ac.kr
접수일자 : 2009년 10월 13일
최종완료 : 2009년 10월 16일

composed of the image error between the position of a mobile robot and the goal position and the distance between the position of a mobile robot and the position of the obstacle.

The paper is organized as follows. In section 2, the kinematic model of a mobile robot is presented. Perspective transformation is also addressed for the task space to the image plane. The image-based visual servo navigation with the obstacle avoidance is presented using nonlinear least squares optimization method with the modified cost function in section 3. In order to evaluate the proposed visual servoing, some simulation results are shown in Section 4. Finally, brief conclusions are presented in Section 5.

2. Kinematic Model of a Mobile Robot

2.1 Kinematics of a Mobile Robot in the Task Space

Kinematics is the most basic study about mechanical behavior of robot system. Relative position of mobile robots can be estimated using kinematic models.

Kinematics for mobile robots is somewhat different from robot manipulators. Robot manipulators can be considered to be more complex than mobile robot in some way because standard robot manipulators generally have six or more joints, whereas differential drive robots have only two wheels. A robot manipulator is fixed to the environment; therefore the pose of its end effector can be achieved by the relation between its end effector and its fixture. However, a mobile robot is not fixed to the environment; therefore its pose can be achieved in its environment.

The major difference between a mobile robot and a robot manipulator is the method of position estimation. For the case of a robot manipulator, the pose of its end effector can be measured by the kinematics of the robot and the position of all intermediate joints. When we know the position of all joints, the pose of the robot end effector is always measurable. However, we cannot directly measure the pose of a mobile robot instantaneously because a mobile robot can move by itself in its environment.

The pose of a mobile robot in the global reference frame can be defined as shown in Fig. 1 as:

$$q_R = \begin{bmatrix} x_R & y_R & \theta_R \end{bmatrix}^T \tag{1}$$

where x_R, y_R, and θ_R denote the position and orientation of a mobile robot, respectively.

The kinematic model of a differential drive robot with wheel diameter r is shown by using Jacobian matrix as[12][13]:

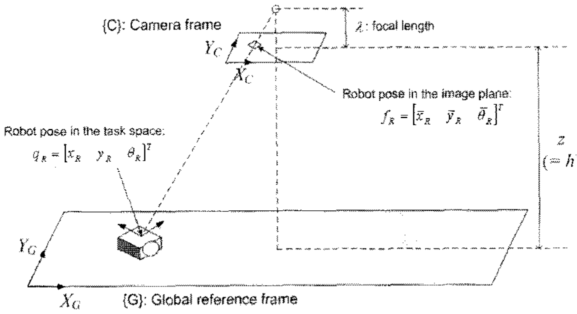


Fig. 1 Configuration of robot and camera system

$$\dot{q}_R = J_{kin}\cdot\dot{\varphi} \quad where\ J_{kin} = \begin{bmatrix} r\cos(\theta_R/2) & r\cos(\theta_R/2) \\ r\sin(\theta_R/2) & r\sin(\theta_R/2) \\ r/W & r/W \end{bmatrix} \tag{2}$$

where $\dot{\varphi}$ is the rotating speed of each wheel, $\dot{\varphi}_r$ and $\dot{\varphi}_l$ and W is the distance between two wheels.

Using the linear and angular velocity of a mobile robot, the speed of a mobile robot can be acquired as:

$$\dot{q}_R = T(q_R)\cdot\begin{bmatrix} v_R \\ \omega_R \end{bmatrix} \quad where\ T(q_R) = \begin{bmatrix} \cos\theta_R & 0 \\ \sin\theta_R & 0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

where v_R and ω_R are the linear and angular velocity of a mobile robot, respectively.

2.2 Perspective Transformation for the Task Space to the Image Plane

The kinematic model in the image plane can be modeled using the similar manner in the previous section. The pose of a mobile robot in the image plane as shown in Fig. 1 can be defined as:

$$f_R = \begin{bmatrix} \bar{x}_R & \bar{y}_R & \bar{\theta}_R \end{bmatrix}^T \tag{4}$$

where $\bar{x}_R$, $\bar{y}_R$, and $\bar{\theta}_R$ denote the position and orientation of a mobile robot in the image plane, respectively.

The configuration of robot and camera system is shown in Fig. 1. The camera is fixed on the ceiling and its image plane is assumed to be parallel to the plane of the robot workspace. And we assume that the origin and the axes in the task space correspond to the origin and the axes in the image plane.

The kinematic model of a mobile robot in the image plane is shown by using the linear and angular velocity in the image plane as:

$$\dot{f}_R = \bar{T}(f_R) \cdot \begin{bmatrix} \bar{v}_R \\ \bar{\omega}_R \end{bmatrix} \ where \ \bar{T}(f_R) = \begin{bmatrix} \cos\bar{\theta}_R & 0 \\ \sin\bar{\theta}_R & 0 \\ 0 & 1 \end{bmatrix} \tag{5}$$

where $\bar{v}_R$ and $\bar{\omega}_R$ are the linear and angular velocity of a mobile robot in the image plane, respectively.

In order to find the position and orientation of a robot in the image plane, we know the relationship between the position in the task space and the position in the image plane. The position of a robot in the image plane can be acquired using the position of a robot in the task space by the perspective transformation which projects 3-D points onto a plane as:

$$\begin{bmatrix} \bar{x}_R \\ \bar{y}_R \end{bmatrix} = \frac{\lambda}{h} \begin{bmatrix} k_u & 0 \\ 0 & k_v \end{bmatrix} \begin{bmatrix} x_R \\ y_R \end{bmatrix} \tag{6}$$

where λ is the focal length of the camera and k_u, k_v are the conversion parameters (unit: pixel/m) to convert the unit of the task space to the pixel level in the image plane.

After taking the time derivative of (6) and substituting the velocities along the axes in the task space, $\dot{x}_R$ and $\dot{y}_R$, in (3), we obtain the equation as follows:

$$\begin{bmatrix} \dot{\bar{x}}_R \\ \dot{\bar{y}}_R \end{bmatrix} = \begin{bmatrix} \alpha v_R \cos\theta_R \\ \beta v_R \sin\theta_R \end{bmatrix} \tag{7}$$

where α and β are $\lambda \cdot k_u/h$ and $\lambda \cdot k_v/h$, respectively [6]. Using (5), the following equation can be acquired as:

$$\begin{bmatrix} \bar{v}_R \cos\bar{\theta}_R \\ \bar{v}_R \sin\bar{\theta}_R \end{bmatrix} = \begin{bmatrix} \alpha v_R \cos\theta_R \\ \beta v_R \sin\theta_R \end{bmatrix} \tag{8}$$

We multiply $\bar{v}_R \cos\bar{\theta}_R$ by $\cos\theta_R/\alpha$ and also multiply $\bar{v}_R \sin\bar{\theta}_R$ by $\sin\theta_R/\alpha$. Then, the following equation can be obtained as:

$$\begin{bmatrix} \frac{1}{\alpha} \bar{v}_R \cos\bar{\theta}_R \cos\theta_R \\ \frac{1}{\beta} \bar{v}_R \sin\bar{\theta}_R \sin\theta_R \end{bmatrix} = \begin{bmatrix} v_R \cos^2\theta_R \\ v_R \sin^2\theta_R \end{bmatrix} \tag{9}$$

Add rows of the vector in (9), and then we have the relationship as follows.

$$v_R = \underbrace{\left(\frac{1}{\alpha} \cos\bar{\theta}_R \cos\theta_R + \frac{1}{\beta} \sin\bar{\theta}_R \sin\theta_R \right)}_{J_1 \in R^1} \bar{v}_R \tag{10}$$

In order to relate $\bar{\omega}_R$ to ω_R, we use (5) for eliminating v_R and obtain the following equation:

$$\dot{\bar{y}}_R = \dot{\bar{x}}_R \tan\bar{\theta}_R \tag{11}$$

After substituting (7), we arrange (11) as:

$$\tan\theta_R = \frac{\alpha}{\beta} \tan\bar{\theta}_R \tag{12}$$

We take the time derivative of (12) and we acquire the equation as:

$$\frac{1}{\cos^2\theta_R} \dot{\theta}_R = \frac{\alpha}{\beta} \cdot \frac{1}{\cos^2\bar{\theta}_R} \dot{\bar{\theta}}_R \tag{13}$$

Using some manipulation of (13) the equation is obtained as follows.

$$\dot{\theta}_R = \underbrace{\left(\frac{\alpha}{\beta} \cos^2\theta_R + \frac{\beta}{\alpha} \sin^2\theta_R \right)}_{J_2 \in R^1} \dot{\bar{\theta}}_R \tag{14}$$

We can find the Jacobian matrix which represents the relationship between the linear and angular velocity in the task space and the linear and angular velocity in the image space as follows:

$$\begin{bmatrix} v_R \\ \omega_R \end{bmatrix} = J_{img} \cdot \begin{bmatrix} \bar{v}_R \\ \bar{\omega}_R \end{bmatrix} \ where \ J_{img} = \begin{bmatrix} J_1 & 0 \\ 0 & J_2 \end{bmatrix} \tag{15}$$

The final goal of this section is to find the composite image Jacobian which represents the relationship between the speed of wheels of a mobile robot and the robot's overall speed in the image plane. A mobile robot can be directly controlled in the image plane using the composite image Jacobian, which is called the image-based visual servo control.

The composite image Jacobian, $J_\varphi \in R^{3 \times 2}$, can be acquired as:

$$\dot{f}_R = \bar{T}(f_R) \cdot J_{img}^{-1} \cdot T^{+}(q_R) \cdot J_{kin} \cdot \dot{\varphi} = J_\varphi \cdot \dot{\varphi} \tag{16}$$

where $T^{+}(q_R)$ is the pseudo inverse matrix of $T(q_R)$ as $T^{+}(q_R) = (T^T T)^{-1} \cdot T^T$.

The rotational speed of wheels of a mobile robot can be directly related to the overall speed of a mobile robot in the image plane using the composite image Jacobian in (16).

3. Nonlinear Least Squares Optimization for Mobile Robot Navigation with the Obstacle Avoidance

We define the visual servo navigation with obstacle avoidance of a mobile robot as the unconstrained optimization problem to move a mobile robot to a goal position. In order to avoid the obstacle, the combined cost function is proposed which is composed of the image error between the position of a mobile robot and the goal position and the distance between the position of a mobile robot and the position of the obstacle. The nonlinear least squares optimization method with the modified cost function is used for solving this problem. Fig. 2 shows the control architecture of the image-based visual servo control system.

3.1 Modified Cost Function for Visual Servoing with the Obstacle Avoidance

Considering the eye-to-hand vision system, the camera can observe the pose of the mobile robot in the image plane as shown in Fig. 2. In the image plane, the goal position is virtually represented by f^* and the pose of the mobile robot is represented by $f_R(\varphi)$ as the function of the robot wheel variables, φ. The image error between the goal position and the pose of the mobile robot is defined as:

$$e(\varphi)=f_R(\varphi)-f^* \tag{17}$$

In order to avoid the obstacle, the distance function between the pose of the mobile robot and the position of the obstacle is also defined as:

$$d(\varphi)=f_R(\varphi)-f_{obs} \tag{18}$$

where f_{obs} is the position of the obstacle in the image plane.

The control problem which is to move a mobile robot to a goal position with the obstacle avoidance can be defined as the minimization of the image error.

In order to minimize the image error between the goal position and the pose of the mobile robot and avoid the obstacle concurrently, we define the combined cost function as:

$$E(\varphi)=\begin{cases}\frac{1}{2}e^T(\varphi)e(\varphi)+\frac{K}{2}\left(d_{\max}^2-d^T(\varphi)d(\varphi)\right) & \text{if } \|d(\varphi)\|<d_{\max}\\ \frac{1}{2}e^T(\varphi)e(\varphi) & else\end{cases} \tag{19}$$

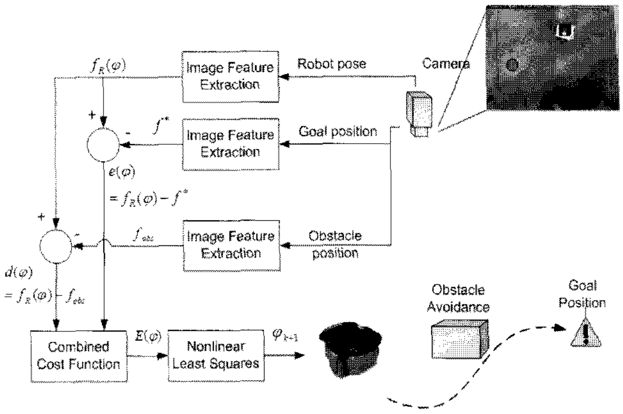


Fig. 2 The control architecture of the proposed image-based visual servo control system

where K is a gain factor on the repulsive gradient and $d_{\max}$ is the maximum distance which allows the robot to ignore the obstacle sufficiently far away from it.

The combined cost function is defined by the square of the image error and the cost function for the obstacle avoidance. This cost function is a nonlinear function because the image feature of a mobile robot is determined by the complex geometric relationship.

3.2 Gauss-Newton's Method for Nonlinear Least Squares Optimization

The nonlinear least squares optimization problem for moving a mobile robot toward a goal position with the obstacle avoidance can be defined as:

$$\min_{\varphi\in R^n} E(\varphi)=\min_{\varphi\in R^n}\left\{\frac{1}{2}e^T(\varphi)e(\varphi)+\frac{K}{2}\left(d_{\max}^2-d^T(\varphi)d(\varphi)\right)\right\} \tag{20}$$

which is minimized at the robot joint configuration, φ^*, satisfying the equation, $\partial E(\varphi^*)/\partial\varphi=0$. If we assume the linear model in the neighborhood at $\bar{\varphi}$, the cost function can be approximated using the Taylor series expansion as:

$$\hat{E}(\varphi)=E(\bar{\varphi})+\nabla E(\bar{\varphi})\cdot(\varphi-\bar{\varphi}) \tag{21}$$

If we assume that the cost function is the second order differentiable for φ, the gradient of the approximation model is shown as:

$$\frac{\partial\hat{E}(\varphi)}{\partial\varphi}=\nabla E(\bar{\varphi})+\nabla^2 E(\bar{\varphi})\cdot(\varphi-\bar{\varphi}) \tag{22}$$

We define the composite image Jacobian of robot, $J_\varphi(\varphi)=\partial f_R(\varphi)/\partial\varphi$, in (16). The cost function can be the minimizer of the cost function if the gradient of the approximation model at φ_k is zero. The first and second order differential terms of the cost function are shown as:

$$\begin{aligned}\nabla E(\varphi)&=\sum_{i=1}^{n}\left(e_i(\varphi)\cdot\nabla e_i(\varphi)-Kd_i(\varphi)\cdot\nabla d_i(\varphi)\right)\\&=J_\varphi(\varphi)^T(e(\varphi)-Kd(\varphi))\end{aligned}\tag{23}$$

$$\begin{aligned}\nabla^2E(\varphi)&=\sum_{i=1}^{n}\left(\nabla e_i(\varphi)\cdot\nabla e_i(\varphi)^T+e_i(\varphi)\cdot\nabla^2e_i(\varphi)\right)\\&\quad-K\sum_{i=1}^{n}\left(\nabla d_i(\varphi)\cdot\nabla d_i(\varphi)^T+d_i(\varphi)\cdot\nabla^2d_i(\varphi)\right)\\&=J_\varphi(\varphi)^TJ_\varphi(\varphi)+R(\varphi)-K\left(J_\varphi(\varphi)^TJ_\varphi(\varphi)+R_d(\varphi)\right)\end{aligned}\tag{24}$$

where the residual terms derived by (17) and (18) are $R(\varphi)=\nabla(J_\varphi(\varphi))^Te(\varphi)$ and $R_d(\varphi)=\nabla(J_\varphi(\varphi))^Td(\varphi)$, respectively.

The iterative form of the joint value to minimize the cost function becomes:

$$\begin{aligned}&\varphi_{k+1}=\varphi_k-(M_{robot}-M_{obs})^{-1}J_\varphi(\varphi_k)^T(e(\varphi_k)-Kd(\varphi))\\&where\begin{cases}M_{robot}=J_\varphi(\varphi_k)^TJ_\varphi(\varphi_k)+R(\varphi_k)\\M_{obs}=K\left(J_\varphi(\varphi_k)^TJ_\varphi(\varphi_k)+R_d(\varphi_k)\right)\end{cases}\end{aligned}\tag{25}$$

These equations contain the Hessian term. For the zero residual case, these terms can be ignored. Therefore, the residual terms are set to be zero.

If the norm of the distance function between the robot and the obstacle is sufficiently large, M_{obs} and $Kd(\varphi)$ in (25) will be zero by the definition of the combined cost function in (19).

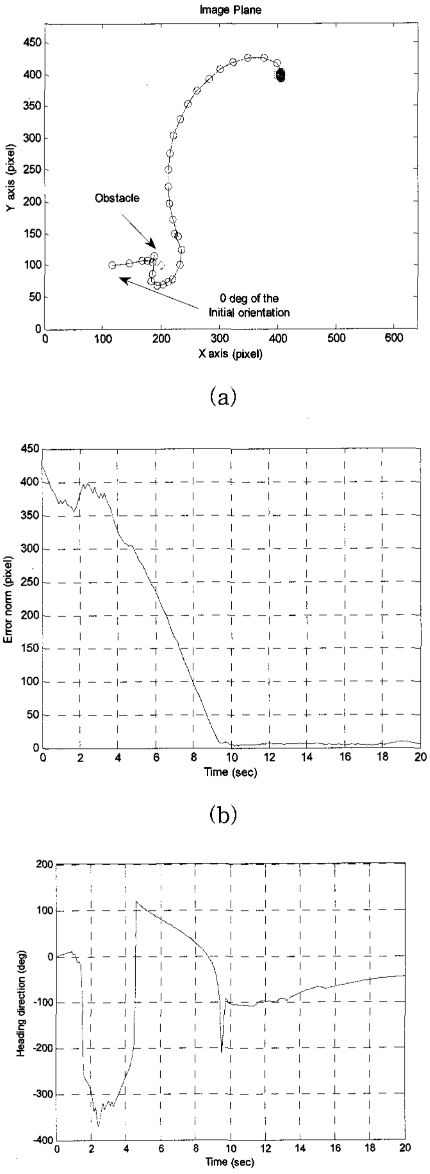
4. Simulation Results

The proposed methods were applied on a differential drive mobile robot for the eye-to-hand configuration. The simulation was performed for the visual servo navigation with the obstacle avoidance using the proposed algorithm.

A mobile robot is nonholonomic system. Therefore, performance of navigation is greatly affected by the orientation data of a mobile robot at the initial position. Therefore, the simulation was performed for different orientations at the same position of a mobile robot. An obstacle is set to be located on the robot path.

The initial position of a mobile robot is (100, 100) and the goal position is (400, 400) in the image plane. The gain factor, K is set to be 10 and the maximum distance, $d_{\max}$ is set to be 30 pixels in (19). The sampling time is 100 ms. The steady-state is defined as the state after achieving $\| e(\varphi_k)\|_2\le 10$ pixels.

Fig. 3, Fig. 4 and Fig. 5 present the results of the visual servo navigation with the obstacle avoidance for the different initial orientation. The result for the initial orientation of 0 deg. is shown in Fig. 3. The obstacle is located at (200, 100) in the image plane. The average steady-state error norm is 5.6648 pixels and the convergence time is 9.5 sec. In Fig. 4, the result for the initial orientation of 45 deg. is presented. The obstacle is located at (200, 200) in the image plane. The average steady-state error norm is 8.309 pixels and the convergence time is 17.1 sec.

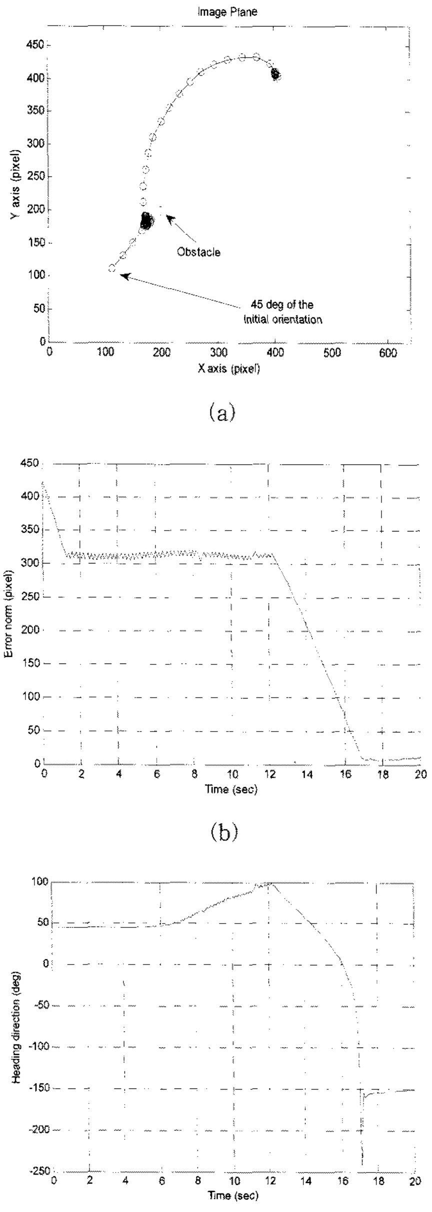


(a)

(b)

(c)

Fig. 3 The simulation result when the initial orientation is 0° and the obstacle is located at (200, 100): (a) the trajectory of a mobile robot, (b) the image error and (c) the heading direction of a mobile robot



(a)

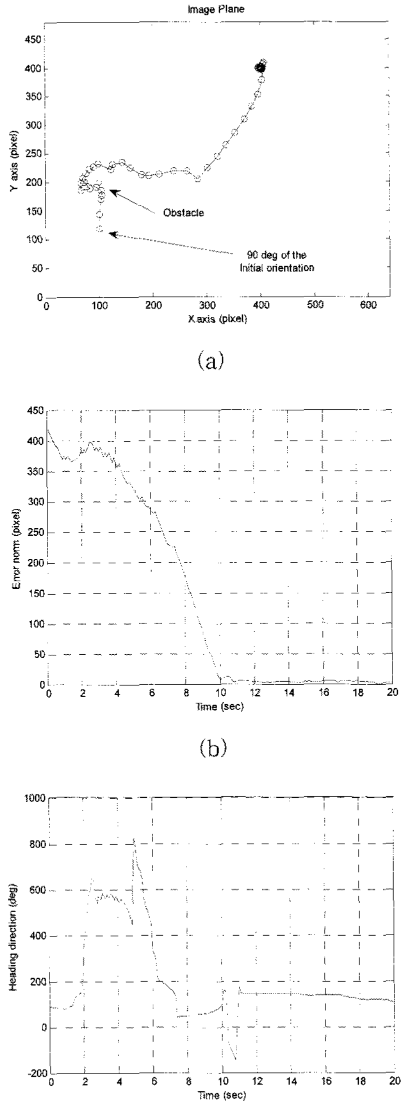
(b)

(c)

Fig. 4 The simulation result when the initial orientation is 45° and the obstacle is located at (200, 200): (a) the trajectory, (b) the image error and (c) the heading direction

Finally, the result for the initial orientation of 90 deg. is presented in Fig. 5. The obstacle is located at (100, 200) in the image plane. The average steady-state error norm is 5.6648 pixels and the convergence time is 9.5 sec.

According to the simulation results, the proposed visual servo navigation algorithm with obstacle avoidance is feasible for the autonomous navigation. The results show the suitable performance of navigating toward the goal and avoiding the obstacle, simultaneously.



(a)

(b)

(c)

Fig. 5 The simulation result when the initial orientation is 90° and the obstacle is located at (100, 200): (a) the trajectory, (b) the image error and (c) the heading direction

5. Conclusions and Future Works

We proposed a navigation algorithm with the obstacle avoidance using image-based visual servoing utilizing a fixed camera. The composite image Jacobian was proposed using the kinematic model of a wheeled mobile robot and the perspective transformation. Using the composite image Jacobian, the rotational speed of wheels of a mobile robot can be directly related to the overall speed of a mobile robot in the image plane. Nonlinear least squares algorithm was adopted for solving the unconstrained optimization problem.

The composite image Jacobian was applied to nonlinear least squares algorithm. For avoiding the obstacle, we proposed the composed cost function for the nonlinear least squares algorithm. The simulation results showed the validity of the proposed image-based visual servo navigation algorithm with the obstacle avoidance.

This research has been performed as the fundamental research in the general visual servo navigation algorithm using the numerical optimization. The future work will include consideration of the nonholonomic constraint and experimental evaluation using the real robot system and be also focused on the extension of the general mobile robot navigation algorithm using the numerical optimization.

감사의 글

본 연구는 2009년도 원광대학교의 교비를 지원에 의해서 수행되었습니다.

참고문헌

[1] G. W. Kim, and B. H. Lee, "Target Tracking using the Efficient Estimation of the Image Jacobian with Large Residual," ROBOTICA, vol. 24, 2006, pp. 325-327.

[2] J. A. Piepmeier, G. V. McMurray, A. Pfeiffer, and H. Lipkin, "Uncalibrated target tracking with obstacle avoidance," IEEE Int'l Conf. Robotics and Automation, 2000, pp. 1670-1675.

[3] F. Conticelli, B. Allotta, and P. K. Khosla, "Image-Based Visual Servoing of Nonholonomic Mobile Robots," Int'l Conf. Decision and Control, 1999, pp. 3496-3501.

[4] H. Y. Wand, S. Itani, T. Fukao, and N. Adachi, "Image-Based Visual Adaptive Tracking Control of Nonholonomic Mobile Robots," Int'l Conf. Intelligent Robots and Systems, 2001, pp. 1-6.

[5] K. Hashimoto, and T. Noritsugu, "Visual Servoing of Nonholonomic Cart," Int'l Conf. Robotics and Automation, 1997, pp. 1719-1724.

[6] Y. Ma, J. Kosecka, and S. Sastry, "Vision Guided Navigation for a Nonholonomic Mobile Robot," IEEE Trans. Robotics and Automation, vol. 15, no. 3, 1999, pp. 521-536.

[7] H. Zhang, and J. P. Ostrowski, “Visual Motion Planning for Mobile Robots,” IEEE Trans. Robotics and Automation, vol. 18, no. 2, Apr. 2002, pp. 199-208.

[8] M. Defoort, J. Palos, A. Kokosy, T. Floquet, W. Perruquetti, and D. Boulinguez, "Experimental Motion Planning and Control for an Autonomous Nonholonomic Mobile Robot," IEEE Int'l Conf. Robotics and Automation, 2007, pp. 2221-2226.

[9] N. Ohnishi and A. Imiya, "Corridor Navigation and Obstacle Avoidance using Visual Potential for Mobile Robot," Fourth Canadian Conference on Computer and Robot Vision, 2007, pp. 131-138.

[10] S. M. Han and K. W. Lee, "Mobile Robot Navigation using Circular Path Planning Algorithm," Int'l Conf. Control, Automation and Systems 2008, 2008, pp. 2082-2086.

[11] J. Chen, W. E. Dixon, D. M. Dawson, and M. McIntyre, "Homography-Based Visual Servo Tracking Control of a Wheeled Mobile Robot," IEEE Trans. Robotics, vol. 22, no. 2, 2006, pp. 407-416.

[12] G. W. Kim, K. T. Nam, S. M. Lee, and W. H. Shon, "Visual Servo Navigation of a Mobile Robot using Nonlinear Least Squares Optimization for Large Residual," J. Korea Robotics Society, vol. 2, no. 4, 2007, pp. 326-332.

[13] W. E. Dixon, D. M. Dawson, E. Zergeroglu, and A. Behal, "Adaptive Tracking Control of a Wheeled Mobile Robot via an Uncalibrated Camera System," IEEE Tras. Systems, Man, amd Cybernetics, vol. 31, no. 3, June, 2001, pp. 341-352.

저자소개

김곤우 (金坤佑)

1974년 5월 10일생. 2000년 중앙대학교 전자전기제어공학부(공학사). 2002년 서울대학교 전기컴퓨터공학부(공학석사). 2006년 동 대학원(공학박사). 2006년~2008년 한국생산기술연구원 로봇기술본부 위촉연구원, 2008년~현재 원광대학교 전자및제어공학부 조교수. 관심분야는 Visual servoing, Robot Navigation, Sensor Fusion, Map Building and Localization.