

Collision Avoidance Control for Mobile Robot Based on Online Analysis of Walking Pattern

Tomoyuki NAKAO * and Naoki WADA * and Ken'ichi YANO *

Abstract—In obstacle avoidance control between several types of objects, when interactive avoidance occurs, if the objects avoid each other by moving in the same direction at the same time, they will get into a blocking situation. In this study on the basis of an analysis of a walking pattern and avoidance behavior, an avoidance control method for interactive avoidance between a robot and pedestrian is developed. Our proposed method can estimate and determine the states of a pedestrian during walking that are the acceleration of a hidden unmeasurable leg, the right or the left and the idling leg or the supporting leg. On the basis of our analysis, the timing for the robot to start to avoid and the direction of avoidance is generated to indicate a safe way for it to avoid to a pedestrian. Through a verification experiment with actual equipment, the applicability of our method will be shown.

Keywords: Mobile Robot, Collision Avoidance Control, Motion Analysis, Human intention, Kalman Filter

1 Introduction

In recent years, future generation intelligent robots that can autonomously execute tasks have actively been developed. Most autonomous moving robots are for use in service businesses, for instance, security robots, guidance robots and tray service robots. Autonomous moving robots can move around a workspace with moving mechanisms, for instance, wheels, crawlers and legs. In an actual workspace with service robots, both humans and robots exist together, and both must move so as to avoid collisions with each other. If a robot cannot execute a cooperative avoidance with a human, a collision will be highly possible. This puts humans in danger and causes a deterioration in work efficiency.

Collision avoidance control of static obstacles and dynamic obstacles has actively been researched[1][2][3]. On collision avoidance of dynamic obstacles, previous methods are effective for an obstacle moving linearly and following prepared paths. But in the case of a robot passing

an oncoming human, those methods involve the possibility of a collision because they are based on unilateral avoidance by the robot and do not consider actual human's avoidance behaviors against the robot. Therefore, an avoidance system for cooperating with pedestrians is required.

To make a robot understand the intention of pedestrians, a system is required that can estimate the intention of someone's behavior and communicate it to someone. In a method that uses a camera, there is the problem of insufficient control speed resulting from time delays due to huge quantities of data processing. A system is thus required that can estimate intention with less information. For a collision avoidance control system that uses the methods of Artificial Potential Fields, a robot necessarily changes movement in an adverse direction toward pedestrian. However, it is not necessarily the case that a pedestrian will avoid it in a staggered direction toward a robot. If the avoidance direction of a robot and pedestrian is the same, a collision or a blocked passage is unavoidable.

In this study, to make robots and pedestrians able to pass safely without collisions, we propose a collision avoidance control method that creates voluntary avoidance behavior by focusing on motion constraint in switching an idling leg or a supporting leg.

In this paper, in Section 2, we expound a walking pattern model with a criterion for estimating walking states and a method for estimating the velocity of an idling leg. In Section 3, the details of Voluntary Guidance Type Collision Avoidance Control is expounded. On the basis of an analysis of the walking and avoidance behavior of pedestrians, a collision possibility condition, an avoidance condition, an avoidance starting point and a collision avoidance algorithm are expounded. In Section 4, through a verification experiment with actual equipment, the applicability of our method will be shown.

2 Estimation of Walking Pattern

2.1 Acceleration Based Walking Model

The roles of a leg during walking are separated into an idling leg and a supporting leg; they switch alternately

*Manuscript submitted December 27, 2009. T. Nakao, N. Wada and K. Yano are with Department Human and Information Systems Engineering, Gifu University, 1-1 Yanagido, Gifu, Gifu 501-1193, JAPAN, Email: yanolab-mail@gifu-u.ac.jp

with each other as the idling leg lands. To formalize the walking state, a cycle of walking is separated into four Stages with respect to the state of a leg, as showing Fig.1[4]. The initial state is with both feet on land and with the feet wide apart back and forth. Stage 1 involves swinging the back leg to a place where both legs are together. In Stage 2 the idling leg moves past the supporting leg to a landing. The states after the idling leg switches places with the supporting leg are Stages 3 and 4 and are similar to the first two stages.

In Fig.2 a change of acceleration and the velocity in each stage is shown where the foot motion is simplified to an uniform accelerated motion. In Stage 1 and Stage 3, the velocity of the foot of the idling leg increases at uniform acceleration and in Stage 2 and Stage 4, it decreases at uniform acceleration. The velocity of the foot of the supporting leg is zero due to landing.

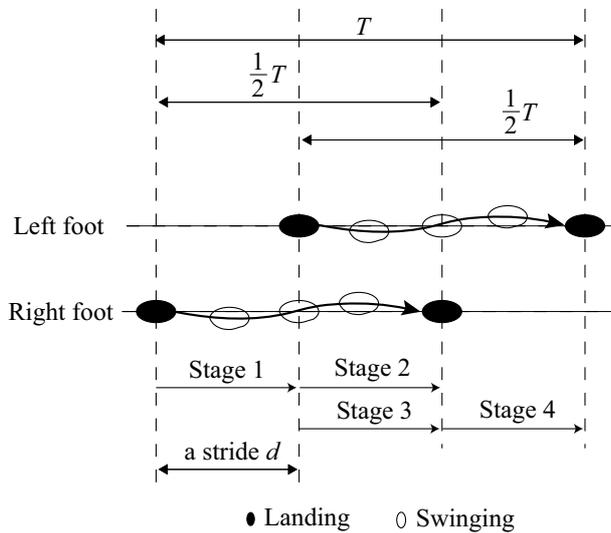


Figure 1: Partitioned a cycle walking

Let a cycle of walking be T . Let the time, acceleration and velocity be respectively t , a and v . Right and left are presented by index l and r ; a walking model using acceleration and velocity is defined by $WM_i = [a_l \ a_r \ v_l \ v_r]$, where i represents Stages $i = 1, 2, 3, 4$. On n th cycle walking, WM_i can be represented by Eq.(1) ~ Eq.(4) in every Stage. f is the acceleration function of the leg, \dot{v}_l is the direction vector of velocity, and $v_{st1,n}$ and $v_{st3,n}$ are, respectively, the velocity at the end of Stage 1 and Stage 3. As using this model with the actual measured parameter, the states of a pedestrian will be estimated.

$$\text{Stage 1 : } Tn \leq t < Tn + \frac{1}{4}T$$

$$WM_1 = [0 \ f_r \dot{v}_r \ 0 \ a_r(t - Tn)] \quad (1)$$

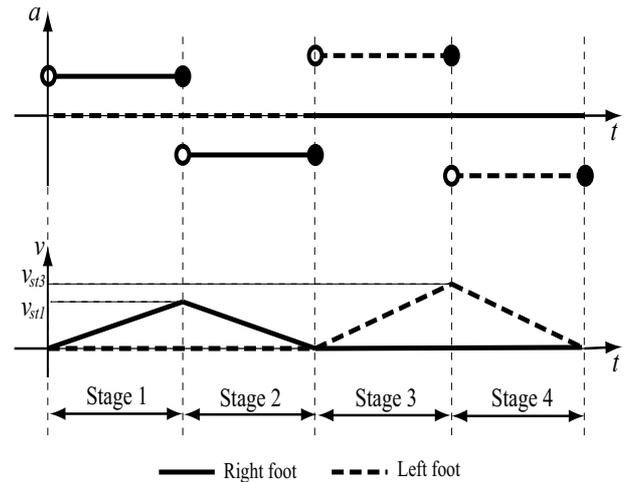


Figure 2: Acceleration based walking model

$$\text{Stage 2 : } Tn + \frac{1}{4}T \leq t < Tn + \frac{1}{2}T$$

$$WM_2 = \begin{bmatrix} 0 & -f_r \dot{v}_r & 0 & a_r \{t - T(n + \frac{1}{4})\} + v_{st1,n} \end{bmatrix} \quad (2)$$

$$\text{Stage 3 : } Tn + \frac{1}{2}T \leq t < Tn + \frac{3}{4}T$$

$$WM_3 = \begin{bmatrix} f_l \dot{v}_l & 0 & a_l \{t - T(n + \frac{1}{2})\} & 0 \end{bmatrix} \quad (3)$$

$$\text{Stage 4 : } Tn + \frac{3}{4}T \leq t < Tn + T$$

$$WM_4 = \begin{bmatrix} -f_l \dot{v}_l & 0 & a_l \{t - T(n + \frac{3}{4})\} + v_{st3,n} & 0 \end{bmatrix} \quad (4)$$

2.2 Application of Kalman Filter

Let us consider measuring the feet position with a 2D range sensor to estimate the walking pattern using as little information as possible. Because the range sensor can only measure the shortest distance to the objects, both legs cannot be measured at the same time, i.e., the idling leg motion in Stage 1 and Stage 3 cannot be measured. Changes in the measurement is plotted as a square-wave along the direction of movement from side to side. This method is thus not directly appropriate for use in the above walking model. However, to execute collision avoidance control, real-time velocity data for the idling leg are required. Thus, a Kalman Filter is applied to estimate the unmeasurable idling leg motion.

On destination accession control the relationship between a robot and pedestrian on a world coordinate system \sum_W is modeled as shown in Fig.3. Setting the direction of the movement of the robot as reference line; ${}^R\theta_g$ is an argument for the direction to a destination; ${}^R\theta_o$ is an argument for the direction to an obstacle. The direction of the arguments and turnings define anti-clockwise

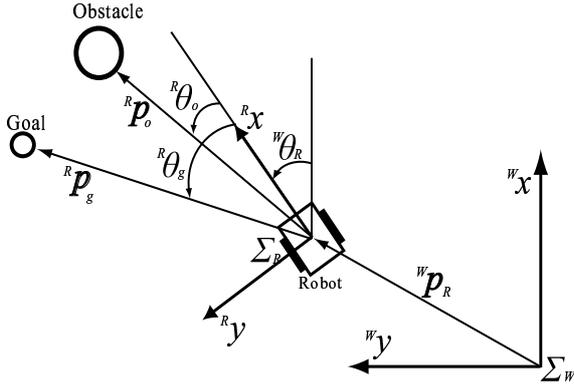


Figure 3: World coordinate system and robot coordinate system

as positive. The position, velocity and acceleration of a pedestrian are, respectively, ${}^W p_o = ({}^W p_{ox}, {}^W p_{oy})$, ${}^W v_o = ({}^W v_{ox}, {}^W v_{oy})$ and ${}^W a_o = ({}^W a_{ox}, {}^W a_{oy})$. Because the change of acceleration is discontinuous due to the switching between the idling and supporting legs, a nonlinear Kalman Filter is applied. With the sampling time Δt , a state equation is represented by the following, where ω is the noise of the state model.

$${}^W x_o(k+1) = F \cdot {}^W x_o(k) + G \cdot {}^W u_o(k) + \omega \quad (5)$$

$${}^W x_o(k) = [{}^W p_{ox}(k) \quad {}^W p_{oy}(k) \quad {}^W v_{ox}(k) \quad {}^W v_{oy}(k)]^T \quad (6)$$

$${}^W u_o(k) = [{}^W a_{ox}(k) \quad {}^W a_{oy}(k)]^T \quad (7)$$

Then, let the state transition matrixes F and G be derived. The position and velocity are varied by the acceleration during the sampling time Δt , and the following equation is obtained.

$$F = \begin{pmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad G = \begin{pmatrix} \frac{1}{2}\Delta t^2 & 0 \\ 0 & \frac{1}{2}\Delta t^2 \\ \Delta t & 0 \\ 0 & \Delta t \end{pmatrix} \quad (8)$$

${}^W u_o(k)$ is discontinuous and varies by the vector of the direction of the acceleration. Accelerations of each Stage are presented below.

Stage 1 :

$${}^W a_{lx}(k) = 0 \quad , \quad {}^W a_{ry}(k) = A_{ave} \dot{v}_r(k) \quad (9)$$

Stage 2 :

$${}^W a_{lx}(k) = 0 \quad , \quad {}^W a_{ry}(k) = -A_{ave} \dot{v}_r(k) \quad (10)$$

Stage 3 :

$${}^W a_{lx}(k) = A_{ave} \dot{v}_l(k) \quad , \quad {}^W a_{ry}(k) = 0 \quad (11)$$

Stage 4 :

$${}^W a_{lx}(k) = -A_{ave} \dot{v}_l(k) \quad , \quad {}^W a_{ry}(k) = 0 \quad (12)$$

$$A_{ave} = \frac{2d}{T_i^2} = \frac{2d}{(\frac{T}{2})^2} = \frac{8d}{T^2} \quad (13)$$

T_i and d are, respectively, the average idling leg measuring time and average stride. If T_i and d have not measured yet, the general average values are applied. ${}^W v_o(k)$ is a unit vector corresponding to the direction of velocity. The observation vector ${}^W y_o(k)$ is represented by the state vector ${}^W x_o(k)$ as follows, where ϵ is the noise of observation.

$${}^W y_o(k) = H {}^W x_o(k) + \epsilon \quad (14)$$

$${}^W y_o(k) = [{}^W p_{ox}(k) \quad {}^W p_{oy}(k)]^T \quad (15)$$

$$H = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad (16)$$

A nonlinear Kalman Filter is developed with the above models and estimates the behavior of both legs and updates it. In the course of that for the unmeasurable hidden leg, the filter estimates its behavior only with a forecast update.

The simulation result of estimates for the right and left legs from actual measurements data is shown in Fig.4. The origin (0,0) is the relative observing position of the robot. The result of strides of about 0.7[m] and about 0.4[m] are shown, respectively, in (a) and (b). According to the above, we see that the estimate is achieved regardless of the difference between the strides.

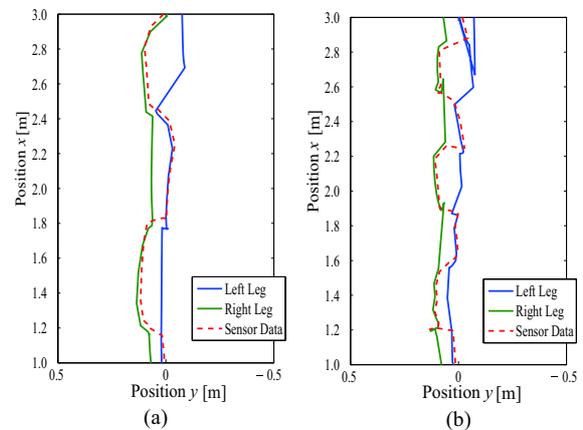


Figure 4: Estimated result of walking pattern with Kalman Filter

3 Voluntary Guidance Type Collision Avoidance Control

3.1 Characteristics of Avoidance Behavior

The characteristics of the avoidance behavior can be separated into two types: that concerning the relationship between the legs and obstacle, shown in Fig.5(a); and that concerning the interactive avoidance, shown in Fig.5(b). First, the former additionally can be separated into four cases: avoidances to the right or the left with the right idling leg, avoidances to the right or the left with the left idling leg in an adverse direction toward the obstacle. Secondly, the cases of interactive avoidance can be considered when a pair of moving objects walks head-on into each other. The possible situations for interactive avoidance also have four cases. As shown in Fig.5(b), the cases of b-1 and b-2 are without collision; the cases of b-3 and b-4 have a high possibility of collision. Especially, the case of b-3 actually happens very often when two men walk head-on into each other. Interactive avoidance should be considered for collision avoidance control with the robot.

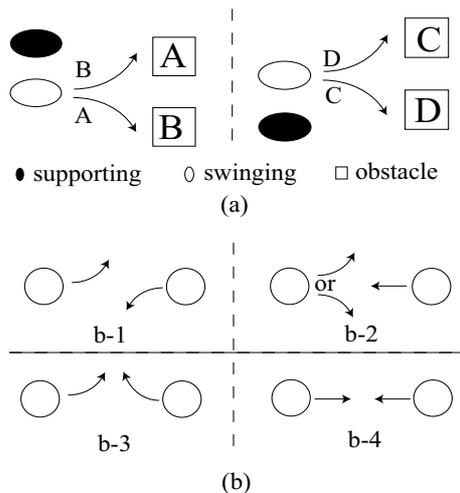


Figure 5: Characteristics of avoidance behavior

3.2 Collision Avoidance Condition

Regarding collision avoidance control, we must consider real time judgments about whether or not there is a possibility of a collision in the future. In our method, by using the relative position and relative velocity between a pedestrian and a moving robot, judgments about the possibility of a collision are executed. In Fig.6 these for the robot are shown. Let the argument of the relative velocity of idling leg for the robot be $\psi(t)$. The argument of the two tangents from the point where the idling leg starts its swinging to the collision judgmental circle of the robot with a radius D_R are, respectively, φ_a and φ_b , $\varphi_a < \varphi_b$. The reference line of the arguments of $\psi(t)$, φ_a

and φ_b is the direction of movement of the robot. We can see that if Eq.(17) is satisfied, a collision will not occur in the future. The condition for the possibility of a collision is Eq.(18).

$$\psi(t) < \varphi_a \quad \text{or} \quad \varphi_b < \psi(t) \quad (17)$$

$$\varphi_a \leq \psi(t) \leq \varphi_b \quad (18)$$

By setting the area with a certain amount of width along the direction of the robot's movement, the control method is switched to a superior one on the inside or outside of the area. If it is inside, our proposal method is applied; if it is outside, the acceleration and deceleration method that is previous method[3] is applied.

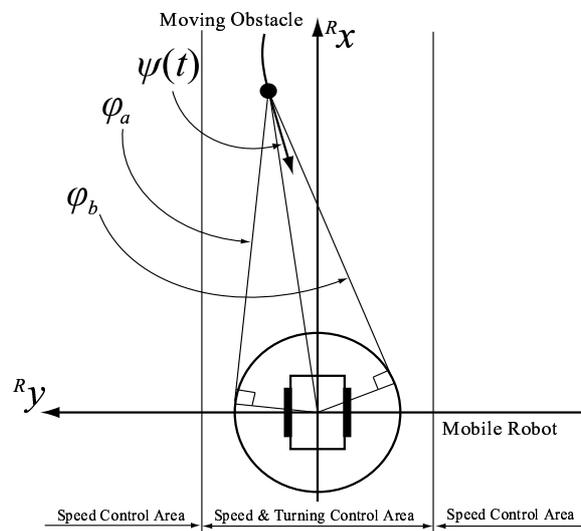


Figure 6: Direction of relative velocity

3.3 Avoidance Starting Point

Voluntary Guidance Type Collision Avoidance is a method that the robot executes avoidance behavior before a human based on the walking pattern estimation, and motivates a human to carry out safety avoidance, as in Fig.5 b-1. We realize that the timing of the robot to start avoidance is important.

Turning motion of human is based on the swings of the idling leg and the movements about the center of gravity. According to the Ballistic walking model[5] proposed by Mochon, a muscle force operates on the generating velocity in the anterior half of a swing and the posterior half that operates passively. Thus in Stages 2 and 4, it is difficult to turn suddenly, but if the safe direction of interactive avoidance is indicated to pedestrian until the beginning of Stages 1 and 3, one will be able to apply force to the idling leg for avoidance. There is an instance

in which it is impossible for the pedestrian to avoid a collision: this is where the idling leg is landing and where constraints on both feet prevent the pedestrian from being able to apply force to the next idling leg. By the robot starts to avoid a collision in this instance, the safe direction of the interactive avoidance is indicated to the pedestrian. According to the reasoning above, the instance in which the idling leg is landing is defined as the avoidance starting point t_{avo} .

3.4 Avoidance Condition Algorithm

When the robot detects a pedestrian, the Avoidance Condition Algorithm is applied. The system outline is shown in Fig.7. The motion of both legs is estimated by the Kalman Filter. Then after determinations regarding the idling leg or supporting leg and right or left, which stage the pedestrian is in can be estimated. After the stages are estimated, the avoidance starting point t_{avo} and direction of avoidance turning are generated.

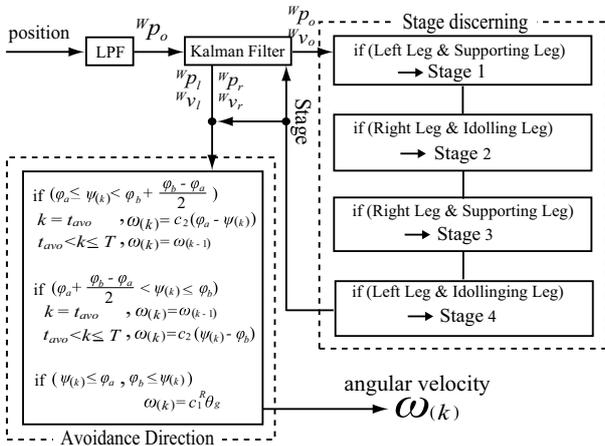


Figure 7: System of obstacle avoidance

The idling leg or supporting leg is determined with a threshold. For the time k , let the velocity of the idling leg and the threshold, respectively, be $v(k)$ and v_{min} ; if $v(k) > v_{min}$, it is the idling leg; if $v(k) < v_{min}$, it is the supporting leg. The right or left is determined by the argument $\theta(k)$. The argument between the segment connecting the last measured point of the supporting leg with the current point of the idling leg and the direction of movement is calculated by Eq.(19); if $\theta(k) > 0$, it is the right; if $\theta(k) < 0$, it is the left. The condition Eq.(19) is effective under the collision possibility condition Eq.(18). The stage identification is completed by the integration of determinations.

$$\theta(k) = \tan^{-1} \frac{p_{idly}(k) - p_{supy}}{p_{idlx}(k) - p_{supx}} \quad (19)$$

Finally, we expound a method of determining the turn-

ing direction of robot. When the collision possibility condition Eq.(18) is acknowledged, the turning direction is derived by the relationship between the walking direction $\psi(k)$ and $\varphi_a(k)$ and $\varphi_b(k)$ at the avoidance starting point t_{avo} . To satisfy Eq.(17) making a comparison between $\varphi_a(k) - \psi(k)$ and $\psi(k) - \varphi_b(k)$, a lower deviation is applied. Turning toward the avoidance direction is executed during t_{avo} to a walking cycle T ; the turning angular acceleration is kept till $t_{avo} + T$, as shown in Eq.(21) and Eq.(23). If Eq.(18) is satisfied after $t_{avo} + T$, a recovery motion in a direction toward the destination is executed as Eq.(24), where $c_1 > 0$ and $c_2 > 0$.

$$\text{if } \varphi_a \leq \psi(k) < \varphi_a + \frac{\varphi_b - \varphi_a}{2} \quad (20)$$

$$k = t_{avo} \quad , \quad \omega_k = c_2(\varphi_{ak} - \psi_k)$$

$$t_{avo} < k \leq T \quad , \quad \omega_k = \omega_{k-1} \quad (21)$$

$$\text{if } \varphi_a + \frac{\varphi_b - \varphi_a}{2} \leq \psi(k) < \varphi_b \quad (22)$$

$$k = t_{avo} \quad , \quad \omega_k = c_2(\psi_k - \varphi_b)$$

$$t_{avo} < k \leq T \quad , \quad \omega_k = \omega_{k-1} \quad (23)$$

$$\text{if } \psi(k) \leq \varphi_a \quad , \quad \varphi_b \leq \psi(k) \quad (24)$$

$$\omega_k = c_1 R\theta_g$$

4 Experimental Result

This section presents a verification of our proposed method with a 2-wheel drive robot (PowerBot/MobileRobots,Inc., equipped with a laser sensor/SICK,Co.). The shortest distance to an obstacle and its argument can be measured by a laser sensor. As shown in Fig.8, this laser sensor is mounted on front of the PowerBot, can site horizontal surface 0.1[m] high from the floor, can measure position of around an ankle.

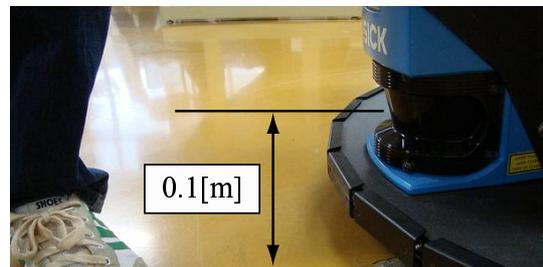


Figure 8: Measurable height of laser sensor

The method of verification involves the case where the robot and pedestrian are face to face and perform interactive avoidance behavior with each other. The robot has a destination five meters ahead, where is also a start point of walking. A experimental result is shown in Fig.9:

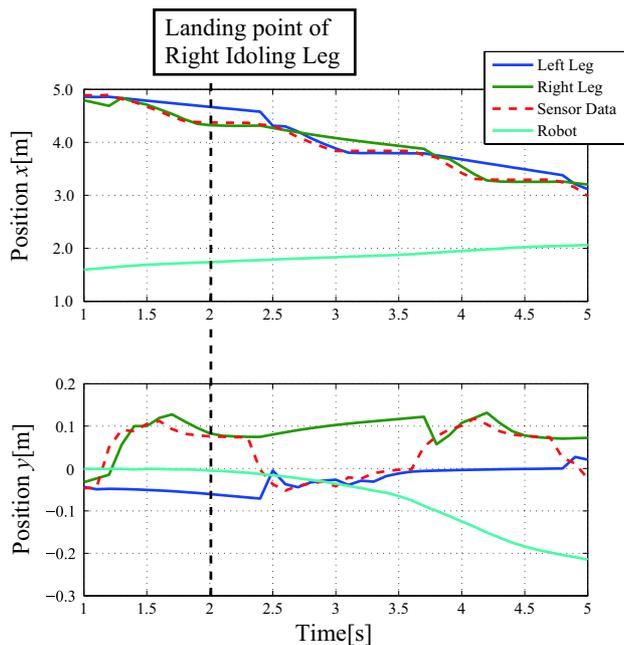


Figure 9: Experimental result of timing of robot turning.

The filtered trajectories of both legs and a trajectory of the robot are shown. We can see a landing point of the right idling leg at around 2.0[s] because the measured position of the right leg is constant during from around 2.0[s] to 2.3 [s], i.e., this period is in Stage 3. Simultaneously with this, the robot starts to turn toward the left side of pedestrian. Successive pictures of another result is shown in Fig.10. Here, when the left idling leg lands, the robot starts to turn right. Because of this, we can see that causing the pedestrian to turn right with the right idling leg is achieved. The effectual avoidance direction is generated by the avoidance condition algorithm and so collision avoidance is achieved with safety timing by voluntary guidance.

5 Conclusions and Future Work

It has been shown in this paper a collision avoidance control method with a autonomous moving robot considering interactive behavior between robot and pedestrian. The avoidance starting point and the conditions to avoid a collision and to estimate the states of pedestrian is derived by an analysis of the walking pattern and avoidance behavior. We proposed a method that motivates pedestrians to carry out the voluntary behavior by indicating the direction of interactive avoidance to pedestrian. Finally, we verified the applicability of our method by experiments with actual equipment.

Future work will involve the expansion of applications to cases where there are over two pedestrians and in which the walking pattern is not a biped but that of an animal. To improve the accuracy of estimations, the use of a net-

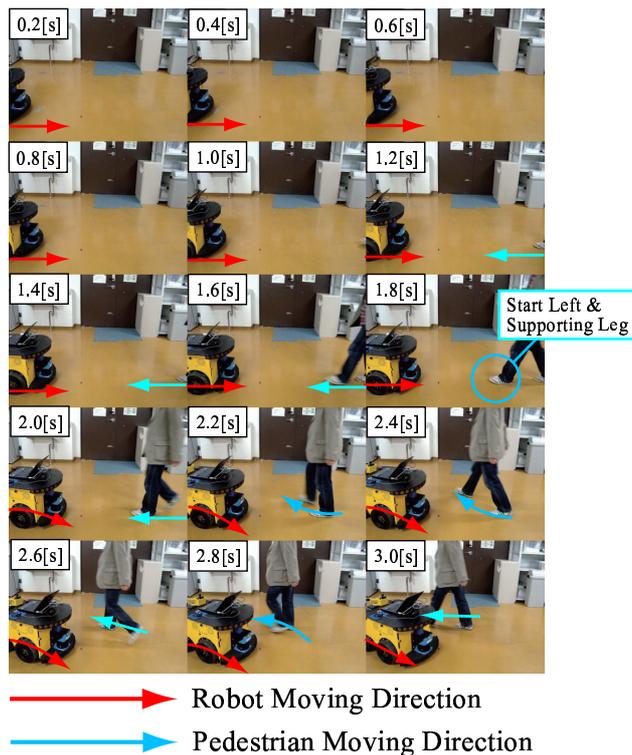


Figure 10: Experimental result with sufficient turning speed

work system with several laser sensors may be effective.

References

- [1] W. Huang, B. R. Fajen, J. Fink and W. H. Warren, "Visual navigation and obstacle avoidance using a steering potential function," *Robotics and Autonomous Systems*, 54(4), pp. 288–299, 2006
- [2] H. Koyasu and J. Miura, "Mobile Robot Motion Planning Considering Path Ambiguity of Moving Obstacles," *Proc. of the 9th Int. Conf. on Intelligent Autonomous Systems*, pp. 85–93, 2006
- [3] T. Minami, K. Tsushima, "Moving Obstacle Avoidance based on Speed Control without Changing Trajectory of Autonomous Mobile Robot In Case of Considering Dynamics of Robot(in Japanese)," *Proc. of 2004 JSME Conf. on Robotics and Mechatronics*, Paper No. 1P1-L1-70 (CD-ROM), 2004
- [4] H. Zhao and R. Shibusaki, "A novel system for tracking pedestrians using multiple single-row laser-range scanners," *IEEE Trans. on Systems, Man and Cybernetics*, 35, pp. 283–291, 2005
- [5] S. Mochon and T. A. McMahon, "Ballistic walking," *J. Biomechanics*, vol.13, (1980), pp.49–57