Realization of a Human Riding a Unicycle by a Robot

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Abstract

In this paper, we designed and manufactured a unicycle robot according to the idea proposed in the previous paper. By using the new method for detecting the posture of the robot in three dimensions, we conducted experiments on this robot under proposed control method. The robot's posture is stabilized successfully both in longitudinal and in lateral directions in three dimensions. And the experimental results tell us that the proposed model and control method are effective and active for us to emulate a human riding a unicycle system by a robot. We believe that this is the first complete success on emulating a human riding a unicycle by a robot in the world.

1 Introduction

On the research of robotics, it's always one of important fields to emulate some intelligence or capabilities which are inherited by human being or animals. As to locomotive capability, we all know that the human being and some animals have quite excellent locomotion on walking, running or jumping. And we believe it'll be benefitable and helpful to emulate human being's walking, animal's running or jumping by robot. In fact, in recent years research results are reported by some researchers [1]~[3] who emulated human being's walking, animal's running or jumping by robot.

Our attention is on the emulating of a human riding a unicycle by a robot. We know that a person not only uses his flexible body, his good sensory systems, but also uses his skill and computational abilities to stabilize the unicycle, meanwhile its speed and direction also can be controlled. To do research on it, we have to investigate the stability reason why a person can stabilize unicycle, and propose suitable model and control method for the emulating of a human riding a unicycle. Because the process of a human riding a unicycle is quite complex, and there are so many unanswered questions in the system of a human riding a unicycle, the unicycle problem is interesting. Actually, the unicycle problem has attracted some researchers to do investigation on it. Qing Feng et al[4] investigated the unicycle problem by an inverted pendulum with a controlling arm pivoted at its upper end in 1985 and this research was also conducted by Yamafuji et al[5]. Although these research was successful both in simulation and in experiment, the investigation dealt only the two-dimension problem of unicycle. Schoonwinkel[6] conducted the research by modeling the 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 and on the evaluation of balance sensors, but no good experimental result was reported. David W. Vos and Andreas H. von Flotow [7] used Schoolnwinkel's model and carried out the research, their work is mainly on the propose of new LQG structure for the control and on the deal with of the nonlinear problem of dry friction between the wheel and floor in the yaw direction, some experimental results are reported in their paper[7]. However, we haven't 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 nominally always be decoupled, furthermore, they haven't dealt with the nonlinearly coupled problem between lateral and longitudinal dynamics due to large yaw rate and yaw accelerations.

In last paper[8], basing on the analysis of the uni-

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cycle problem by the observation of a human riding a unicycle, we proposed a new model to emulate a human riding a unicycle. In that model, there is a wheel, two closed link mechanisms to present rider's body, thighs, shanks and pedals on a unicycle (The dynamical analysis about closed link mechanisms is reported in our another paper[9]). Meanwhile, on the top of the robot, a rotary turntable is used to present the rider's twisting torso and arms. With that new model and considered about the nonholonomical constraints between the wheel and ground, the dynamic motion equations are developed. By using the developed motion equations and applying the control to the system, the result of computer simulation was obtained. The simulation results indicate that that model is adequate and successful for us to emulate a human riding a unicycle by a robot.

In this paper, we manufactured the unicycle robot according to the idea proposed in the last paper[8]. The experiments are conducted on the robot, in experiments, unicycle robot is stabilized both in longitudinal and in lateral directions, and the postural stability control of a human riding a unicycle system is successfully emulated by this robot. The experiment result indicates that the proposed model and control methods are valid in this unstable system. Meanwhile, the proposed method for detecting robot's posture in three dimensions is proved valid in experiments.

2 Robot and experiment device

The proposed mechanical link model is shown in figure 1 (same as Fig.2 in last paper[8]). In this model, a couple of four-joint closed link mechanisms is used for the control in pitch direction, and the turntable is for the control in roll direction.

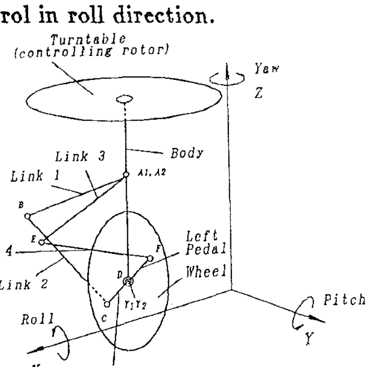

Fig. 1 Model for emulating a human riding a unicycle by a robot

As reported in last paper, there are PATTERN 1 and PATTERN 2 to drive the closed link mechanisms. In PATTERN 1, as shown in the Fig. 1, two motors are used at joint A1 and A2 to drive link 1 and link 3. By this pattern, the wheel is driven by this two motors and the stability in pitch direction is also obtained by these two motors. But from the point of control, it's not so suitable to use a motor for driving the wheel and getting stability in pitch direction at the same time. In PATTERN 2, three motors are used. One motor is for the drive of wheel, another two motors are used for the drive of link 2 and link 4. These two motors for link 2 and link 4 are fixed at joint C and joint F. The robot's stability in pitch direction is expected to be obtained by the control on link 2 and link 4.

From the result shown in last paper[8]. the PATTERN 2 is more practical than PATTERN 1, so our unicycle robot is designed and developed according to the PATTERN 2.

Figure 2 is the defined coordinates for describing robot's posture related to the global reference coordinate. Detail of it is Fig. 4 in last paper [8].

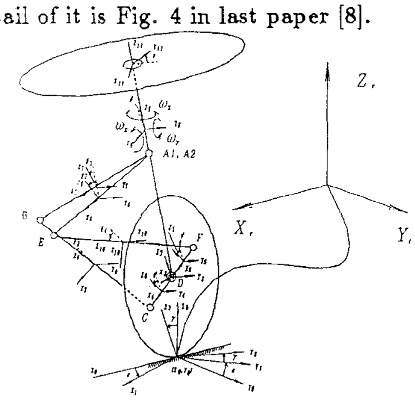

Fig. 2 Description of coordinates

The designed robot based on the analyzed result in last paper is shown in Fig. 3, it consists of wheel with two cranks, body, turntable, left closed link and right closed link. Four motors are used for the control 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)(60w) mounted inside the body of the robot. In order to make it easier for changing robot's movement in yaw direction by turntable's rotation, it's 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 turntable and two closed link mechanism. 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 link 2 and link 4 (motor 3 and 4) respectively, too. Where, the motor 3 is choosed same as motor 4 for the structure's symmetry and balance of the robot.

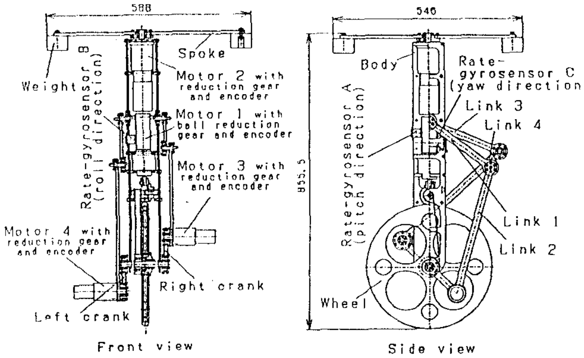

Fig. 3 Mechanism of unicycle robot

In this robot, the turntable is formed by three weights(900g $\times$ 3) and three sticks(or rotor which is used in paper[10]), 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 controlling rotor in one-legged robot[10]. Nevertheless, as pointed out in the later part of this paper, it's 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, refer to the wheel used in a human riding a unicycle system, we manufactured a wheel that the radius is 180mm with 19mm radius of wheel's contacting point with ground and 20mm width by aluminium.

In the design of closed link mechanism, link 1 is designed same as link 3 (220mm), and link 2 is designed same as link 4 (380mm). Of course, the left crank is manufactured same as right crank (110mm), too. Because the crank can rotate infinitely, but link 1 $\sim$ 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 $\sim$ 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. 4. The weight of robot without bumper is 14.8kg, and the weight of robot with bumper is 15.6kg.

Figure 5 is for the description of block diagram of the control system, a 32bit NEC PC-9801FA (CPU's clock frequency is 16Mhz) personal computer is utilized as the controller of the system. The wheel, turntable and closed links are driven through the control of torque cammanded to motors with the well-known software-servo control method, and the program for controlling is written in "C" language.

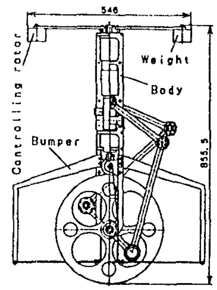

Fig. 4 Robot with bumper

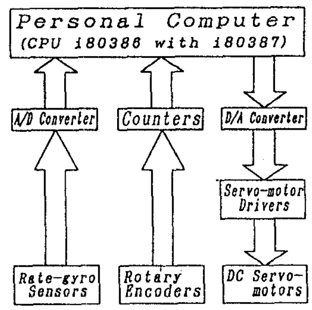

Fig. 5 Block diagram of control system

As shown in Fig. 3, there are three rate-gyrosensors (sensor A, sensor B and sensor C)(resolution: 0.1 degree/second) mounted on the body of robot to measure the angular velocity of body's inclination in the direction of pitch, roll and yaw. Servomotor's rotation angle is detected by optical rotary encoder(500 pulses/revolution) installed on each servomotor.

3 Detection on robot's posture

In the robot's posture control, it's necessary for us to know robot's posture and its change in three dimensions quickly and accurately. As shown in Fig. 3, rate-gyrosensors are fixed on the unicycle in the direction of robot body's three principal axes, it's px_6, py_6, pz_6 in Fig. 2. The measured data is the robot body's rotation angular velocity related to its three principal axes. By using the measured data, we can calculate robot's posture related to the global reference coordinate in three dimensions as below[11].

$$\alpha = \int ((\omega_x \cos\beta - \omega_z \sin\beta)/\cos\gamma)dt \quad (1)$$

$$\beta = \int (\omega_y - (\omega_x \cos\beta - \omega_z \sin\beta)\tan\gamma)dt \quad (2)$$

$$\gamma = \int (\omega_z/\cos\beta + (\omega_x \cos\beta - \omega_z \sin\beta)\tan\beta)dt \quad (3)$$

where ω_x: Rotation angular velocity related to px_6
ω_y: Rotation angular velocity related to py_6
ω_z: Rotation angular velocity related to pz_6
$\dot{\alpha}$: Derivative of α to time
$\dot{\beta}$: Derivative of β to time
$\dot{\gamma}$: Derivative of γ to time

Usually, there are drift on the output of rate-gyrosensor with time and the change of temperature, it'll 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 computer by cable, the experiment is conducted in about 8 second, the drift of gyro-sensor's output within 8 second is not big.

4 Robot's postural stability control and experiment result

The experiment is conducted on this robot, as described in section 2, we know that the wheel is made of aluminium not of plastic tire, that means the unicycle robot's wheel couldn't 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 plastic carpet. The control methods and experiment result are reported in this section.

As pointed out in last paper[8], the wheel is used only to provide a speed to the system and the robot's postural stability is not so depended on the wheel's control by our new model, for the simplity, we can just choose a very simple control method as equation (4) to help wheel overcome the friction force and give wheel a speed.

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

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

The control method to link 2 and link 4 is taken same as the method proposed in previous paper[8]. 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 symmetrily, the clock revolution direction of motor 3 and motor 4 is opposite, so we have to calculate the torque to motor 3 as Eq.(5) and the torque to motor 4 as Eq.(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 torque for link 2 and link 4 respectively; kp_1 and ki_1 are feedback gains.

As shown in Eq.(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[8](equation (21) in paper[8]) 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 control as shown in Eq.(7) to control turntable for lateral stability. We did the experiments many times by this method, from the experiment 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 Eq.(4),(5),(6) and (7). But the robot's postural stability is quite depended on the initial posture of robot and quite depended on the smoothness of ground, that makes the experiment not successful every time, only sometimes the experiment is carried out successfully in 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.

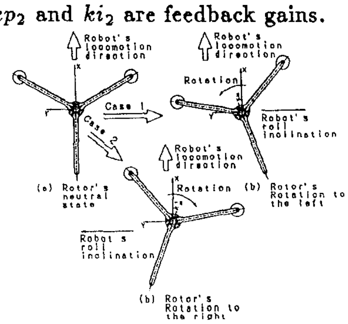

Fig. 6 State of turntable with two weights in control

In the analysis of reason, we found out the controllability of turntable with three weights is worse than that with two weights. The reason is that the turntable with three weights couldn't create big reaction moment for the change of 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.

Refer to the above analysis, one of three weights is taken away in our experiment, and the rest two of weights are always controlled in the state as shown in Fig. 6 by the control method expressed in Eq.(8).

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

From experiment 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 Eq.(4),(5),(6) and (8). And the robot's postural stability is not so depended on the initial posture of robot and not so depended on the smoothness of ground, thus the repeatability of experiment is quite good. The detail analysis on the characteristics of turntable with two weights will be reported in our next paper. From Fig. 7 to Fig. 11, we show the experiment results gotten 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 3.5ms.

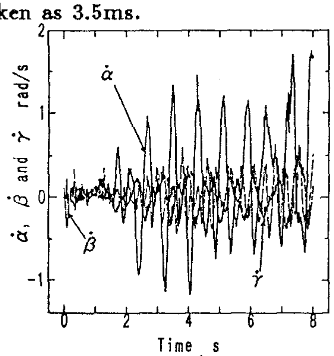

Fig. 7 Change in $\dot{\alpha}$, $\dot{\beta}$, and $\dot{\gamma}$ with time

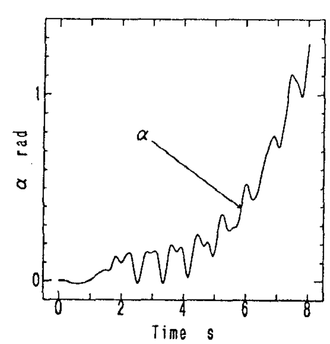

Fig. 8(a) Change in α with time

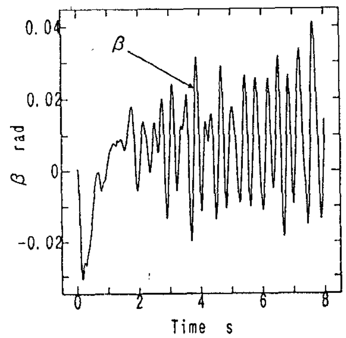

Fig. 8(b) Change in β with time

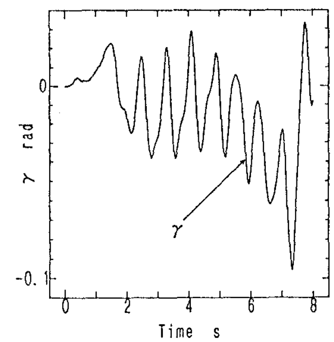

Fig. 8(c) Change in γ with time

Fig. 8 Change of robot's posture with time

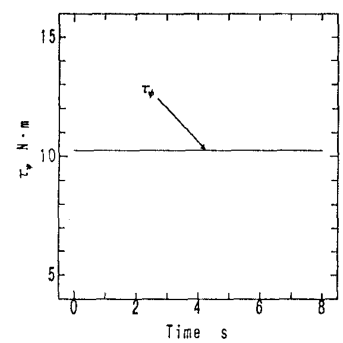

Fig. 9(a) Change in torque to wheel with time

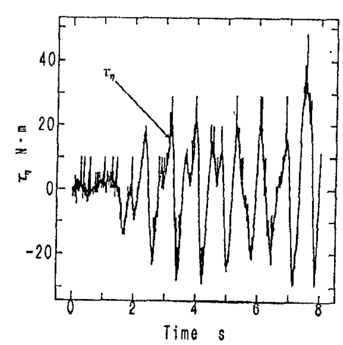

Fig. 9(b) Change in torque to turntable with time

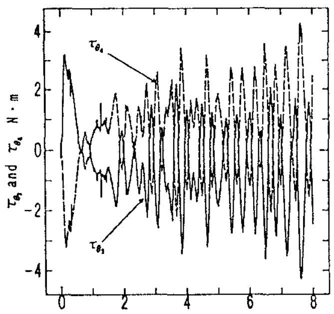

Fig. 9(c) Change in torque to link 2 and 4 with time
Fig. 9 Torque to robot

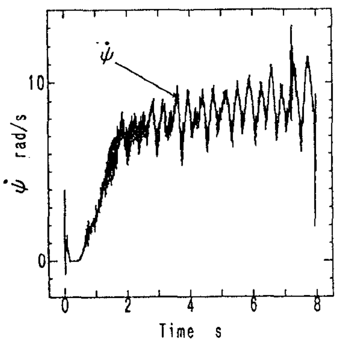

Fig. 10(a) Change in wheel's angular velocity with time

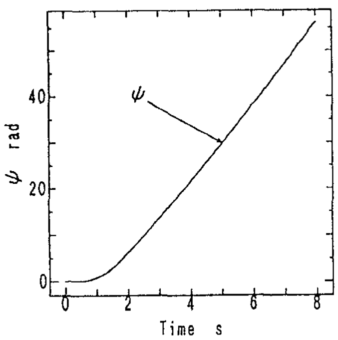

Fig. 10(b) Change in wheel's angle with time
Fig. 10 Change in wheel's angle and angular velocity

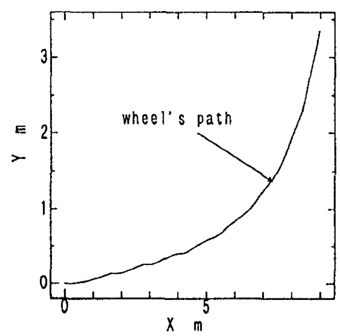

Fig. 11 Wheel's movement path in x-y plane

Figure 7 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. 8. Figure 8(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. Figure 8(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 8s. Our experiment is conducted on the 9.0m $\times$ 4.0m plastic carpet, the experiment is finished when the robot moves out of experiment area at 8s.

From Fig. 8(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.

Figure 9(a), (b) and (c) are the torque for wheel's drive, the torque for turntable, and the torque for link 2 and link 4 respectively.

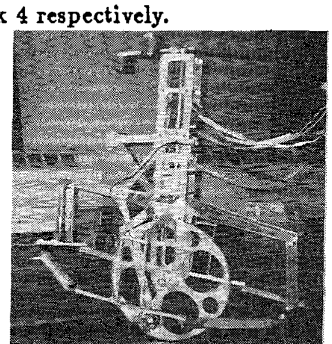

Fig. 12 Photograph of unicycle robot's stabilized posture in experiment

Figure 10(a) and (b) display the wheel's movement distance and wheel's moving speed, the wheel's average moving speed is about 1.2m/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. 11. Fig. 12 is a photograph of robot's posture in three dimensions when the robot is stabilized and controlled in experiment.

5 Discussion on experiment result

To compare the experiment results shown in last section with the simulation results reported in our last paper[8]. From Fig. 13 to Fig. 16, we show the simulation results. Fig. 13(a), (b) and (c) are the change of robot's postural angle (α, β, γ) with time in simulation, the corresponding experiment result is shown in Fig. 8(a), (b) and (c) respectively. The torque to wheel τ_ψ and the torque to link 2 and link 4 in simulation are shown in Fig. 14, they can be compared with result in Fig. 9(a) and (c) respectively. Fig. 15 is the torque to turntable in simulation, its corresponding result is in Fig. 9(b). Fig. 16 shows the wheel's rotation speed, the corresponding experiment result is in Fig. 10(a).

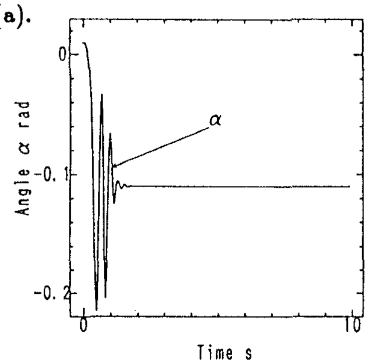

Fig. 13(a) Change in α with time (Simulation)

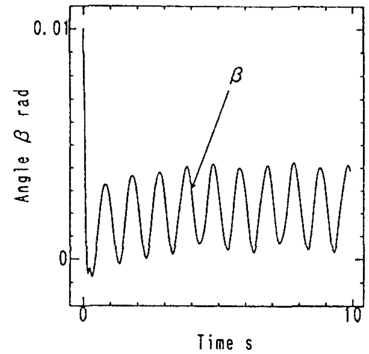

Fig. 13(b) Change in β with time (Simulation)

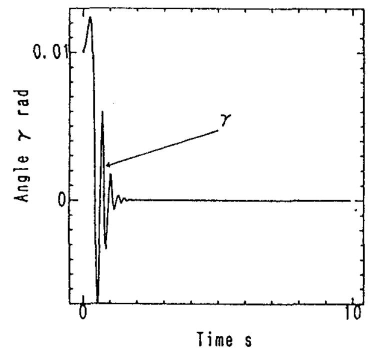

Fig. 13(c) Change in γ with time (Simulation)

Fig. 13 Change in robot's posture with time (Simulation)

Compare the experiment results (From Fig. 8 to Fig. 10) with simulation results (From Fig. 13 to Fig. 16), we found out that the simulation and experiment are similar on 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.

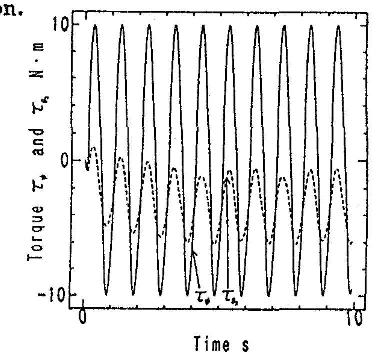

Fig. 14 Torque to wheel, link 2 and 4 (Simulation)

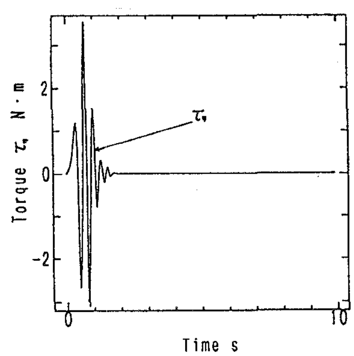

Fig. 15 Torque to turntable (Simulation)

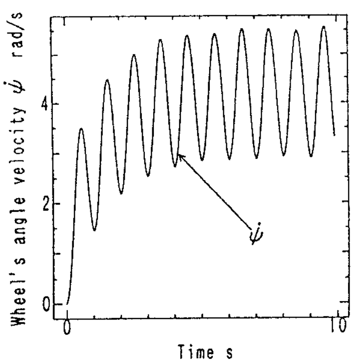

Fig. 16 Change in wheel's angular velocity (Simulation)

Although the experiment result is not just as same as 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 that simulation analysis.

6 Conclusion

In this paper, experiment is conducted successfully by developed unicycle robot with proposed control method, the conclusions can be summarized as follows. (1) According to the proposed model reported in previous paper[8], the unicycle robot is designed and manufactured. (2) The experiment result shows that the postural stability control of a human riding a unicycle system can be emulated by this robot successfully, the experiment result indicates us that our proposed model and control method are effective. (3) Similar with a human riding a unicycle, the robot's longitudinal stability is realized by the control on the two closed link mechanisms. And robot's lateral stability is obtained by the control on turntable. (4) Experiments show the robot's controllability with asymmetric turntable is better than that with symmetric turntable. (5) The proposed method for detecting the posture of robot in three dimensions by three gyrosensors is valid.

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