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Balancing control of a single-wheel inverted pendulum system using air blowers: Evolution of Mechatronics capstone design

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ABSTRACT

Inverted pendulum systems are one of typical control systems suitable for cross-disciplinary education. This article delivers the historical evolution of inverted pendulum systems as Mechatronics capstone design projects for undergraduate students. A wheeled inverted pendulum system is quite a challenging and interesting system to appeal students as a design project. Several design examples from two-wheel to one-wheel inverted pendulum system are elaborated. As a current design, a one-wheel inverted pendulum system which is our main contribution, is presented to deliver novel ideas of using air power to balance the system. The roll angle is regulated by air pressure generated from ducted fans while the pitch angle is controlled by a dc motor. Air pressure is controlled by linear control methods to keep the balancing in the roll direction. Experimental studies demonstrate the successful balancing performance.

1. Introduction

Balancing control is crucial for maintaining upright position. In particular, robotic and motion control systems need to achieve balancing while performing.

Balancing control of inverted pendulum systems has attracted the attention of both researchers and educators, and has applications to walking control of humanoid robots. A simple method for balancing a humanoid robot is to change the location of its center of gravity by moving the inverted pendulum as a mass balancer when one leg is lifted [1,2]. Using mass balancers helps humanoid robots such as ASIMO [3] and HUBO [4] for achieving stable walking directly or indirectly.

Inverted pendulum systems can assume various configurations, with multiple degrees of freedom [5–10]. An inverted pendulum system can also be controlled to balance while following a desired circular trajectory on the x–y plane [11].

Inverted pendulum systems moving on a fixed track have evolved into two-wheel inverted pendulum systems (TWIPSs) moving on a plane as shown in Fig. 1. A TWIPS is designed to have two points of contact with the ground. Thus, its control objectives are maintaining balance by controlling a balancing pitch angle and a maneuvering yaw angle on the plane using independent wheel velocities [12–30]. Feedback linearization control for TWIPS is considered in [13,14]. Intelligent non-model-based control approaches can be applied to TWIPS control [15,16], and sensor integration methods for detecting accurate balancing angles for TWIPSs are investigated in [17–21].

Balancing angle θ, position movement (x, y), and heading angle ϕ on the x–y plane can be controlled by two independent wheel velocities.

A TWIPS is developed and used to control a series of balancing robots (BalBOT). In particular, BalBOT I and BalBOT II combine the structures of two systems, namely, an inverted pendulum system and a mobile robot system [15,16]. Neural network control methods are embedded in a DSP and applied to the control of both the pendulum angle and the cart position. The role of the neural network is to compensate for the uncertainties in dynamics of unsymmetrical structure and disturbances. BalBOT III, which has a fully symmetrical structure, uses linear controllers for the balancing angle and position tracking control [19]. BalBOT IV is an extension of BalBOT II with arms, thereby enabling it to play a boxing game [21]. Successive BalBOTs are large enough to carry human beings [22]. Navigation control of BalBOT V is demonstrated in [23].

The TWIPS is transformed into a one-wheel inverted pendulum system (OWIPS), which is more challenging to control because it has only one contact point, and thus can fall in any direction [31,32]. A balancing control demonstration of Gyrover, which has a one-wheel structure, is presented in [31].

The OWIPS differs slightly in structure from a disk-type one-wheel robot, Gyrover [31] in that the OWIPS has an upper body with two arms and a head. Although pitch-angle control is the only consideration for balancing the TWIPS, balancing the OWIPS requires the consideration of three directional angles, because it becomes unstable due to its one-point contact with the ground. An experiment on the control of the pitch angle of the OWIPS is

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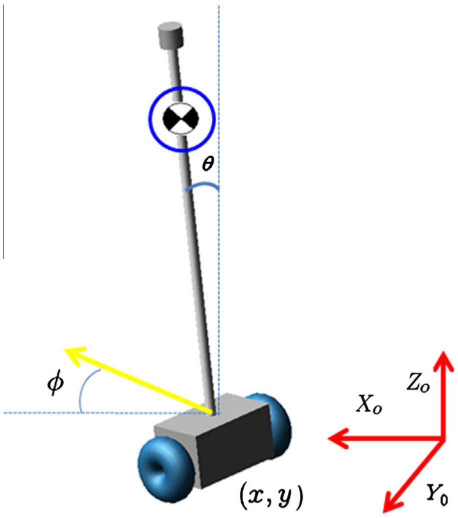


Fig. 1. Schematic design of TWIPS.

described in [32]. Table 1 lists and compares various design characteristics of inverted pendulum systems.

The Furuta pendulum has a revolute joint to balance the pendulum. A pendulum with a multiple linkage structure is used for balancing. Wheels are replaced with a guided rack. A one-wheel structure is more challenging because three angles, including the roll in addition to the pitch and the yaw of a two-wheel structure, need to be controlled.

This article presents the development and control of an OWIPS called CNU Blower, which starts as an undergraduate project. The goal of this article is to apply linear control techniques for balancing an OWIPS by using air power. CNU Blower, which is shown in Fig. 2 uses a concept that is different from lateral force control to achieve balance in the roll-angle direction. One of balancing mechanisms uses a large flywheel rotating at high speed to generate forces induced from gyro effects [31].

Instead of using gyro effects, CNU Blower uses the movement of air to generate lateral forces for balance. Two blowers made of ducted fans generate air pressure to achieve balance in the roll direction. The pitch and roll angles are controlled separately. By relying on PD and PID controllers, CNU Blower maintains its balance and follows the desired trajectory in the pitch direction, while being remotely controlled by a joystick. A gain scheduling method is used for the roll-angle control to achieve stable balance.

2. Design of OWIPS

Several designs of OWIPS are presented. The first design replaces the fixed rack of inverted pendulum systems with one wheel having two support wheels. The second design removes two support wheels and uses two wings actuated by ducted fans to balance the roll angle. The third design modifies the location of the position of two wings to enhance the balancing performance.

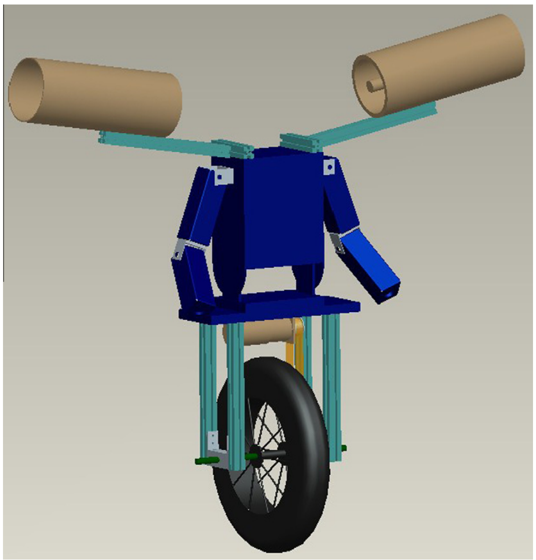


Fig. 2. Schematic design of OWIPS. CNU Blower is a unicycle robot. The pitch angle and position are controlled by a dc motor. CNU Blower has two ducted fans for blowing air.

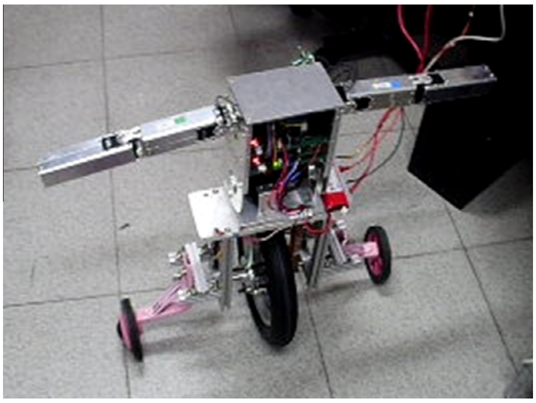


Fig. 3. The first model that can balance in pitch direction.

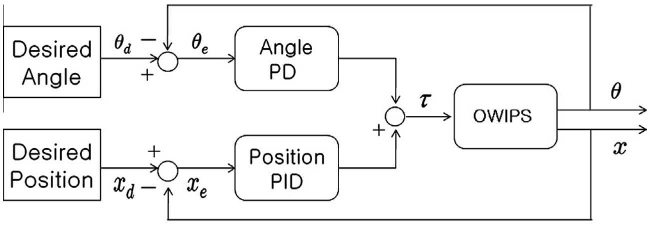


Fig. 4. Control block diagram of the first OWIPS.

Table 1
Characteristics of inverted pendulum systems.

Models	Pendulum type	Cart type	Reference
Furuta pendulum system	Single rod	One revolute joint	[5]
Multiple linkage inverted pendulum system	Multiple serial linkage	One linear prismatic joint	[6–10]
2 DOF inverted pendulum system	A single rod	Two linear prismatic joints	[11]
TWIPS	Single mass	Two-wheel mobile robot	[12–16,18,19,22–24,26,30]
	Humanoid body with two arms	Two-wheel mobile robot	[21,25,27]
OWIPS	Disk	One-wheel mobile robot	[31]
	Humanoid body with two arms	One-wheel mobile robot	[17,29,32]

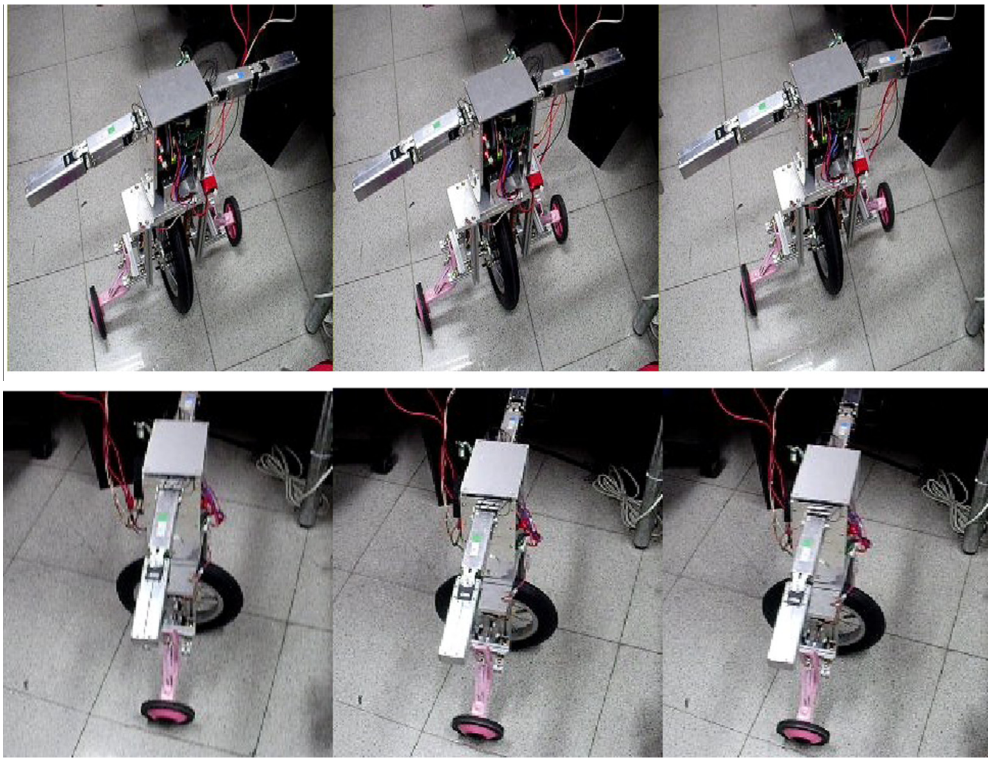


Fig. 5. Controlled motions of OWIPS I.

2.1. First design of OWIPS

Fig. 3 shows the first design of the OWIPS, called OWIPS I. Only the pitch angle and position have to be controlled because the roll angle is kinematically constrained by two support wheels. The control structure of OWIPS I is the same as that of the inverted pendulum system. A PD controller is used for the pitch-angle control, while a PID controller is used for the position control shown in Fig. 4. The controlled motions are presented in Fig. 5.

The lateral direction is kinematically constrained with two support wheels. The pitch angle and position are controlled. The idea is to control the roll angle by the movements of the left and right arms. However, the model failed to achieve this goal because of insufficient forces.

The pitch angle and position are controlled. The PD control method is used for the angle control, while the PID control method is used for position control of OWIPS. The two separate controls are summed together to generate the torque input for the OWIPS.

The actual control performance of balancing the pitch angle and position is demonstrated, although the roll direction is constrained by the two support wheels.

2.2. Second design of OWIPS

Fig. 6 shows the second OWIPS design, called OWIPS II. Two major aspects are modified from OWIPS I, namely, the support wheels are eliminated and two blowers are mounted on the head. The idea

Fig. 6. OWIPS II.

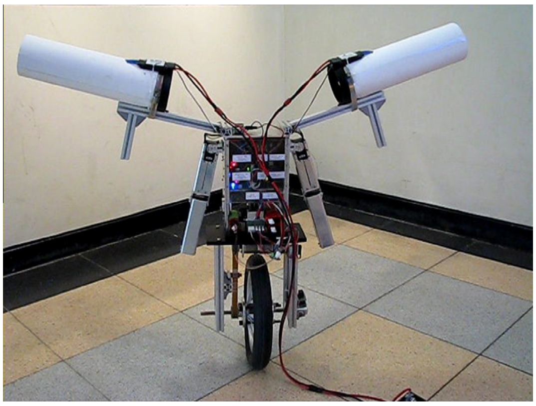


Fig. 7. Current model of OWIPS: CNU Blower.

is to control the roll angle by lateral forces against the body. These lateral forces are generated by the blowers, which consist of ducted fans. The left and right ducted fans push air away from the body. However, each blower creates a disturbance because they are located along the same line as shown in Fig. 6.

In OWIPS II, the two support wheels are eliminated to remove the constraint in the roll direction. Both the pitch direction and roll angle are controlled by the lateral forces generated by the two ducted fans. The alignment of the two ducted fans in the same line causes fan disturbance.

2.3. Third design of OWIPS (OWIPS III)

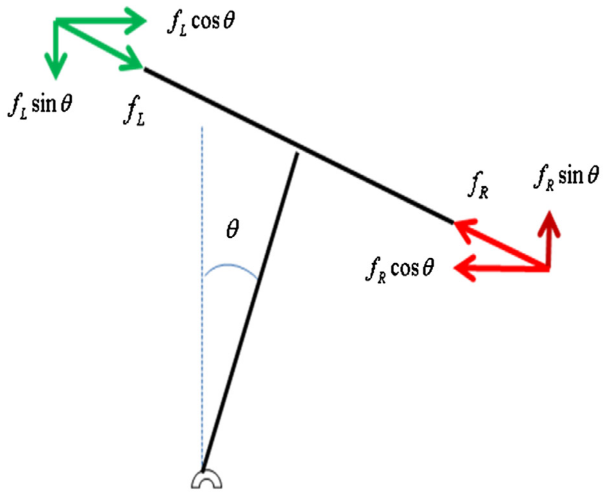
Fig. 7 shows the new design of a modified one-wheel robot with arms, called OWIPS III, which is structurally different from the design shown in Fig. 6. In the new design, the locations of the wings of the robot are modified to give them slightly upward position. In the design shown in Fig. 6, the wings are perpendicular to the body and aligned, causing undesired coupling effects in the air flow between the two ducted fans, with each blocking the other's airflow.

The final design of OWIPS differs from that in Fig. 6 in terms of the blower location. This modification improves the balancing performance in the roll direction by generating larger lateral forces and minimizing the disturbances from each ducted fan.

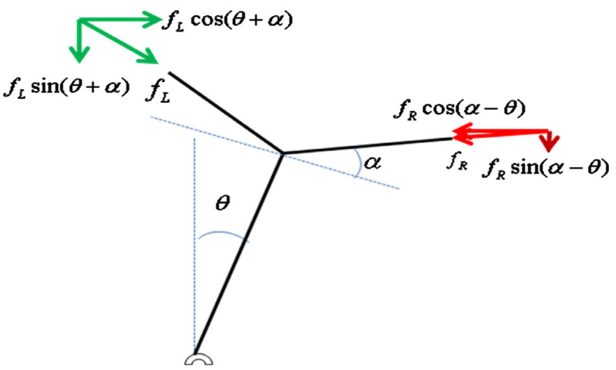
The wings in OWIPS III are tilted at an angle of about 14° in the upward direction to generate larger stabilizing torques in the roll direction by minimizing the coupling effects between the two ducted fans. A more stable balance can be achieved by avoiding the coupled effect of air pressure since air flow collides with each other.

Another advantage of this wing configuration to OWIPS II is its ability to create a larger lateral force against the body. Fig. 8 shows a vector analysis of the force distribution. The normal force acting on the body in Fig. 8a is $f_R \cos\theta$, where the roll-angle θ is small which is less than the critical angle that cannot maintain balance by the controller. Thus, if the slanted angle α is equal to the roll angle, we can then obtain f_R instead of $f_R \cos\theta$, which is a slightly larger force. Although the roll angle is not constant, we can acquire a larger force because the roll angle is close to the slanted angle value.

The blowers are tilted to maximize the lateral force applied to the system. The angle values are obtained from a kinematic analysis.



(a) Roll direction forces in Figure 6



(b) Roll direction forces in Figure 7

Fig. 8. Force vector analyses in the roll direction.

3. Control schemes of OWIPS

3.1. Pitch-direction control

Two angles and $x - y$ position are controlled. The pitch and roll angles are adjusted separately with different sampling times and control hardware. The forward and backward movements are also controlled. Linear controllers are used for the pitch and roll-angle control. The pitch angle and position are controlled together, similar to the control of an inverted pendulum system. The pitch angle is controlled by the PD control

$$u_p = k_{pp}e_p + k_{dp}\dot{e}_p, \tag{1}$$

where $e_p = \theta_d - \theta$, and k_{pp} and k_{dp} are the controller gain values. The PD controller

$$u_x = k_{px}e_x + k_{dx}\dot{e}_x, \tag{2}$$

is designed for the position control, where $e_x = x_d - x$ and k_{px} and k_{dx} are the controller gains. Combining (1) and (2) yields the pitch-direction control torque signal

$$\tau_p = u_p + u_x, \tag{3}$$

The control block diagram for the pitch-direction control is the same as that shown in Fig. 4.

3.2. Roll-angle control

In OWIPS II, PD control is used for the roll angle [32]. To reduce the tracking error, the roll angle α in OWIPS III is controlled by the PID controller

$$u_\alpha = k_{p\alpha}e_\alpha + k_{d\alpha}\dot{e}_\alpha + k_{i\alpha}\int e_\alpha dt, \tag{4}$$

where $e_\alpha = \alpha_d - \alpha$ and $k_{p\alpha}$, $k_{i\alpha}$, $k_{d\alpha}$ are the controller gains. The left and right torques are given by

$$\tau_\alpha = \tau_{\alpha\_l} + \tau_{\alpha\_r}, \tag{5}$$

where $\tau_{\alpha\_l} = k_L u_\alpha$ and $\tau_{\alpha\_r} = k_R u_\alpha$. These gains, k_R and k_L are selected experimentally. The control block diagram is shown in Fig. 9.

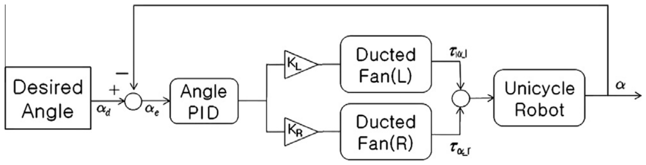


Fig. 9. Roll-angle control block diagram.

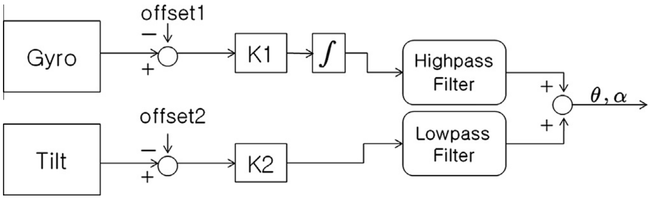


Fig. 10. Sensor fusion of complementary filter.

The roll-angle α is controlled separately by the PID control method. The torque on each ducted fan is compensated for by gains k_L, k_R because the two blowers are not identical.

4. Sensor fusion

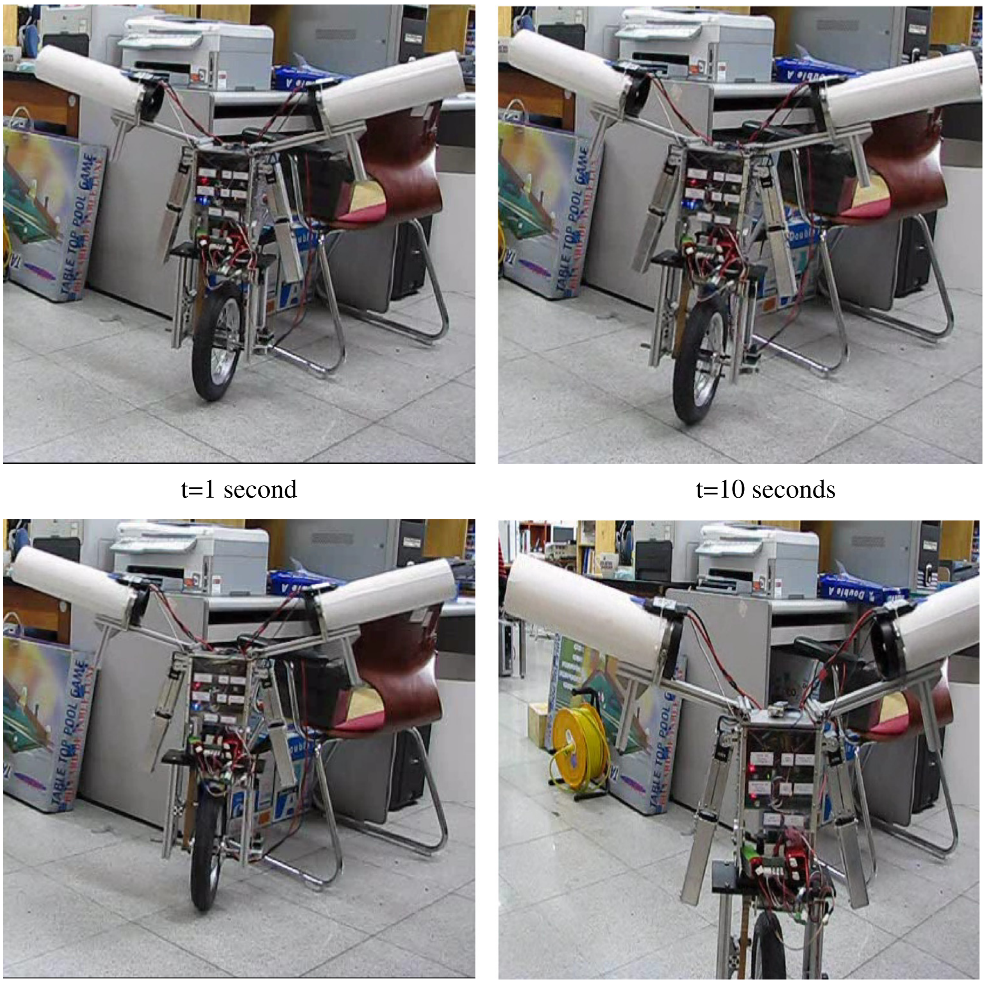
To maintain upright position, we use low-cost gyro and tilt sensors to measure the inclination angle. The rate gyro sensors are used mostly to obtain angles from the integrated angular velocity. The integration of angular velocity values causes a drift problem with respect to time. Conversely, a tilt sensor detects an inclination angle directly, but with a slower response compared with that of a rate gyro sensor, making it unsuitable for high-frequency sensing.

Table 2
PID gains for the roll-angle control.

Angle range (rad)	Gain value					
	P Gain		I Gain		D Gain	
	L	R	L	R	L	R
$-\pi/180 \leqslant \theta \leqslant \pi/180$	105	100	25	25	35	30
$-2\pi/180 \leqslant \theta \leqslant -\pi/180$ $\pi/180 \leqslant \theta \leqslant 2\pi/180$	115	110	25	25	36	31
$\theta < -2\pi/180$, $\theta > 2\pi/180$	125	120	25	25	38	33

The different characteristics of these two sensors necessitate their fusion. A complementary filter is designed to combine a rate gyro sensor, which has a suitable high-frequency response, and a tilt sensor, which has a suitable low-frequency response. This filter is shown in Fig. 10 [19,21]. The description of Fig. 10 provides details about the offset values for the two sensors. Since tilt and rate gyro sensors have their own offset values as reference outputs, average offset values for calibration are experimentally obtained. For the pitch-angle control, the tilt sensor offset is 0.2624 rad, while the rate gyro sensor offset is −0.3456 rad/s. For the roll-angle control, the tilt sensor offset is 0.2538 rad, and the rate gyro sensor offset is 0.0119 rad/s. The data from the two sensors are combined.

The gyro and tilt sensors are fused with the complementary filter, which uses the frequency response characteristics of the two sensors. The rate gyro sensor has a good high frequency response, while the tilt sensor's response is good at a low frequency.



t=1 second

t=10 seconds

t=20 seconds

t=60 seconds

Fig. 11. Balancing control results.

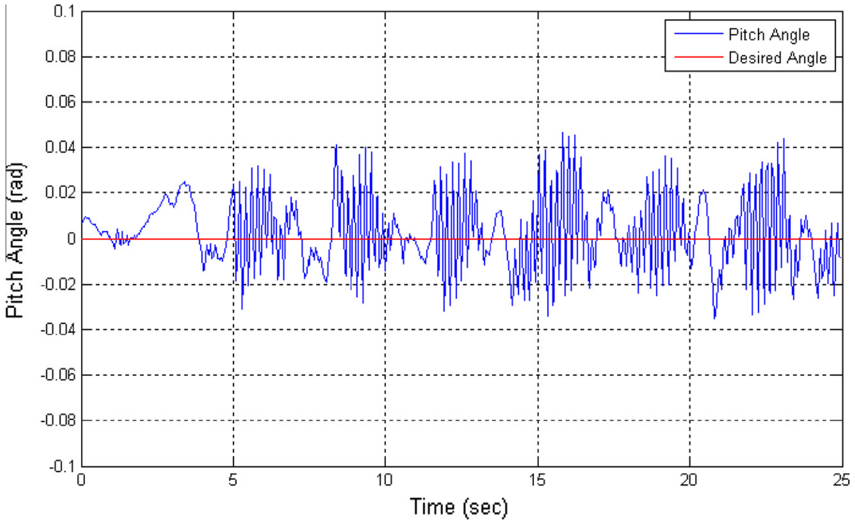


Fig. 12. Pitch-angle error.

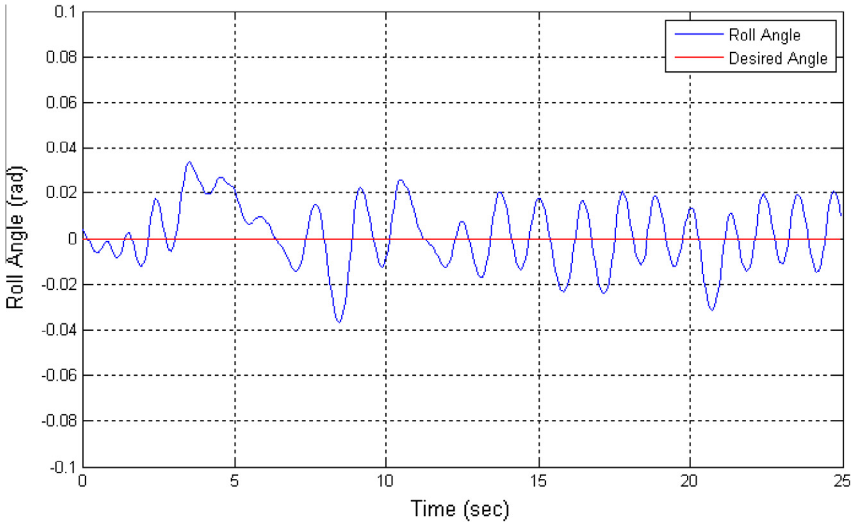


Fig. 13. Roll-angle error.

5. Experimental studies

5.1. Experimental setup

Fig. 7 shows OWIPS III, with two microprocessors for separate angle control. The control frequency of 200 Hz is used for the roll-motion control and 100 Hz is used for the pitch-motion control. Sensor data for both angles are sampled at the sampling frequency of 500 Hz.

The PD gains are selected experimentally, with $k_{pp} = 210$ and $k_{dp} = 1.3$ for the pitch-angle control, and $k_{px} = 2.15$ and $k_{dx} = 6.0$ for the pitch-position control. For the roll motion, gains depend on the angle. The PID gain values for roll-angle control are listed in Table 2.

A gain scheduling method is used for the roll-angle control. Different gain values are used for the different range of the roll angle θ. Gains are obtained from experimental studies.

5.2. Experimental results

Fig. 11 shows several frames of a video of the balancing control performance of OWIPS III. In this clip, the OWIPS III is moved forward through a remote control device. OWIPS III maintains suitable balance as it moves forward. The corresponding angle error plots are shown in Figs. 12 and 13. The pitch-angle error shown in Fig. 12 is within ±0.4 rad and the roll-angle error shown in Fig. 13 is within ±0.03 rad. The response of the roll angle is smoother than that of the pitch angle because different actuators are used. As OWIPS III moves forward, the response of the pitch angle is relatively fast. The integral action of the roll-angle controller maintains the balance, preventing OWIPS III from falling. Integrated errors have positive effects on the roll-angle balance, while they have negative effects on the pitch-angle balance.

An actual demonstration of the current model is presented. The OWIPS maintains balance, as it follows the command given remotely by the joystick. Pictures are taken during 60 s. Movements of OWIPS III are captured to show actual balancing and moving performance.

The pitch directional angle error is plotted as the OWIPS moves forward as shown in Fig. 11.

The pitch angle is oscillating around 0°, which means that OWIPS is balancing.

The roll directional angle error is plotted as the OWIPS moves forward as shown in Fig. 11. The roll angle is balanced similarly.

6. Conclusion

Various modifications of inverted pendulum systems presented in the literature have been categorized based on their characteristics. Several TWIPS and OWIPS as evolved models from inverted pendulum systems were presented as capstone design projects.

The OWIPS has an interesting structure for control research and education. A new concept for balancing the OWIPS using air blowers is discussed, and control is demonstrated. Since the navigation and balancing of the OWIPS is challenging, the control and sensor integration are performed carefully. Linear controllers are used to control two angles, pitch and roll angles. This system can be used from a control education perspective, with students learning to design new systems, implement hardware, perform sensing and filtering, and finally, control the systems to satisfy the given control specifications. The systems have to be kinematically well designed, and control functions using sensors and filters must be available for the succeeding control stages. Adding yaw-angle control to the OWIPS is planned in future research.

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