Postural Stability of a Human Riding a Unicycle and Its Emulation by a Robot

Zaiquan Sheng and Kazuo Yamafuji

***Abstract*—A unicycle is an inherent unstable system in three dimensions. As shown by a human riding a unicycle, rider's complicated successive dynamic control actions are needed for the postural stability control of unicycle, and the rider's actions for stability are quite nonlinear and jerky. By emulating the performance of a human-riding-unicycle, we can do tests of different classic and modern control methods used in 3-D inherent unstable systems, where a theoretical analytical methodology for the stability of this unstable system is expected to be developed. Because the longitudinal and lateral stability are coupled to each other in this system, and no actuator can be used directly for the control of unicycle's posture in 3-D (pitch, roll, and yaw angles), it is not easy for us to emulate the performance of a human-riding-unicycle. In this paper, a unique unicycle robot is developed based on the work reported in our previous paper. The postural stability control of a human-riding-unicycle in 3-D is realized by this robot, successfully, for the first time in the world.**

***Index Terms*—Closed-link mechanism, dynamics, gyrosensors, nonlinear system, postural stability, three-dimensional (3-D), unicycle.**

I. Introduction

IN THE RESEARCH field of robotics, it is always important to emulate some intelligence or capabilities which are inherited by human beings or animals. As to locomotive capability, we all know that the human being and some animals have quite excellent locomotion in walking, running, or jumping; and we believe it will be benefitial and helpful to emulate a human being's walking or an animal's running or jumping by a robot. In fact, in recent years, research results have reported such results [1]–[3].

Our attention is on the emulating of a human riding a unicycle by a robot. As we can observe from a human-riding-unicycle, there are five kinds of interesting performances shown in a human-riding-unicycle. First, both longitudinal and lateral stability can be attained. Second, the wheel's moving speed can be controlled. Third, the unicycle can be controlled to the direction that the rider likes to go toward. Fourth, the unicycle's postural stability can be achieved at a fixed place by moving forward and backward with wheel's small average moving velocity near to zero. Fifth, the unicycle's posture can be kept even on the floor which is quite uneven with small slope. For the first performance, the stability of pitch angle and roll angle is enough. For the second and third performance, not only the stability of pitch angle and roll angle is needed, but also the control on the wheel's speed and unicycle's yaw angle is needed. The fourth one is most difficult but most interesting performance. At the moment when the wheel's speed is zero, as shown in a human-riding-unicycle, the system is impossible to be stabilized, that means the system is uncontrollable. In this performance, the unicycle's posture is stabilized by controlling a dynamic system which oscillates between a controllable and an uncontrollable state. For the fifth performance, quite active control action is needed for overcoming the influence given by disturbance from uneven floor with slope. As analyzed in the above, there are quite difficult, complicated, and interesting control phenomenons existing in a human-riding-unicycle. In our project of unicycle research, we propose to do modeling on the dynamics of a human riding a unicycle, emulate this system by a robot, test different classic and modern control methods on the developed unicycle robot, and develop a new approach or analysis method for the stability analysis of unstable problem in three dimensions like a unicycle.

Before our investigation on the unicycle problem, some researchers have done some work on unicycle problem and tried to emulate this system by a robot.

Ozaka *et al.* [4] undertook the research in 1980 by a unicycle robot which consists of a wheel, a rigid body, and a movement weight. In that robot, postural stability in pitch direction was proposed to be obtained by the control on wheel, and postural stability in roll direction was proposed to be achieved by the control on movement weight that can move in roll direction. That investigation was conducted in three dimensions, but the experiment was not successful. In 1984, a One Wheel-Locomotive Robot was developed by Honma *et al.* [5], although the robot can travel on the rough, inclined, and narrow road such as the innerpipe path, the robot's postural stability was achieved by gyroprecession, in fact, it's not a study on a unicycle problem. Feng *et al.* [6] investigated the unicycle problem in 1985 by an inverted pendulum with a controlling arm pivoted at its upper end. This research was also conducted by Yamafuji *et al.* [7]. Although this research was successful both in simulation and in experiment, the investigation dealt only with the two-dimension problem of a unicycle.

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Schoonwinkel [8] conducted the research by modeling a human riding a unicycle with three rigid bodies which are a wheel, a frame to present the unicycle frame and lower part of the rider's body, and a rotary turntable to present the rider's twisting torso and arms. His research is mainly concentrated on the robot's construction, on the theoretical analysis of stability through linearizing the dynamic equation of motion of a unicycle robot, and on the evaluation of balance sensors, from his work, we can know that the unicycle system will be uncontrollable if the wheel's speed is zero. But no successful experimental result was reported in his work, and in fact, it is not suitable to linearize the dynamic equation of motion of unicycle robot since the linearized equation is far from the real model. Vos and von Flotow [9] used Schoolnwinkel's model and carried out the research, their work is mainly on the puropose of a new LQG structure for the control and dealt with the nonlinear problem of dry friction between the wheel and floor in the yaw direction based on the linearized dynamic equation of motion given by Schoolnwinkel. Some experimental results are reported in their paper [9]. However, we have not found out the experimental result about roll angle or roll angular velocity from that paper. In fact, the yaw rate and the rotary turntable rate are not always so small that the lateral and longitudinal dynamics can always nominally be decoupled and the dynamic motion of equation can be linearized; furthermore, they have not dealt with the nonlinearly coupled problem between lateral and longitudinal dynamics due to large yaw rate and yaw accelerations. The investigation of the unicycle problem was also conducted by Ito [10] in 1993. In Ito's research, the robot was developed according to Schoonwinkel's model, but no successful result in three dimensions can be reported.

Because the longitudinal and lateral stability are coupled to each other in this system, and no actuator can be used directly for the control of unicycle's posture in 3-D (pitch, roll, and yaw angles), as shown by the previous work related to the research of unicycle problem, the stability of a human-riding-unicycle in 3-D is not easy to emulate by a robot. The postural stablity of a human riding a unicycle has not been emulated successfully by a robot in 3-D until now. By analyzing the previous failed work [4]–[10], we found out the reason of failure is because they have not done suitable modeling on the dynamics of a human-riding-unicycle, so our first work is to do modeling on the dynamics of a human-riding-unicycle. The result of this work is reported in our previous paper [11]. In the current paper, based on the analyzed result shown in our previous paper [11], the first performance of a human-riding-unicycle is successfully emulated by our developed unique unicycle robot. By this emulation, our proposed model is tested and the experimental results indicate to us that the classic PD and D controller is possible for us to get posture stability control by the proposed model. Also, the proposed method for the robot's posture detection in 3-D is valid. Furthermore, the experimental results help us to understand the rider's performance for lateral stability is asymmetric. The asymmetric turntable is more efficient than a symmetric turntable for the robot's lateral stability.

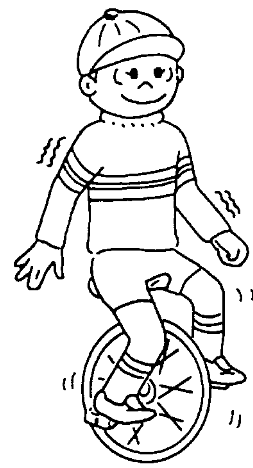


Fig. 1. Configuration of a rider's riding on a unicycle.

To understand the concept of a unicycle's postural stability, the definition of such is given in the following. Usually, if a system is stabilized, some variables in that system will be controlled to be constant value. However, because the unicycle system is an inherent unstable system and the postural stability is achieved by a centrifugal force created by the rider's actions dynamically, the pitch, roll, and yaw angles are always changable. It is impossible to stabilize these three variables to a constant value. Generally, the change of yaw angle is for the stability control of the roll angle. If the roll angle changes, the yaw angle will also be changed. The change of pitch and roll angle is often within some range. The biggest value of possible range is 90°, nevertheless, from the observation of a human riding a unicycle, we know that the postural stability is often broken if either pitch angle or roll angle becomes bigger than about 16°. If there is not enough centrifugal force created by control on this system, the postural stability will be broken in 1 s. And if there is no control on the system, the postural stability will also be lost in 1 s. That means if the postural stability is kept longer than 1 s, it will indicate that the used control method is acting in the system.

Based on the characteristics of posture change in a unicycle system, we can give the definition of postural stability of unicycle as below. We can say the posture of a unicycle is stabilized if following conditions are met.

1) Neither pitch angle nor roll angle increases. Usually, both pitch and roll angle can be changable, but the change is within some range (the biggest value of range is 90°, because of the power limit of motor, the range will be much less than 90°).
2) The posture should be kept at least longer than 1 s.

II. Dynamics of a Human Riding a Unicycle and its Modeling

A. Dynamic Characteristics of a Human Riding a Unicycle and Its Stable Principle

The process of a human riding a unicycle is quite complicated. Fig. 1 shows the configuration of a rider riding on a unicycle, and the simplified model of the posture of a rider

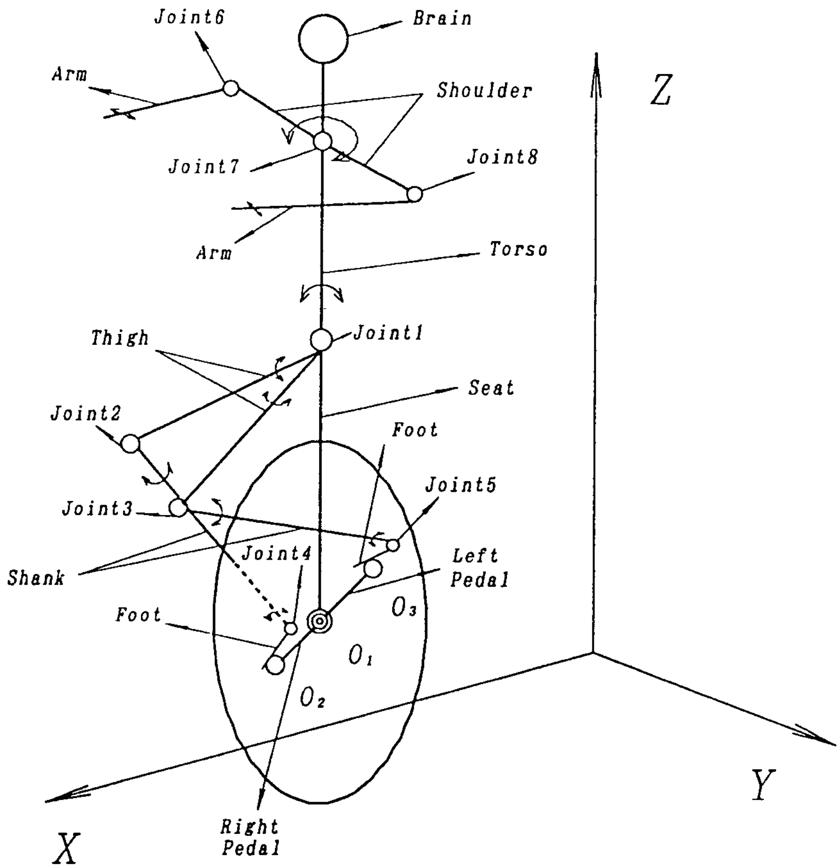


Fig. 2. Schematic diagram of a human riding a unicycle.

on a unicycle is shown in Fig. 2. As shown in Fig. 2, the rider's posture is stabilized by many dynamic actions created through rider's intelligence, vestibular system, visual system, proprioceptive sensors, tactile sensors, flexiable body, and so on [8]. The dynamic characteristics of this process can be summarized from the observation results.

1) As shown in Section I, five kinds of performance can be demonstrated by a human-riding-unicycle, and the rider's control action is quite jerky and nonlinear.
2) The unicycle's posture is kept by the centrifugal force created by the rider's actions dynamically. It is not obtained by changing the rider's gravity center or moving speed statically and simply.
3) A person on a unicycle maintains longitudinal stability by pedaling faster or slower with one side of thighs and shanks; by leaning his torso forward or backward; and by moving his arms forward and backward. The two sides of his thighs and shanks are used alternately, not simultaneously. Lateral stability is obtained by steering the wheel into the direction that he is falling through leaning his torso sideways, pulling an arm in or stretching it out, and twisting motions at the hip joints. The lateral and longitudinal stabilities are highly coupled together, and usually the lateral stability is realized by turning the unicycle into the direction that he is falling and then using the longitudinal control system to erect the unicycle. Both longitudinal and lateral control systems are important, but the longitudinal one seems more important in the postural stability control of system.

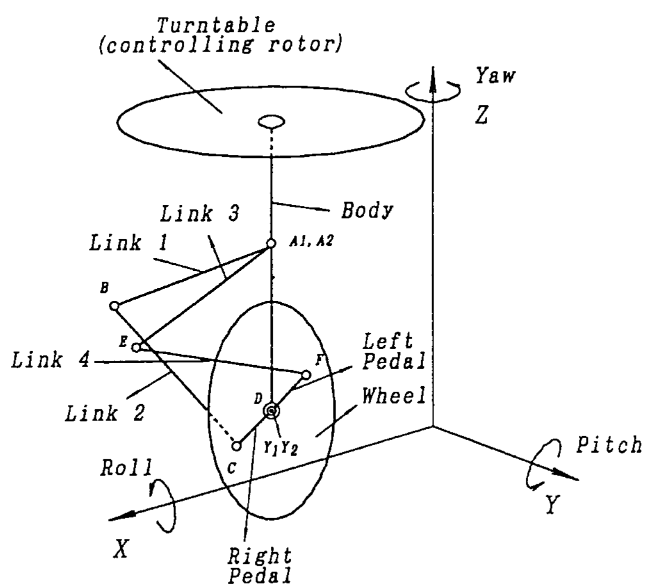


Fig. 3. Model for emulating a human riding a unicycle by a robot.

Basing on the above results, we can advocate that there exists following stable principle in this system.

1) The rider's body, thighs, shanks, and pedals on the unicycle form two closed-link mechanisms. This special structure plays an important role on the postural sta-

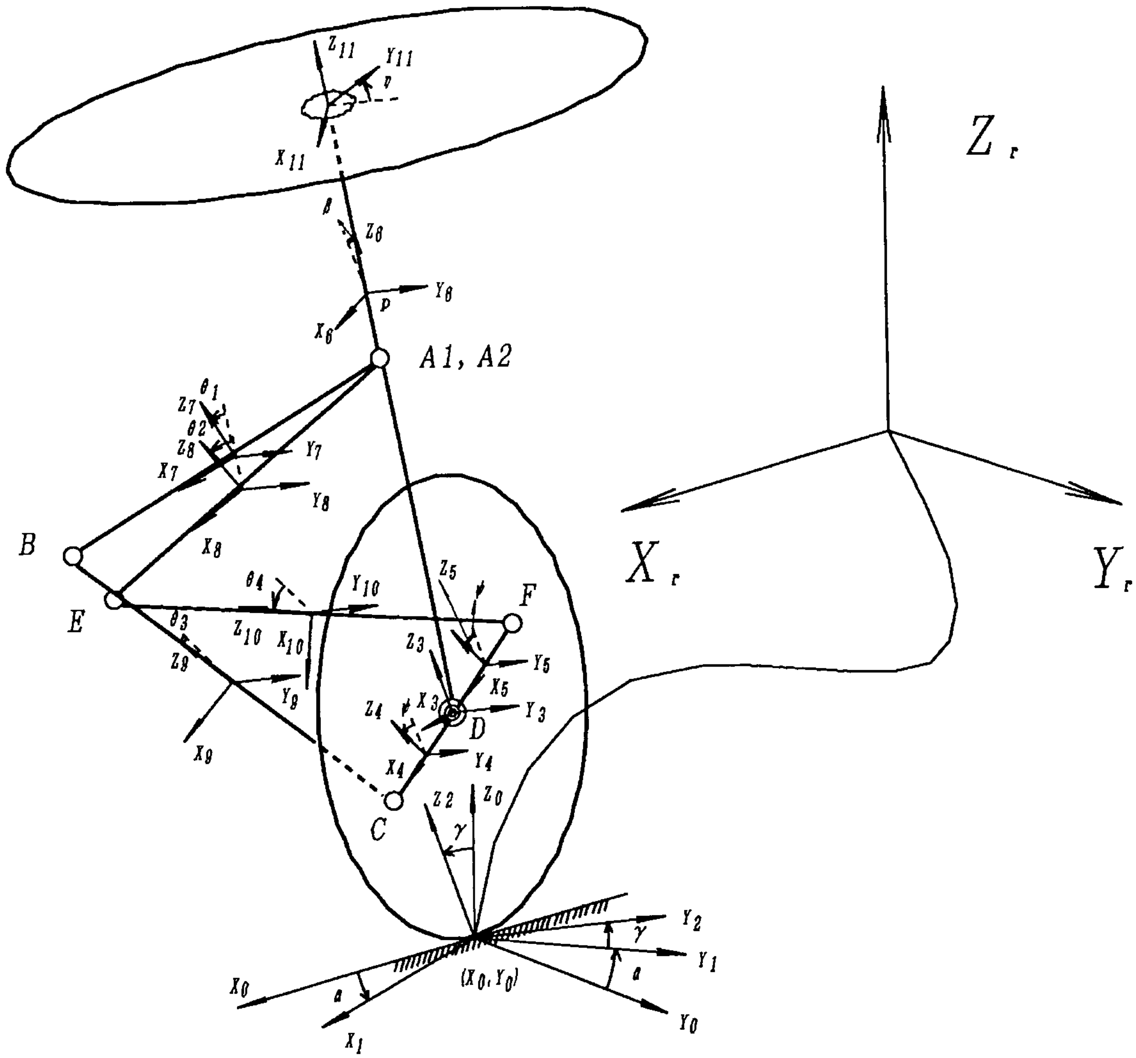


Fig. 4. Description of coordinates.

bility control of a unicycle (especially for longitudinal stability).

2) Lateral stability is achieved through longitudinal stability by turning the unicycle into the direction that he is falling.

B. Modeling

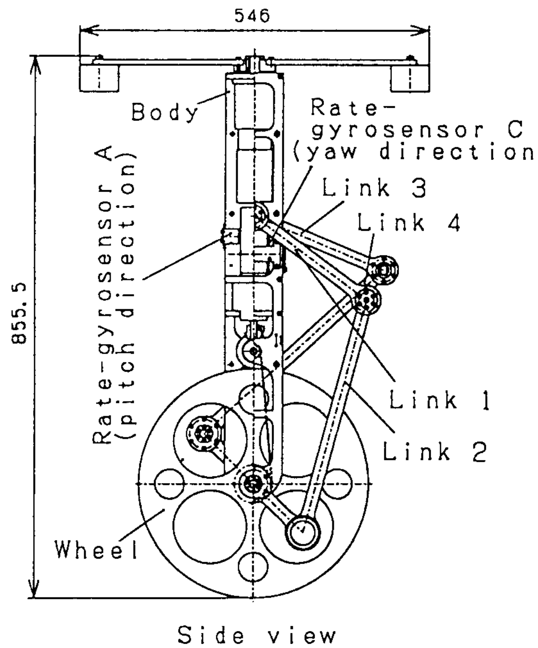
According to the stable principle advocated in the above, a new model is proposed as shown in Fig. 3. In this model, there is a wheel, two closed link mechanisms to present rider's body, thighs, shanks and pedals on a unicycle. Meanwhile, a rotary turntable to present the rider's twisting torso and arms. On the driving of this model, it will be too complicated to use so many motors for emulating a rider's action at joint 1–8 as shown in Fig. 2, and it is not suitable, either. We propose to emulate the similar actions in a human riding a unicycle by two closed link mechanisms and one turntable with simple driving methods. There are two kinds of possible patterns for the driving of this model, they are PATTERN 1 and PATTERN 2.

On the control of turntable, one motor is used both in PATTERN 1 and PATTERN 2. But on the control of closed link mechanisms, PATTERN 1 and PATTERN 2 are different.

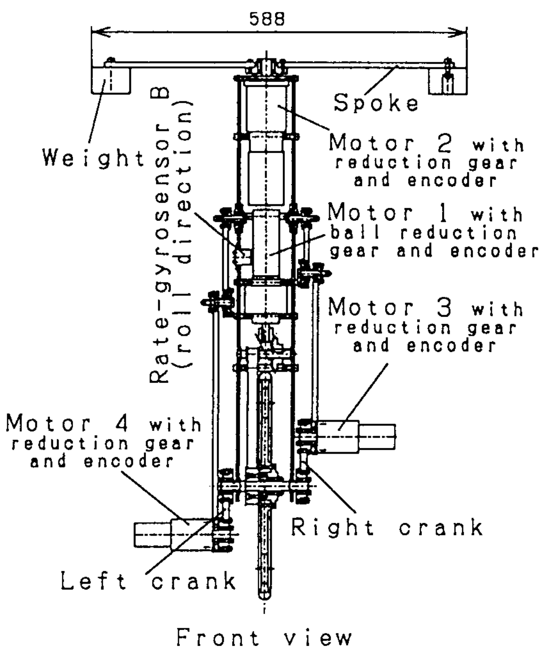
A person drives the unicycle by providing torque to his right or left thigh alternately. In PATTERN 1, the wheel of the emulated unicycle is also driven by inputing torque to the motor that drives link 1 or link 3 at joint A1 or A2. Meanwhile, these two motors which drive link 1 or link 3 will be also needed to do contribution to the longitudinal stability. In PATTERN 2, three motors are used, one is for the wheel's driving, the other two motors are used to drive link 2 or link 4 at joint C or joint F for keeping longitudinal stability.

In our previous paper [11],we considered the nonhonolomic constraints between the wheel and the ground, and considered the speciality of closed-link mechanisms, the dynamic equations of motion for this new proposed model was developed, and the simulations by proposed control methods with driving PATTERN 1 and PATTERN 2 were conducted. The simulation results show us the unicycle's posture in 3-D can be stabilized successfully both by PATTERN 1 and PATTERN 2 with proposed control methods, and PATTERN 2 is more practical than PATTERN 1. By this way, the validity of the proposed model is tested.

In order to make the paper concise and explicit, in this paper, the analysis about PATTERN 1 and PATTERN 2 is not



(a)



(b)

Fig. 5. Mechanism of unicycle robot.

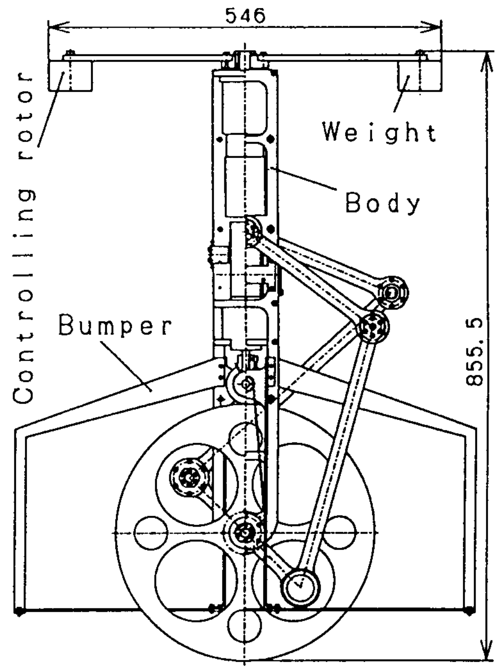


Fig. 6. Robot with bumper.

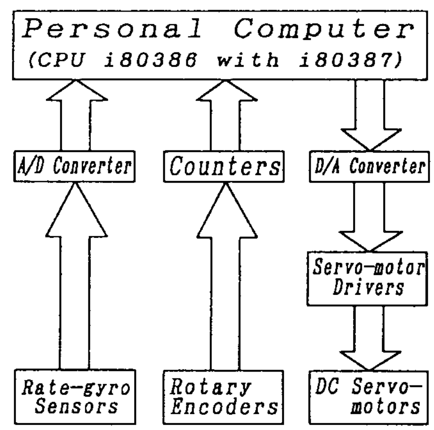


Fig. 7. Block diagram of control system.

reported, and the analysis about the closed-link mechanisms is not reported, either. For those particular details, the reader is referred to previous papers [11] and [12].

III. Robot and Experiment Device

The unicycle robot is designed and developed according to the PATTERN 2.

Fig. 4 shows the defined coordinates for describing the robot's posture related to the global reference coordinate. It is defined and described in detail in our previous paper [11].

The designed robot is shown in Fig. 5. It consists of a wheel with two cranks, body, turntable, left closed link, and right closed link. Four motors are used for the driving of the robot. The wheel is driven through a ball reduction gear (the reduction ratio is 1/5), a couple of spiral bevel gears (the reduction ratio is 1/2) and a timing belt (the reduction ratio is 1/3) by a dc servomotor (motor 1) (60 W) mounted inside the body of the robot. In order to make it easier for the robot's changing movement in yaw direction by turntable's rotation, it is better for us to design the robot's other parts (except turntable) as light as possible. Thus we prefer to choose three harmonic drivers to drive the turntable and two closed link mechanisms. In this case, the turntable is driven by a harmonic driver (motor 2) (the reduction ratio is 1/50) mounted inside the body of robot directly, meanwhile, the left closed link mechanism and right closed link mechanism are driven directly by a harmonic driver (the reduction ratio is 1/50) mounted on

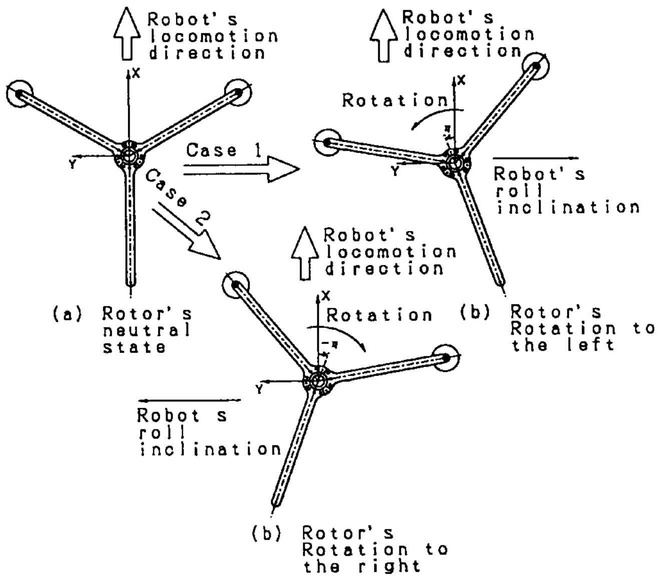


Fig. 8. State of turntable with two weights in control.

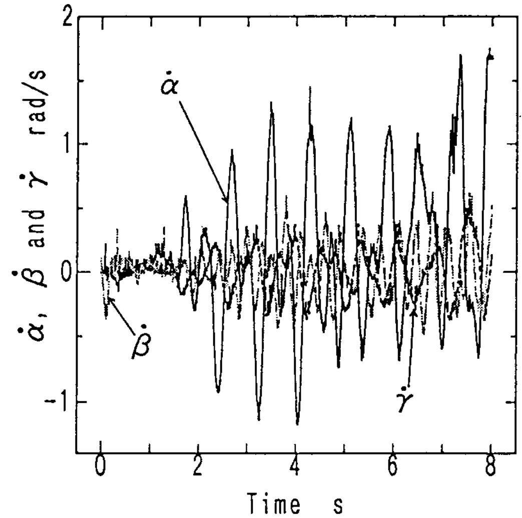


Fig. 9. Change in $\dot{\alpha}, \dot{\beta},$ and $\dot{\gamma}$ with time.

link 2 and link 4 (motor 3 and 4), respectively, too. Where, the motor 3 is chosen same as motor 4 for the structure's symmetry and balance of the robot.

In this robot, the turntable is formed by three weights (900 g $\times$ 3) and three sticks (or rotor which is used in [13]), the three weights are fixed on the tip of sticks to make the turntable have bigger inertia than the total inertia of robot's other parts except turntable in the turntable's rotation direction, this kind of mechanism is quite similar to the design of a controlling rotor in a one-legged robot [13]. Nevertheless, as pointed out later in this paper, it is more efficient for the control in the yaw direction if one of three weights is taken away and make the turntable's gravity center not at the center of turntable. About the wheel, we refer to the wheel used in a human riding a unicycle system. We manufactured a wheel with the radius of 180 mm, a 19 mm radius of the wheel's contacting point with the ground, and 20 mm width by aluminum.

In the design of closed link mechanism, link 1 is designed same as link 3 (220 mm), and link 2 is designed same as link 4 (380 mm). Of course, the left crank is manufactured the same as the right crank (110 mm). Because the crank can rotate infinitely, link 1–4 can rotate repeatedly with limit, thus the cable for the supply of electric power to motor 3 and 4 can be fixed on link 1–4.

The unicycle robot is an inherently unstable system, for the safety, a bumper is fixed on the lower part of robot as shown in Fig. 6. The weight of robot without bumper is 14.8 kg, and the weight of the robot with a bumper is 15.6 kg.

Fig. 7 shows the description of a block diagram of the control system, a 32-bit NEC PC-9801FA (CPU's clock frequency is 16 MHz) personal computer is utilized as the controller of the system. The wheel, turntable, and closed links are driven through the control of torque commanded to motors with the well-known software-servo control method, and the program for controlling is written in "C" language.

As shown in Fig. 5, there are three rate-gyrosensors (sensor A, sensor B, and sensor C) which are mounted on the body of the robot to measure the angular velocity of a body's inclination in the direction of pitch, roll, and yaw, and the resolution of the rate-gyrosensor is 0.1 degree/s. The optical rotary encoder (500 pulses/revolution) is installed on each servomotor to detect the rotation angle caused by the rotation of servomotor.

IV. Detection on the Robot's Posture in 3-D

In the robot's posture control, it's necessary for us to know a robot's posture and its change in three dimensions quickly and accurately. From the relationship [14] between robot's posture angle (α, β, γ) related to the global reference coordinate and the angular velocity $(\omega_x, \omega_y, \omega_z)$ around the robot body's three principal axes shown in Fig. 4, the robot's posture related to the global reference coordinate in three dimensions can be calculated as below from data measured by three rate-gyrosensors that are fixed on the unicycle in the direction of robot body's three principal axes [15].

$$\alpha = \int ((\omega_z \cos\beta - \omega_x \sin\beta)/\cos\gamma)\, dt \tag{1}$$

$$\beta = \int (\omega_y - (\omega_z \cos\beta - \omega_x \sin\beta)\tan\gamma)\, dt \tag{2}$$

$$\gamma = \int (\omega_x/\cos\beta + (\omega_z \cos\beta - \omega_x \sin\beta)\tan\beta)\, dt \tag{3}$$

where ω_x is the rotation angular velocity related to px_6, ω_y is the rotation angular velocity related to py_6, and ω_z is the rotation angular velocity related to pz_6.

Usually, there is a drift on the output of rate-gyrosensor with time and the change of temperature, it will be bad for experiment. In our experiment, we choose rate-gyrosensors which have small drift with time and temperature from many rate-gyrosensors. Furthermore, the robot is connected with a computer by cable, the experiment is conducted in

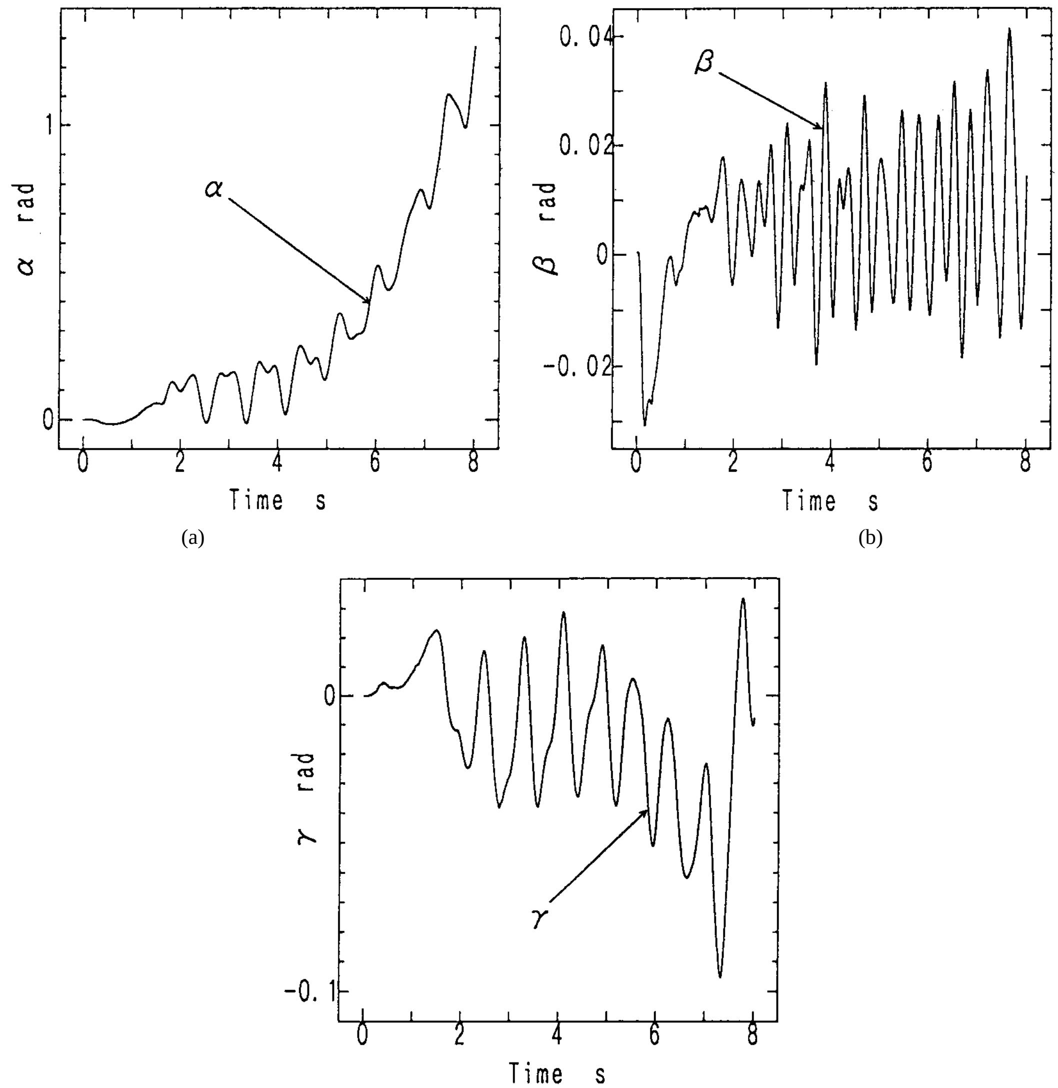


Fig. 10. (a) Change in α with time. (b) Change in β with time. (c) Change in γ with time. Change in robot's posture with time.

about 8 s, the drift of the gyrosensor's output within 8 s is not big.

V. Robot's Postural Stability Control and Expeirment Result

The experiment is conducted on the robot, as described in Section III, and we know that the wheel is made of aluminum not of plastic tire. That means that the unicycle robot's wheel could not change its shape as easy as the wheel used in a human riding a unicycle system. To make it easier for the control and to make the friction force between wheel and ground bigger for not making the wheel slip on the ground, the experiment is conducted on the synthetic rubber carpet. The control methods and experiment result are reported in this section.

As pointed out in our last paper [11], the wheel is used only to provide speed to the system and the robot's postural stability (especially the longitudinal stability) is not so dependent on the wheel's control by our new model. For simplicity, we can choose a very simple control method as shown in (4) to help the wheel overcome the friction force and to give the wheel a speed.

$$\tau_{\psi} = A \tag{4}$$

where τ_{ψ} is torque for wheel and A is a constant value.

The control method to links 2 and 4 is taken same as the method proposed in previous paper [11]. The torque for link 2 is same as for link 4, because the motor 3 and motor 4 are fixed on link 2 and link 4 symmetrically, the clock revolution direction of motor 3 and motor 4 is opposite, so we have to calculate the torque to motor 3 as (5) and the torque to motor 4 as (6) in order to apply the same torque to motor 3 and motor 4.

$$\tau_{\theta_2} = -kp_1 \times \beta - ki_1 \times \dot{\beta} \tag{5}$$

$$\tau_{\theta_4} = -\tau_{\theta_2} \tag{6}$$

where τ_{θ_2} and τ_{θ_4} are the torque for links 2 and 4, respectively; kp_1 and ki_1 are feedback gains.

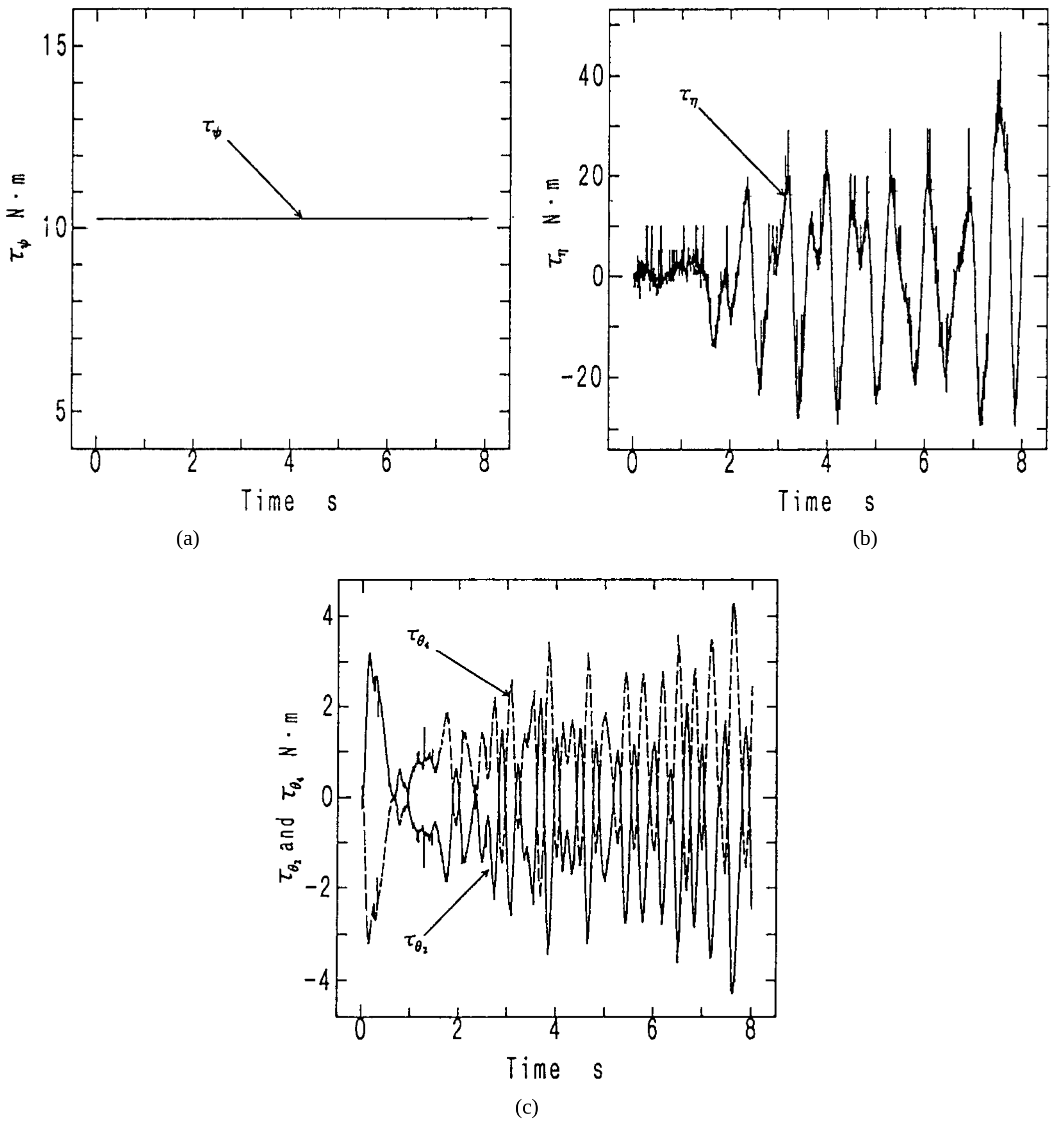
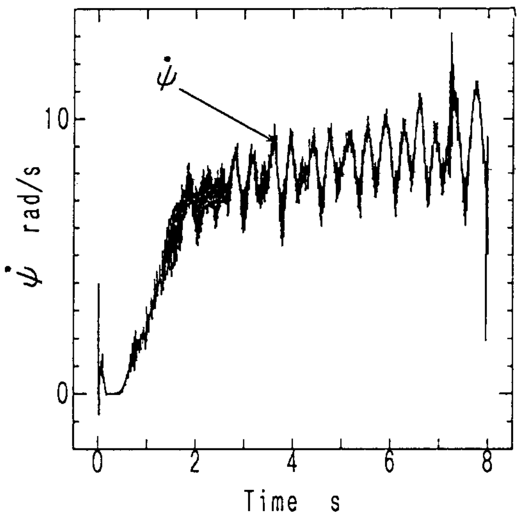


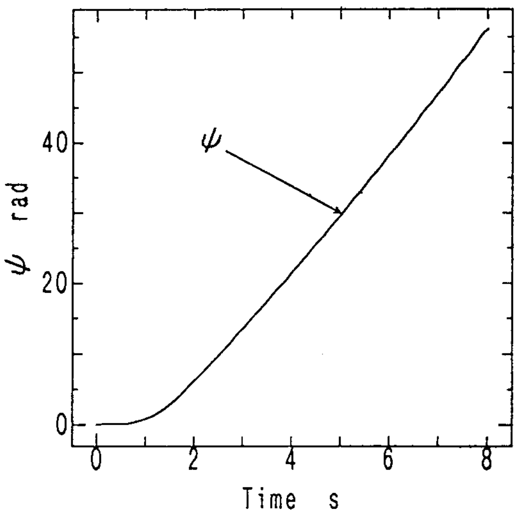
Fig. 11. (a) Change in torque to wheel with time. (b) Change in torque to turntable with time. (c) Change in torque to links 2 and 4 with time. Torque to robot.

As shown in (5) and (6), the torque is decided by the pitch angle and pitch angular velocity. That is because these two motors are used for the pitch stability control and the simulation shows this method is valid.

About the control on turntable, because the experiment ground is uneven, the robot's stability in roll direction will always be broken. That requires us to have an active control which can stabilize the robot in roll direction quickly, if the control is not fast enough, the robot will fall down quickly. From the experiments, we found out the control method on turntable proposed in previous paper [11, eq. (21)] is not practical, because the feedback gain will become bigger and bigger with wheel's movement forward by that method, but sometimes the roll angle and roll angular velocity will be not so small due to the unevenness of ground, that will make the calculated torque for motor 2 too big to be realized by motor 2. So, we propose a commom PD controller as shown in (7) to control turntable for lateral stability. In this controller, only information about roll angle and roll angular velocity is used, the information about the turntable's rotation angle or angular velocity is not considered. The reason being because control to the turntable is to change the yaw angle or yaw angular velocity, and by the change of yaw angle or yaw angular velocity, the roll angle is controlled. In this case, the information about the turntable's rotation angle or angular velocity is not needed. Of course, if there is a linear relationship between yaw angle and roll angle, it is better for us to use information from yaw in this controller, but the change of roll angle is not only dependent on the change of yaw angle and yaw angular velocity, but also dependent on the wheel's speed and wheel's acceleration. So the PD controller is formed like (7). We did the experiments many times by this method, and from the results, we found out the robot can be stabilized both in longitudinal and lateral directions if we control the robot by applying torque to motor 1, motor 3, motor 4, and motor 2 according to (4)–(7). But the robot's postural stability is quite dependent on the initial posture of robot and quite dependent on the smoothness of ground. That makes the experiment not successful every time, only sometimes the experiment is carried out successfully in



(a)



(b)

Fig. 12. (a) Change in wheel's angular velocity with time. (b) Change in wheel's angle with time. Change in wheel's angle and angular velocity.

a short time, the repeatability of experiment is quite bad.

$$\tau_\eta = kp_2 \times \gamma + ki_2 \times \dot{\gamma} \tag{7}$$

where kp_2 and ki_2 are feedback gains.

In the analysis of reason, we found out the controllability of the turntable with three weights is worse than that with two weights. The reason is that the turntable with three weights could not create a big reaction moment for the change of the robot's posture in yaw direction as the turntable with two weights due to the change of gravity center from the center of turntable when there are only two weights used in the system. The structure of turntable with two weights can play a similar performance not only as rider's torso but also as rider's arms in a human riding a unicycle system.

Referring to the above analysis, one of three weights is taken away in our experiment, and the remaining two weights are always controlled in the state as shown in Fig. 8 by the control method expressed in (8) which is a D controller.

$$\tau_\eta = ki_2 \times \dot{\gamma}. \tag{8}$$

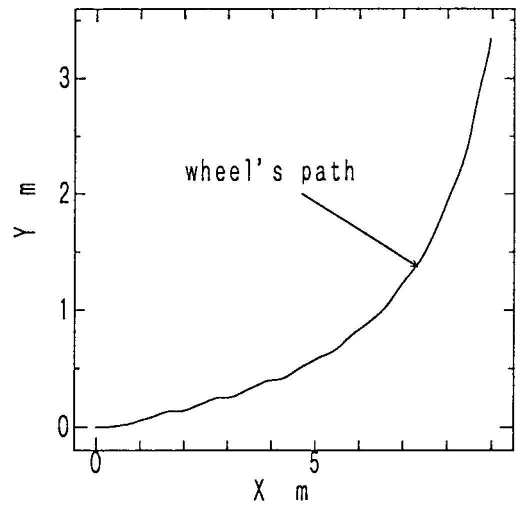


Fig. 13. Wheel's movement path in x-y plane.

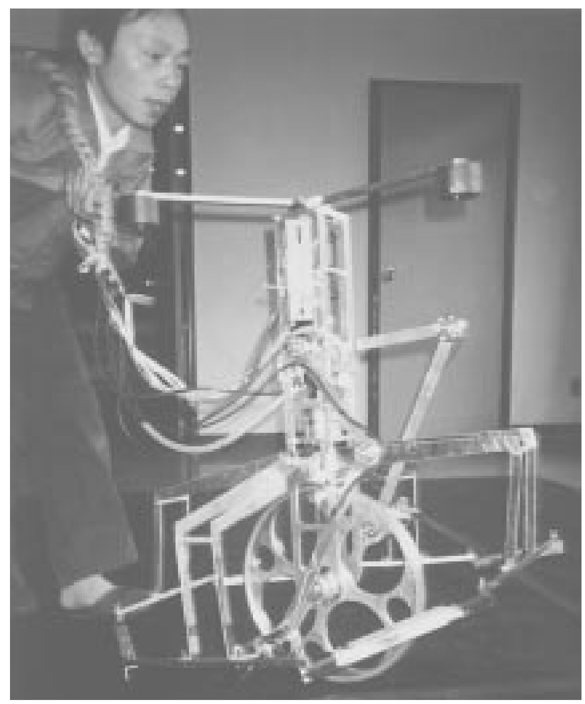
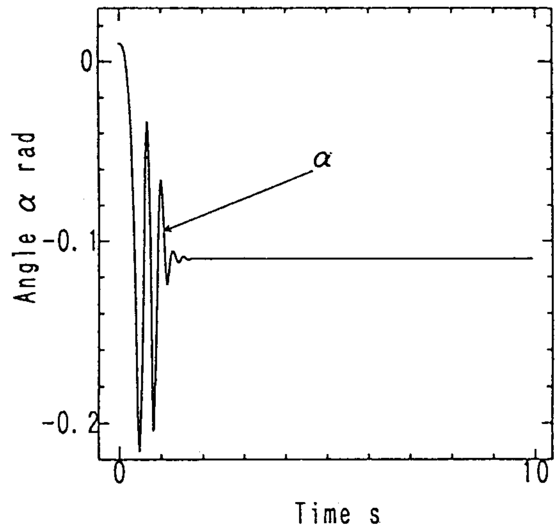


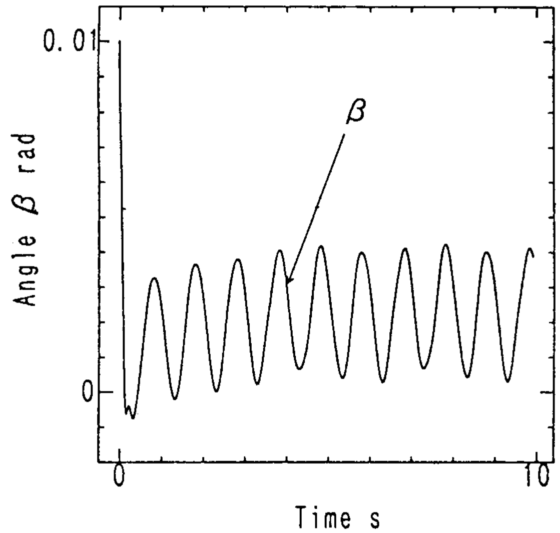
Fig. 14. Photograph of a unicycle robot's stabilized posture in experiment.

From experimental results, we found out this method is quite active and valid for the robot's lateral stability control. The robot's postural stability both in longitudinal direction and lateral direction is obtained successfully by applying torque to motor 1, motor 3, motor 4, and motor 2 according to (4)–(6) and (8). And the robot's postural stability is not so dependent on the initial posture of robot and not so dependent on the smoothness of ground, thus the repeatability of this experiment is quite good. The detail analysis on the characteristics of turntable with two weights will be reported in another paper.

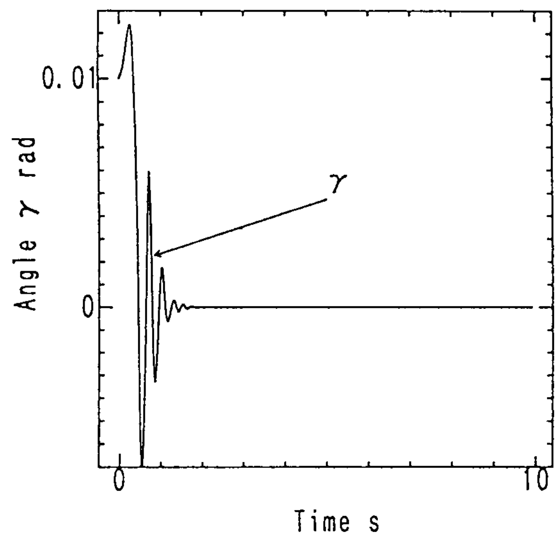
From Figs. 9–13, we show the experimental results from one of our experiments. In this experiment, $kp_1 = 6000.0, ki_1 = 120.0$, and $ki_2 = 2450.0$ are used, and the sampling time is taken as 3.5 ms.



(a)



(b)



(c)

Fig. 15. (a) Change in α with time (Simulation). (b) Change in β with time (Simulation). (c) Change in γ with time (Simulation). Change in robot's posture with time (Simulation).

Fig. 9 is the change of robot's angular velocity with time in pitch, roll and yaw direction. The change of robot's posture with time is shown in Fig. 10. Fig. 10(a) displays that the robot's posture in yaw direction is changed quickly in the experiment. The reason is that the control on yaw is for the robot's roll stability control, the change of the ground's unevenness will make the robot's posture in roll direction change, and the change of robot's posture in roll direction requires the robot's posture in yaw direction to be changed. Fig. 10(b) indicates that the robot's postural stability in pitch direction is obtained efficiently due to the active usage of closed link mechanism in this robot. The angle β is changed with time as a small value in 8 s. Our experiment is conducted on the 9.0 m $\times$ 4.0 m synthetic rubber carpet, the experiment is finished when the robot moves out of experiment area at 8 s.

From Fig. 10(c), we know that the robot's stability in roll direction is realized, but the roll angle is changeable with the ground's unevenness and robot's control.

Fig. 11(a)–(c) shows the torque for wheel's drive, the torque for turntable, and the torque for links 2 and 4, respectively.

Fig. 12(a) and (b) displays the wheel's movement distance and wheel's moving speed, the wheel's average moving speed is about 1.2 m/s, this speed is similar to the moving speed as we observed from the performance of rider's riding a unicycle. The robot's path in experiment is shown in Fig. 13. Fig. 14 shows a photograph of the robot's posture in three dimensions when the robot is stabilized and controlled in experiment.

VI. Discussion of Experimental Result

A. Comparison with Simulation Results

We compare the experimental results shown in the last section with the simulation results reported in our last paper [11]. From Figs. 15–18, we show the simulation results. Fig. 15(a)–(c) shows the change of a robot's postural angle (α, β, γ) with time in simulation, the corresponding experi-

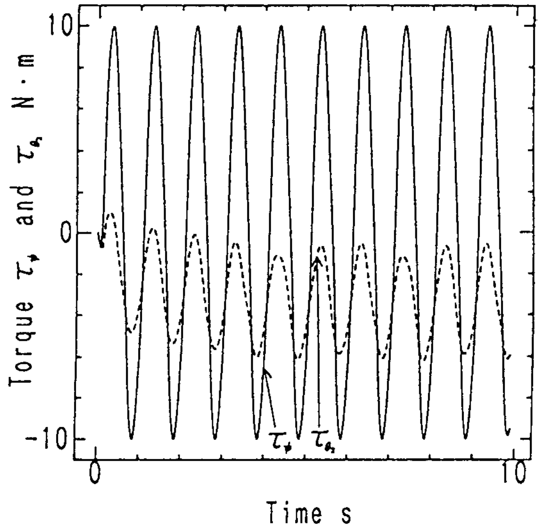


Fig. 16. Torque to wheel, links 2 and 4 (Simulation).

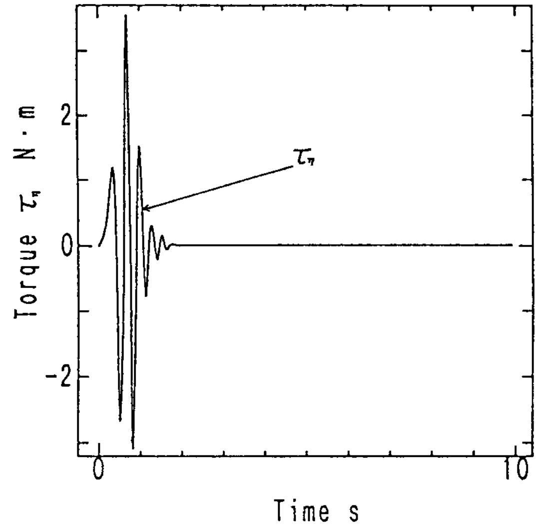


Fig. 17. Torque to turntable (Simulation).

ment result is shown in Fig. 10(a)–(c), respectively. The torque to wheel τ_ψ and the torque to links 2 and 4 in simulation are shown in Fig. 16. They can be compared to the result in Fig. 11(a) and (c), respectively. Fig. 17 shows the torque to turntable in simulation, its corresponding result is shown in Fig. 11(b). Fig. 18 shows the wheel's rotation speed, and, the corresponding experimental result is shown in Fig. 12(b).

In comparing the experimental results (from Fig. 10–12) with simulation results (from Fig. 15–18), we found out that the simulation and experimental are similar in the showing of robot's postural stability; but they are not same on the quantity. The reason is that the condition for simulation and experiment are different as following.

1) The parameters used in simulation are different from the real robot, such as the length, the weight, the friction coefficient, etc.
2) In simulation, the turntable is supposed to be formed by three weights symmetrily, but in experiment, one of three weights is taken away.
3) In simulation, the ground is taken as a complete smooth ground, but in the experiments, the ground is impossible to be an ideal smooth ground. The unevenness of ground means the robot's stability will be always broken by the surrounding, thus the robot's posture in roll direction is changable as shown in experiments, and the robot changes its yaw direction quickly for getting roll stability.
4) In experiment, the initial posture of robot is decided by human being's hand, thus the initial posture of robot is always changeable according to the setting by human being's hand, in this case, the initial state of robot is not easy to be measured. But in simulation, the initial posture of robot is set clearly before calculation.

Although the experimental result is not the same as same the simulation result in quantity, the simulation result tells us this model can be stabilized from initial unstable state in yaw, roll, and pitch direction by applying suitable control to the model, that implies the system is controllable and the proposed model can be used to emulate a human riding a unicycle system practically. The success on experiment is based on the simulation analysis results.

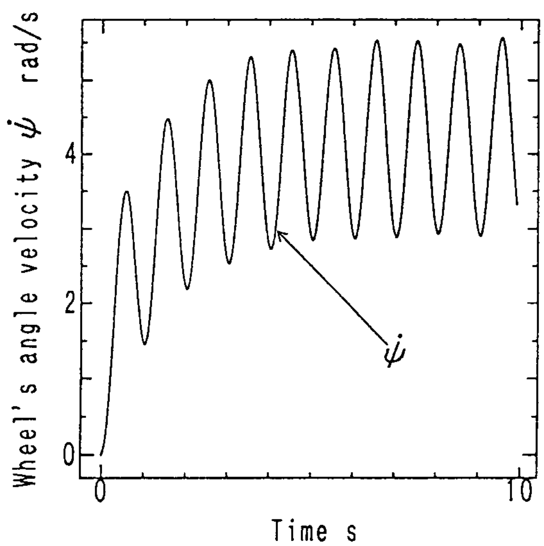


Fig. 18. Change in wheel's angular velocity (Simulation).

B. Comparison with a Human Riding a Unicycle

By comparing the experimental results with the observed results from a human riding a unicycle, we know that the postural stability of a human riding a unicycle is emulated successfully by this robot. Similar with a rider's riding a unicycle, the longitudinal stability is achieved by two closed link mechanisms, and the lateral stability is obtained by turning the unicycle robot into the direction that the robot is falling through control on turntable and then using the longitudinal control system to erect the unicycle robot. Of course, it is neither suitable nor needed for us to use so many motors for emulating rider's actions at joint 1–5 as shown in Fig. 2. The same functions of two closed link mechanisms in a human riding a unicycle are emulated satisfactorily by using three motors for the driving of two closed link mechanisms. The experimental results show that the asymmetric turntable is effective on the emulation of the functions of rider's shoulder, torso, and arms in a human riding a unicycle.

The emulation of the rider's other performance on a unicycle will be reported in our further investigation on unicycle problem.

VII. Conclusion

In this paper, the stable principle used in a human riding a unicycle system is investigated. The first performance of a human-riding-unicycle is emulated by a developed unicycle robot successful in experiment with proposed control methods. The conclusions can be summarized as follows.

1) The stable principle used in a human riding a unicycle system is advocated basing on the observation results, and a unique unicycle robot is developed.
2) The experimental result shows that the postural stability control of a human-riding-unicycle can be emulated by this robot in 3-D successfully. The experimental result indicates to us that our model based on advocated stable principle and the proposed control method are effective.
3) Same as a human-riding-unicycle, the robot's longitudinal stability is realized by the control on the two closed-link mechanisms. The robot's lateral stability is obtained by the control on turntable.
4) From experiments, we found out the turntable's compound gravity center does not necessarily have to be designed at the center of the turntable; and the controllability of the turntable with two weights is better than that with three weights.
5) The proposed method for detecting the posture of a robot in 3-D by three gyrosensors is valid.

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Professor Yamafuji was a member of the SCARA Robot Research Consortium during 1978–1981 and the founding Editor-in-Chief of the *International Journal of Robotics and Mechatronics* during 1988–1989. As is well known, the SCARA-type robot has become one of the most famous robots in the world.