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Reactive Visual Navigation based on Omnidirectional Sensing - Path Following and Collision Avoidance-

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Abstract

Described here is a visual navigation medhod for navigating a mobile robot along a man-made route such as a corridor or a street. We have proposed an image sensor, named HyperOmniVision, with a hyperboloidal mirror for vision based navigation of the mobile robot. This sensing system can aquire an omnidirectional view around the robot in real time. In the case of the man-made route, road boudaries between the ground plane and wall appears as a close-looped curve in the image. By making use of this optical characteristic, the robot can avoid obstacles and move along the corridor by tracking the close-looped curve with an active countour model. Experments that have been done in a real environment are described.

1 Introduction

Researchers have investigated a variety of vision-based navigation of autonomous vehicles. While visual information is important for safety in autonomous navigation, most robots view things only in front of them and avoid obstacles. As a result, they may collide against objects moving from the side or behind. If considered from the standpoint of machine perception, autonomous navigation needs the field of view as wide as possible. We have built several omnidirectional image sensors, named COPIS, MISS and HyperOmni Vision which acquires an omnidirectional view around the robot, in real-time, by using convex mirrors [1-3].

From another point of view, the most representative low-level action commands for autonomous navigation are road (path) following and collision avoidance. Dickmanns et al have developed a high-speed road following system at the Military University of Munich [4]. Researchers at Carnegie-Mellon University have proposed the vehicle controlled system, named ALVINN, which memorized the relation between the steering angle of the vehicle and appearance of road patterns by a neural network [5]. An interesting visual navigation method, developed by Santos-Victor et al, is based on optical flows from two cameras directed opposite direction each other and pointed laterally to the navigation direction [6]. By balancing the flow measurements on the left and right sides, the robot can path the center of the corridor.

Another important task for navigation is obstacle avoidance. Inverse perspective transformation, divergence and time to contact are often used for obstacle avoidance [1,7,8]. For instance, Cipolla et. al. have detected a forward obstacle from divergence of active contours which fixed on the frontal object (rear window of automobile)

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[7]. We have proposed a method where objects moving along collision paths are detected by monitoring azimuth changes (divergence) of vertical edges. [1].

These low-level action commands such as road following and collision avoidance need capability of fast reaction. An artificial potential field is a common approach to realize a reactive collision avoidance behavior. Holenstein et al have investigated a behavior based robot system that collision avoidance behavior is created by potential field, as a repulsion-force obtained by ultrasonic sensors, around the robot itself instead of the obstacles [9]. Zapata et al have proposed a collision avoidance behavior for frontal obstacles [10]. Range boundary of readings of ultrasonic sensors are deformed by presence of obstacles, control strategies of the robot are generated in response to remove the deformation of the range boundary.

In this paper, we describe a new method for reactive visual navigation based on omnidirectional sensing. The robot is projected at the center of the input image by the omnidirectional image sensor HyperOmni Vision. Therefore, rough free space around the robot can be extracted by active contour model. The method produces low-level commands that keep the robot in the middle of the free space and avoid collision by balancing shape of extracted active contours. Basic idea to follow a path and avoid collision is similar with a combination of Santos-Victor's method [6] and Holenstein's method [9], respectively. Santos-Victor is based on optical flows from two cameras directed opposite direction each other and just follow the corridor. it may collide against objects moving from the side or behind because of only lateral observation. For collision avoidance, Holenstein measured omnidirectional range data by setting 24 ultrasonic sensors around the robot. We can generate both behaviours at the same time by making use of characteristic of omnidirectional image sesnor, the robot can avoid obstacles and move along the corridor by tracking the close-looped curve with an active countour model. Furthermore, the method can directly represent the spatial relations between the environment and the robot on the image coordinate. Thus the method can control the robot without geometrical 3D reconstruction.

2 HyperOmni Vision

We. have proposed an omnidirectional image sensor using a hyperboloidal mirror. Its name is HyperOmni Vision [3] (See Fig. 1). Mounting HyperOmniVision on a robot so that optical axis is vertical, we acquire a 360-degree view around the robot. Fig. 2 shows an example of the input image. HyperOmni Vision maps a scene onto the image plane through a hyperboloidal mirror and a lens. This mapping is called "hyperboloidal projection". The hyperboloidal mirror has a focal point, which makes possible easy generation of any desired image projected on any designated image plane, such as a perspective image or a panoramic image, from an omnidirectional input. This easy generation of perspective or panoramic images allows the robot vision to use existing image processing methods for autonomous navigation.

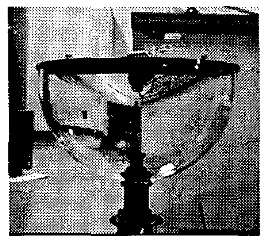


Fig. 1 HyperOmniVision

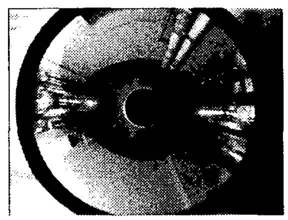


Fig.2 An Example of Input Image

3 Overview

A boundary of free space around the robot can be represented by a close-looped line in the input image because the robot is projected to the center of the input image by HyperOmni Vision. First, a rough free space region around the robot is detected by using a contour extraction model, which is small influence of environmental changes, basically based on an active contour model, first introduced by Kass et al [11]. Then, by evaluating a shape of extracted free space region, the method produce low-level motor commands that avoid the obstacle and keep the robot in the center of the free space.

4 Active Contour Model for Free Space Detection

An active contour model (ACM) first introduced by Kass et al[11], is an effective model for extracting smooth continuous contour. The ACM is controlled by internal and external. The internal forces enforce smoothness and the external forces guide the active contour to the image feature such as the image intensity data. The ACM is defined by

$$E_{snake}(v(s)) = \int_0^1 (E_{\text{int}}(v(s)) + E_{ext}(v(s)))ds \quad (1)$$

where E_{snake}, E_{int} and E_{ext} represent the total energy, the initial energy of smoothness and continuity, and the external energy for contour deformation, respectively.

The advantage of the ACM is that several different types of contour characteristics, such as image features, shape models and smoothness of contours, can be defined with a simple function. However, the convergent position of the ACM depends on the initial contours due to many local minima within the energy function. Therefore, difficulties in the use of an ACM are how to provide the initial position of the active contours and how to define energy functions. Use of the feature of HyperOmni Vision, we define the internal and external forces of ACM for free space detection.

We assume that initially there is no obstacle around the robot and all obstacles and walls lie on the ground plane. The robot is projected at the center of the input image by HyperOmni Vision. For those obstacles which have some height above the ground plane, their image will appear elongated in the radial direction and lie farther than their ground counterparts on the floor. Free space will appear between robot and obstacle in the image. Therefore, we initially start the active contour from the robot fringe in the image (center of the image) and restrict converging direction of the active contour (each control points) to radial direction because the obstacle elongated in the radial direction. A computational cost can be reduced by restricting the moving direction of each control points. After once convergence of the ACM, an initial position of the ACM at the next frame can set at the position where shrunk a certain times from the current converged position of the ACM.

In case of the corridor, an apparent shape of the free space (floor region) in the image is an oval figure along the corridor as shown in Fig. 2. Therefore, we include the ellipse property as a global constraint on the energy function of the active contour model. The internal energy function is composed of a common smoothness term E_{int1} weighted by w_{int1} and ellipse global shape constraint term E_{int2} weighted by w_{int2}. The external energy E_{ext} which attracts active contours to edges with large image gradients, is defined by a first order differential filter. Total energy of the ACM is defined by

$$E_{snake}(v(s)) = \int_0^1 (w_{\text{int}1}E_{\text{int}1}(v(s)) + w_{\text{int}2}E_{\text{int}2}(v(s)) + w_{ext}E_{ext}(v(s)))ds \quad (2)$$

where w_{edge} is weighting coefficient. Fig. 3 shows an example of extracted free space. The white close-looped curvature is the converged ACM.

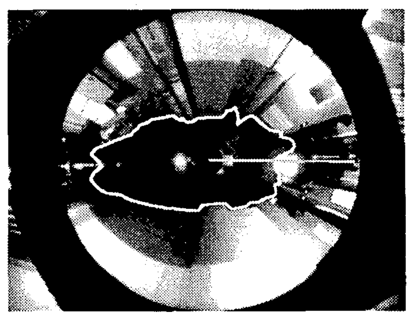


Fig. 3 A Result of Extracted Free Space and Principal Axis of Inertia around the Center of Gravity

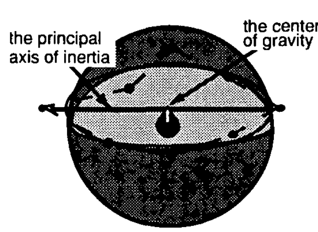


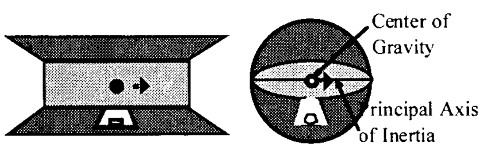
Fig.4 The Principal Axis of Inertia and the Center of Gravity

5 Robot Action Control

By evaluating three features calculated from a shape of extracted free space region (active contours), the method produces low-level motor commands that avoid the obstacle and keep the robot in the middle of the free space. To be more specific, the robot action (moving direction) is determined by combining three features; the principal axis of inertia and the center of gravity of the extracted free space region and repulsive forces from the environment (obstacle and wall) as shown in Fig. 4.

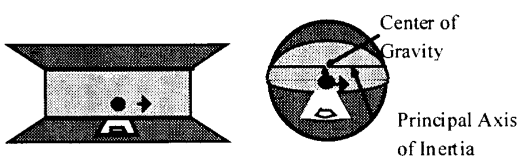
5.1 The principal axis of inertia and the center of gravity

As mentioned above, in case of the corridor and a road, an apparent shape of the free space (floor region) in the image is roughly the oval figure along the corridor as shown in Fig. 4. If the robot is in the middle of the corridor and boundary of the both side of the corridor is parallel, the direction of the principal axis of inertia is parallel to the corridor and the center of the gravity is as same as the image center (See Fig. 5(a)). When the robot moves near one wall, the center of the gravity shifts to an opposite side of near wall as shown in Fig. 5 (b). As shown in Fig. 5 (c), if the robot moves not parallel to the environment but the middle position of the corridor, the direction of the principal axis of inertia is tilted in the opposite direction but the center of the gravity is as same as the image center. It means that the center of gravity can represent the location of the robot relative to the corridor and the principal axis of inertia can show moving direction of the robot relative to the corridor. Grey straight line in Fig. 3 shows the principal axis of inertia around the center of gravity of the extracted free space region.



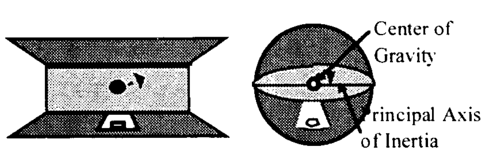
Environment Input Image

(a) The robot moves along the middle position of the corridor



Environment Input Image

(b) The robot moves near one wall



Environment Input Image

(c) The robot cross the corridor

Fig.5 Relation between Environment and Apparent Shape of Free Space (Floor) Region

5.2 Repulsive forces from the environment

An artificial potential field is a common approach to realize a reactive collision avoidance behavior. Holenstein et al have investigated a behavior based robot system which collision avoidance behavior is created by potential field, as a repulsion-force obtained by ultrasonic sensors, around the robot itself instead of the obstacles [9]. Our method is similar with Holenstein's method. The repulsive vector d_r is defined by the following equation.

$$\vec{d}_r = \sum_{i=1}^{\text{Controlpoints}} \left(\frac{1}{l_i} \right)^a \vec{e}_i \tag{3}$$

where $\vec{e}_i$ and l_i are the unit vector that represents direction of each control points from the image center and distance between each control points and the image center, respectively. The number a of the power in (3) was heuristically determined as fifth.

6 Detection of Robot Action

Moving direction of the robot is defined by the resultant of three forces; the principal axis of inertia, the center of gravity and repulsive forces from the environment as follow,

$$d_s = w_i d_i + w_g d_g + w_r d_r \tag{4}$$

where w_i and w_g are weighting coefficients of the vector d_i of the principal axis of inertia and of the vector d_g which passes through the image center and is perpendicular to the principal axis of inertia. w_r is a weighting coefficient of the repulsive vector d_r.

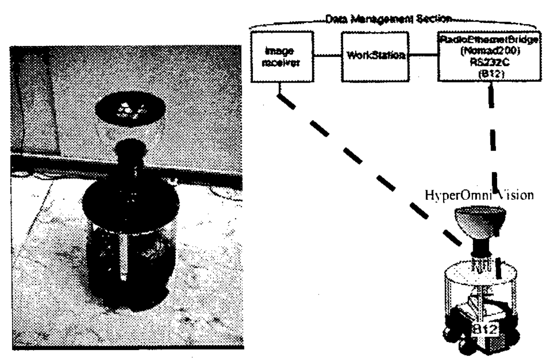
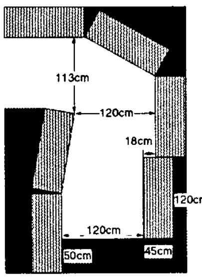


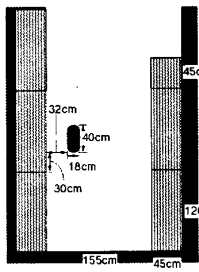
Fig.6 System Configuration

7 Experimental Results

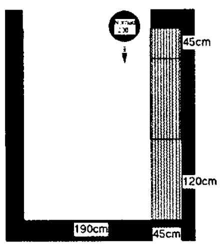
As shown in Fig.6, the robot system has three essential components; an imaging subsystem HyperOmni Vision, an image processing subsystem and a mobile robot. Wireless modems are used for communication between the robot and the image processing subsystem. The image is transmitted by UHF video transmitter and receiver. The image processing subsystem consists of a monitor, an image processor which converts each omnidirectional image into a 640 x 480 8 bit digital image and a workstation.



(a) Case of Curved Road

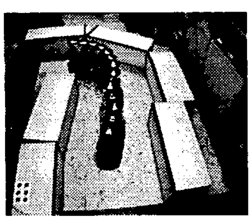


(b) An Obstacle in Front of The Robot

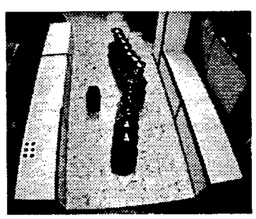


(c) Environment Containing An Unknown Obstacle

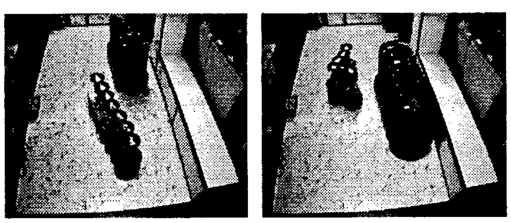
Fig.7 Experimental Environment



(a) An Result of Turning Road Following



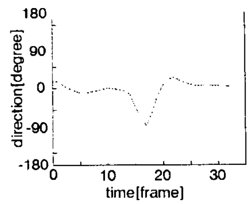
(b) An Result of Obstacle Avoidance



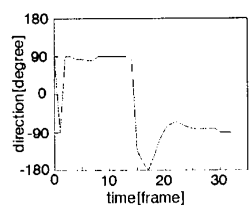
(c) An Result of Collision Avoidance against An Unknown Moving Obstacle

Left : Before passing through the moving obstacle
Right : After passing through the moving obstacle

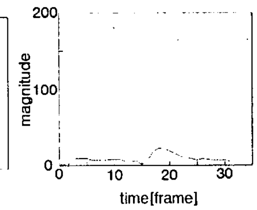
Fig.8 Experimental Results



(1) Direction of the principal axis of inertia

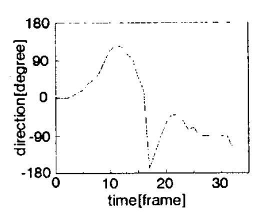


(a) Direction

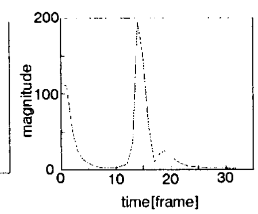


(b) Magnitude

(2) The center of gravity

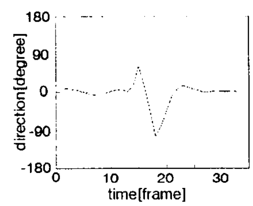


(a) Direction



(b) Magnitude

(3) Repulsive vector



(4) Estimated direction of robot movement

Fig.9 Results of Each Parameters and Robot Control

Experiments were carried out in several environments. As shown in Fig. 7, to evaluate the fundamental performance of the system, we performed three differential situations. First, the robot was tested in a turning corridor setup, as shown in Fig. 7(a). Second one is performed in the straight corridor with static obstacle (Fig. 7(b)). As shown in Fig. 8(a) and (b), the robot can follow a turning corridor smoothly and avoid static obstacle, respectively. Third one is performed in dynamic environment containing an unknown moving obstacle as shown in Fig. 7(c). As shown in Fig. 8(c), the possibility of collision with the unknown object became evident, and the robot changed its direction and moved round the arc toward the left side. Next, as shown in Fig. 8(c). the robot changed its direction and moved round the arc toward the right side, and finally was back to the middle of the corridor.

Fig. 9 shows results of each parameters and robot action. If comparisons are made between Fig. 9 (1) and (4), both of them show similarity in the way of changes of their trajectories with the exception of before and after action of collision avoidance. This means that basic of robot action is defined by the principal axis of inertia. As shown Fig. 9 (2), magnitude of the center of gravity is increased just after passing the moving obstacle. It means that magnitude of the center of gravity contribute with behavior that back to the middle of the corridor. As shown in Fig. 9 (3), before and after avoiding obstacle, the magnitude of repulsive vector is increased just toward the direction to avoid obstacle and wall, respectively. This means that the repulsive vector is useful for collision avoidance.

8 Conclusions

In this paper, we proposed a new method for reactive visual navigation based on omnidirectional sensing. A rough free space region around the robot was detected by using a active contour model. By evaluating a shape of extracted free space region, the method produced low-level motor commands for avoiding the obstacle and keeping the robot in the center of the free space. Moving direction of the robot was defined by the resultant of three forces; the principal axis of inertia, the center of gravity and repulsive forces from the environment. We are currently trying to navigate a long route in both an indoor and outdoor environment.

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