EXAMINATION OF BALL TRACKING AND CATCHING TASK USING A MONOCULAR VISION-BASED MOBILE ROBOT

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Abstract: This paper presents an implementation of a ball catching task using a monocular vision-based mobile robot. We have proposed a motion strategy for catching a ball flying in three-dimensional space. This strategy has its roots in the field of experimental psychology but is more powerful and concentrated on a robot. A practical trajectory control law is derived for a non-holonomic mobile robot to track and catch a ball. This control law educes the full potential of the motion strategy: we experimentally demonstrate that a monocular vision-based mobile robot, coping with the problem due to its non-holonomic constraint, successfully catches a ball.

1 INTRODUCTION

"What information does the fielder sense and how does the fielder run to the right spot in order to catch a fly ball?" This problem has interested researchers in various fields, namely physics, experimental psychology, and robotics. Around 40 years ago, Chapman, physicist, pointed out that the fielder runs so as to maintain the rate of change of tangent of the elevation angle of the ball (Chapman, 1968). Recently, some researches in experimental psychology have shown evidence that partly supports Chapman's hypothesis (McLeod and Dienes, 1993; McLeod et al., 2003).

From a viewpoint of control, some researchers have studied the formulation of human catching strategy in connection with perceptual feedback control. Tresilian examined how Chapman's strategy behaves under the limiting conditions of human through simulations (Tresilian, 1995). Borgstadts and Ferrier focused on how to implement Chapman's strategy and carried out experiments using a mobile robot considering only the case where the fielder exists in the flying ball trajectory (Borgstadts and Ferrier, 2000). Marken also formulated a perceptual-motor feedback law of human catching strategy which is slightly different from Chapman's strategy (Marken, 2001).

Additionally, McBeath et al. proposed a strategy named linear optical trajectory (LOT) (McBeath et al., 1995). Sugar et al. (including McBeath) introduced the moving image plane and derived various traveling control laws, some of which are based on LOT and others are based on Chapman's strategy. They also performed experiments in which a mobile robot tracks and catches a balloon or rolling a ball (Suluh et al., 2001; Sugar and McBeath, 2001; Mundhara et al., 2002; Mundhara et al., 2003).

On the other hand, we have proposed a new motion strategy that is more powerful and concentrated on a robot. Moreover we have implemented a trajectory control law based on the architecture of visual servoing and analytically showed the ability to track and catch a ball (Miyazaki and Mori, 2004). However, in the analysis, we assumed that

1. The horizontal velocity of a ball is negligible;

2. Image Jacobian is exactly available,

which are inadequate in real situation because assumption (1) too much restricts ball's motion and assumption (2) is hard to be achieved in the monocular vision system. In this paper, we remove these assumptions and then derive a new trajectory control law that enables a monocular vision-based mobile robot to track and catch a ball. To demonstrate the validity of the proposed control law, experimental results are also shown.

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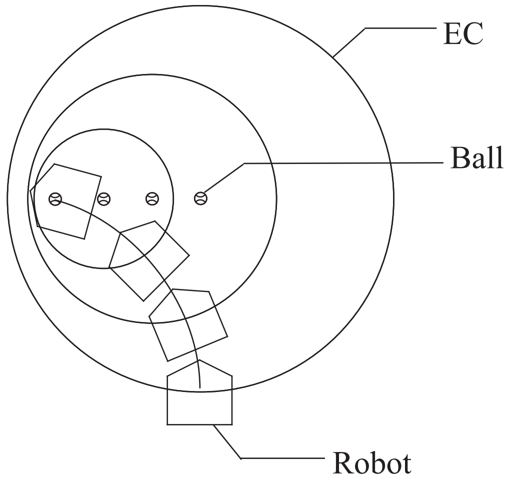

Figure 1: Concept of GAG strategy.

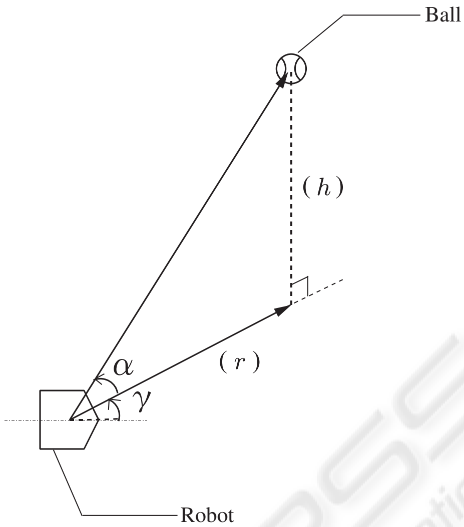

Figure 2: Relative position between the robot and the ball

2 ABOUT GAG STRATEGY

We have proposed the motion strategy named GAG (Gaining elevation Angle of Gaze), which states that the fielders selects a running path to keep the tangent of elevation angle against the ball continuously increasing. For the sake of intuitive understanding, we show the schematic catching based on this strategy in Figure 1. This figure shows a robot pursuing the ball launched from the center to the left. The circle termed EC is the equiangular circle (i.e. the set of points where the measured elevation angle remains unchanged). It should be noted that "gaining the tangent of the elevation angle of gaze continuously" corresponds to "decreasing the radius of EC".

3 TRAJECTORY CONTROL FOR BALL CATCHING

3.1 Kinematic model of the mobile robot

We suppose a wheeled type mobile robot as a robotic fielder. In a typical model of a non-holonomic mobile robot, the two driving wheels are independently driven by two actuators to achieve the translation and orientation. Using the translational velocity v and rotational velocity ω, the kinematic equiation of this model can be expressed as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}, \tag{1}$$

where (x, y) and θ denotes the position and orientation of the mobile robot in a world coordinate frame respectively.

3.2 Relation between the Robot and the Ball

In this section, we formulate the rate of change in the relative position/orientation between the robot and the ball.

As shown in Figure 2, let α be the elevation angle of gaze, and γ be the lateral angle of gaze. It should be noted that these variables can be securely obtained through a monocular vision system fixed on the robot. In order to analyze and evaluate the tracking performance, we introduce the following two variables unavailable with the monocular vision system: r (the horizontal distance between the robot and the ball) and h (the height of the ball from the robot). Then, the rate of change in these variables due to the robot's and ball's motion can be described as

$$\begin{bmatrix} \dot{r} \\ \dot{\alpha} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} -\cos\gamma & 0 \\ \frac{1}{2r}\sin 2\alpha\cos\gamma & 0 \\ \frac{1}{r}\sin\gamma & -1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} + \begin{bmatrix} \boldsymbol{e}^T \\ \frac{1}{r}\boldsymbol{l}^T \\ \frac{1}{r}\boldsymbol{n}^T \end{bmatrix} \boldsymbol{w}, \tag{2}$$

where $\boldsymbol{e}$ is the unit vector on the line extending to the center of EC from the robot, $\boldsymbol{n}$ is the vector obtained by rotating $\boldsymbol{e}$ about a vertical axis counterclockwise in the amount $90°$, $\boldsymbol{l}$ is the vector obtained by rotating the unit vector on the line from the robot to the ball about a line having the direction of $\boldsymbol{n}$ counterclockwise in the amount $90°$, and $\boldsymbol{w}$ is the velocity vector of the ball. The first term in the right hand side is caused by the robot's motion and the second term is by the ball's motion.

3.3 Control Law

The control law which implements GAG strategy is given by

$$v = k_1 \cos\gamma \sin 2\alpha \quad (3)$$
$$\omega = k_2 \sin\gamma \sin 2\alpha, \quad (4)$$

where k_1, k_2 are the positive constants. This control law has two advantages over the one we have already proposed(Miyazaki and Mori, 2004): (i) The image Jacobian is not required. (ii) Tuning parameters k_1, k_2 are easily determined. The validity of this control law is shown in the following section.

3.4 Ball Tracking and Catching

We explain the control law given by Eqs. (3), (4) enables the mobile robot to successfully track and catch a ball in the following three cases.

(A) A case that a ball is suspended in the air

Let us consider a case that a ball is suspended in the air. The task objective in this case is to approach a point just below the ball.

Substituting Eqs. (3), (4) (control inputs) into Eq. (2) and setting $\boldsymbol{w}$ to be zero yields

$$\dot{r} = -k_1 \cos^2\gamma \sin 2\alpha \leq 0. \quad (5)$$

Equality holds if and only if $|\gamma| = \pi/2$.

In case that $|\gamma| = \pi/2$, the robot has its angular velocity $\omega = k_2 \sin\gamma \sin 2\alpha$, thus, $\dot{\gamma} = -k_2 \sin\gamma \sin 2\alpha$, which means the robot rotates instantly and gets out of this situation. Moreover, the robot stops $(v = 0)$ if and only if it arrives at the point just below the ball. As a result, the robot asymptotically approaches to the point just below the ball.

Here arises a simple question we can answer: what path does the robot follow to track a ball? The curvature of the path is given by

$$\rho = \frac{\omega}{v} = \frac{k_2}{k_1} \tan\gamma \quad (6)$$

and consequently proportional to the tangent of ball's lateral angle $\tan\gamma$. Thus, the path of the robot subject to this control law varies according to the initial orientation, namely γ. Figure 3 shows various paths in typical cases. The robot gets forward to just below

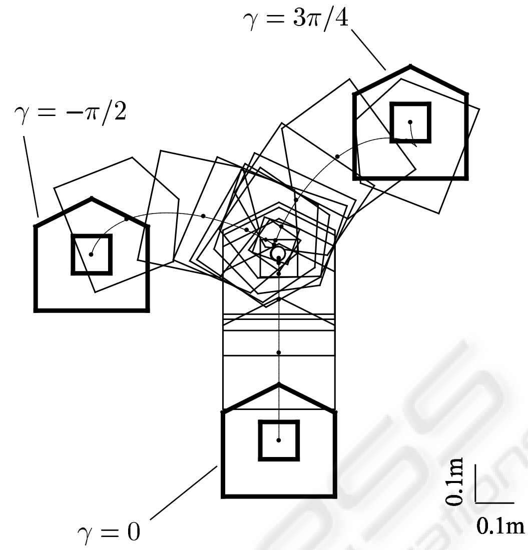

Figure 3: Typical paths of the robot subject to Eqs. (3), (4) illustrated every 0.2 sec ($k_1 = 1$, $k_2 = 13$)

the ball if $\gamma = 0$. If $0 < \gamma \leq \pi/2$, the robot moves toward the inside of EC and gets closer and closer to the center of EC, though the robot does not know where the center is. If $\pi/2 < \gamma \leq \pi$, first the robot rotates toward the center of EC while getting backward, and then starts getting forward after the orientation becomes less than $\pi/2$, that is, $0 < \gamma \leq \pi/2$. In case that γ has a minus sign, the robot moves in the same manner except rotating inversely.

By the way, during the robot's tracking, the tangent of elevation angle is kept increasing. The reason is that its time derivative

$$\frac{d}{dt} \tan\alpha = \frac{k_1 h}{r^2} \cos^2\gamma \sin 2\alpha, \quad (7)$$

is always positive excepting $|\gamma| = \pi/2$. (In case that $|\gamma| = \pi/2$, as already mentioned above, the robot rotates instantly to satisfy $|\gamma| < \pi/2$.) This means that the radius of EC asymptotically vanishes, in other words the robot gets closer and closer to the point just below the ball. This suspended ball case is regarded as one of the special case among the general tracking cases shown in Figure 1.

(B) A case that a ball rises and falls without moving horizontally

Eq. (5) holds in this case as well as in the previous case (A). This means that the path of the robot subject to GAG is not dependent on the ball's vertical motion, provided that the ball does not move horizontally. In other words, the path is uniquely determined by the robot's initial location and orientation as in the case (A). Therefore the robot gets closer and closer to the point just below the ball so as to catch the ball. It is the only difference between the case (A) and the case (B) that the robot has to reach the catching point before the ball falls onto the ground. Increasing the gain k_1, k_2 brings quick approaching to the catching point, and then the robot maintains the path provided the ratio of gain k_1/k_2 is kept unchanged.

(C) A case that a ball rises and falls while moving horizontally

Finally, we explain the robot can catch the ball in general case that the ball rises and falls while moving horizontally. Substituting Eqs. (3), (4) (control input) into Eq. (2) yields

$$\dot{r} \;=\; -k_1 \cos^2\gamma \sin 2\alpha + \boldsymbol{e}^T \boldsymbol{w}. \qquad (8)$$

If $\boldsymbol{e}^T\boldsymbol{w} \leq 0$, the robot approaches the point just below the ball similarly to the case (B). This corresponds to the case that the ball comes up to the robot. Next let us consider the case that $\boldsymbol{e}^T\boldsymbol{w} \leq 0$, that is, the case that the ball flies away from the robot. In such a situation, if $\gamma \simeq 0$ holds after pursuing the ball for a while, the time derivative of r becomes

$$\dot{r} = -k_1 \sin 2\alpha + \|w\|. \qquad (9)$$

Here, from $\sin 2\alpha = 2hr/(h^2+r^2)$, the distance between the ball and the robot converges to r_p given by

$$r_p = \frac{h\|\boldsymbol{w}\|}{2k_1} \qquad (10)$$

provided the gain k_1 is large enough in comparison with the ball's horizontal velocity $\|w\|$. This means that the robot approaches the ball according to Eq. (10) and catches the ball when the ball falls onto ground ($r \rightarrow 0$ as $h \rightarrow 0$).

In the meantime, from Eq. (2) and Eqs. (3), (4), we get

$$\dot{\gamma} = \frac{1}{r} k_1 \sin\gamma \cos\gamma \sin 2\alpha - k_2 \sin\gamma \sin 2\alpha + \frac{1}{r} \boldsymbol{n}^T \boldsymbol{w}, \qquad (11)$$

where the first and second terms in the right hand side are negative provided

$$-k_2 + \frac{k_1}{r} \cos\gamma < 0 \qquad (12)$$

excepting the case that $\gamma = \pi$.

This means that, if

$$\frac{k_2}{k_1} > \frac{1}{r} \qquad (13)$$

is satisfied, Eq. (11) gives

$$\dot{\gamma} < -\frac{k_1}{r}(1-\cos\gamma)\sin\gamma \sin 2\alpha + \frac{1}{r}\boldsymbol{n}^T\boldsymbol{w}. \qquad (14)$$

This implies that $|\gamma|$ remains small if the gain k_1 is large enough compared with $\|\boldsymbol{w}\|$

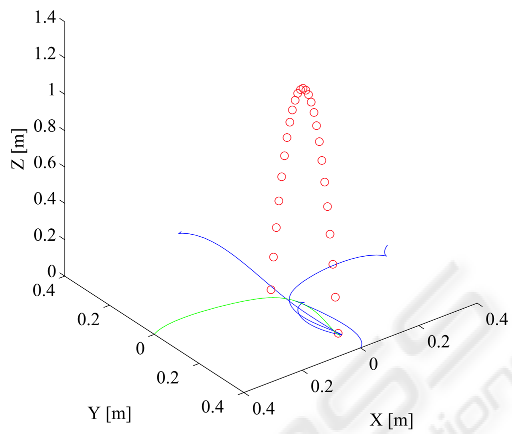

Figure 4: Path of the robot pursuing a ball

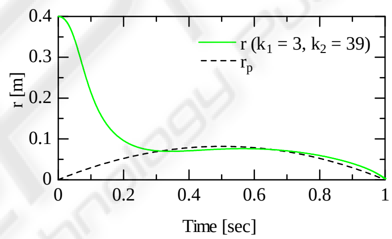

Figure 5: Change in the distance to the ball

From condition Eq. (13) and r_p given by Eq. (13), we can conclude as follows: The horizontal distance between the ball and the robot approaches the value

$$r_p = \frac{h\|\boldsymbol{w}\|}{2k_1} \qquad (15)$$

provided that we choose large enough gains k_1, k_2 satisfying

$$\frac{k_2}{k_1} > \frac{1}{r_p}. \qquad (16)$$

To verify this analysis, we show simulation results obtained by assuming that the ball moves under the influence of gravity. Figure 4 shows typical paths of the robot pursuing a fly ball. From this figure, we can see that GAG works well regardless of the robot's initial location and orientation. The time histroy of the radius of EC is given in Figure 5 for a certain pursuing motion (corresponding to the green curve in Figure 4, which demonstrates that the radius of EC decreases according to the parabolic function of time given by Eq. (10) (the dotted curve in Figure 5).

4 EXPERIMENT

We constructed a monocular vision-based mobile robot to verify our proposed method experimentally. An IEEE1394 camera with a fish-eye lens and ball catching device are mounted on a mobile base that communicates with a desktop PC through RS-232C. The total length and width of the mobile base are 300[mm] and the maximum velocity is 2[m/sec]. The translational and angular velocities of the robot are determined using the information extracted from 2D image, namely elevation angle α and lateral angle γ by Eqs. (3), (4) at the video rate, 33[msec]. The commands of the translational and angular velocities are converted into wheel velocities and transmitted from the desktop PC to the mobile base and the motors of right and left wheels are controlled by a servo controller on the mobile base.

4.1 Method

The experimental procedures are as follows: The ball is thrown by a person or a ball launcher. As soon as the camera mounted on the mobile robot gets sight of the ball, the robot begins running to catch the ball. Every 33 [msec], the frame rate of the video camera, the ball's image is acquired and the velocity command is sent to the robot. The moment the robot reaches the catching point and then catches the ball, the ball gets out of the sight and the robot stops.

4.2 Result and Discussion

We have carried out experiments to verify the effectiveness of the proposed control law based on GAG strategy. The following result demonstrates how the robot behaves in a real situation.

The ball is thrown up about 50 [cm] in front of and 20 [cm] on the right of the robot. The result is shown in Figure 6 and Figure 7. Figure 6 is a sequential photograph where the ball and the robot is extracted. In Figure 7 the location of the ball and the robot is plotted in a world coordinate frame. These results indicate that a mobile robot subject to GAG successfully catches a ball.

Figure 6: Ball catching by a wheeled mobile robot with monocular vision system

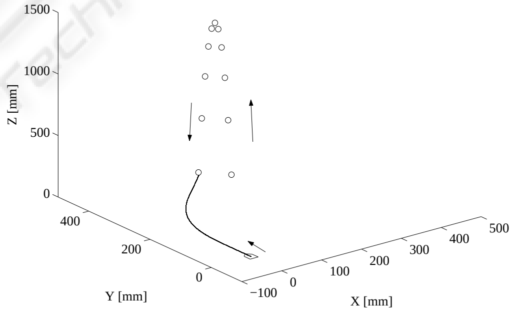

Figure 7: Path of the robot pursuing a ball

5 CONCLUSION

This paper presented an implementation of ball catching task using a monocular vision-based mobile robot: (1) Our proposed GAG strategy was employed as a motion strategy to track a ball; (2) A practical trajectory control law is derived for a non-holonomic mobile robot to track and catch a ball, which is an implementation of GAG strategy. Moreover, we demonstrated that the robot can catch a ball flying in three-dimensional space using the monocular vision system. This demonstration exemplifies the potency of the GAG strategy and the practicality of its control law.

The GAG strategy was devised aiming at robotic fielders rather than explaining of human catching strategy. The robot subject to the GAG strategy is required to have the ability to run faster than the ball for a reliable ball catching. However, we can utilize GAG beyond baseball. For example, GAG is suited to autonomous navigation for mobile robots if we regard a fly ball as a marker in the environment. In the autonomous rendezvous and docking task of spacecrafts, GAG can be extended to a simple and robust onboard rendezvous control strategy by considering a fielder as a chaser spacecraft and a ball as a target spacecraft.

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