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A Self-Balanced Essboard-like Mobile Robot – Essbot

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***Abstract*— With the rapid development of robotics technology, balance and motion control of specific unicycle and two-wheeled vehicles have become achievable, and wheeled self-balanced mobile robots can be developed. Essboard is a wheeled vehicle, having different instability from an ordinary two-wheeled vehicle because of its two wheels that are arranged at the front and rear side. However, there is still a lack of relevant research on its balance control, so at present, it cannot be developed into a self-balanced two-wheeled mobile robot. In order to solve this problem, in this paper, a design concept of developing the Essboard into a two-wheel self-balanced robot Essbot by decomposing its motion is proposed for the first time. Besides, we develop and fabricate the Essbot, and propose its balance and motion control methods. Furthermore, the correctness and effectiveness of the designed Essbot and the proposed balance and motion control methods are verified by virtual prototype technology. Finally, the influence of different control laws on the Essbot's motion is studied for the first time. The research results in this paper represent significant progress in the field of wheeled self-balanced robot and Essboard, and this is the first realization of the development of Essboard into a new type of two-wheeled self-balanced mobile robot.**

***Index Terms*— Self-balanced, Essboard, Wheeled robots.**

I. INTRODUCTION

With the development of robotics technology, wheeled mobile robots have been more and more present in our daily life. A wheeled mobile robot has been widely used in industrial production [1], family service [2], and military applications [3] due to its characteristics of small floor area and flexible and agile movement.

A wheeled self-balanced robot is a type of a wheeled mobile robot. The wheeled self-balanced robots can be divided into single-wheel self-balanced robots and two-wheel self-balanced robots. Due to the inherent instability, a wheeled self-balanced robot has aroused great interest in research. A. Schonwinkel [4] designed and produced a single-wheel self-balanced robot by observing human behavior when riding a unicycle. The balance of the designed robot in left and right directions was mainly regulated by the horizontal turntable at its upper end, while the balance in the front and rear direction was regulated by the front and back movement of its wheel. The robot named Murata Girl [5] that was exhibited at the CEATEC JAPAN 2008 had a lively and lovely image and excellent balance ability, which was once a sensation. With regard to Murata Girl, the inertial flywheel was used to adjust the balance in the left and right directions, and the balance control was realized by controlling the acceleration of the flywheel.

The two-wheeled robots have also been studied. One of the two-wheeled self-balanced robots is Joe [6], which was designed by Grasser et al. Joe can perform the u-shaped turning and zero-radius turning by decoupling and decomposing the motion and simplifying the control, so it has an excellent motion performance. His success has caused a high research interest in a two-wheel robot. Further, the uBot-4 [7] developed by the University of Massachusetts, the United States, can maintain posture balance meanwhile complete tasks such as holding a ball.

As presented, the existing two-wheeled self-balanced mobile robots have some common characteristics; namely, the two wheels are arranged on the left and right sides of a robot, and the rotating axes of the wheels coincide. However, the Essboard has different structural characteristics from the single-wheel balanced robot and ordinary two-wheel balanced robot, and its commercial version is shown in Fig. 1. The Essboard is a variant of Skateboard [8] and Snakeboard [9]. Its remarkable feature is that the two wheels are arranged at the bottom of the front and rear pedals respectively. The axes of the bogie are not perpendicular to the pedals, and the front and rear pedals can relatively rotate. The Essboard has attracted scholars' interest because of its special caster structure and movement form. In 2007, Shamas [10] in Carnegie Mellon University noticed that Essboard had a different structure from Snakeboard for the first time. In 2012, Stoshi Ito [11] in Gifu University simplified the Essboard into a 2D plane model and analyzed its motion in the plane under the force exerted by the rider. In 2013, Kinugasa [12] in Osaka University proposed the concept of Essboard as a Casterboard robot. However, the Casterboard robot needs to install auxiliary wheels touching the ground on both sides to maintain its balance in left and right directions, so it cannot provide the balance in the

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sense of a self-balanced robot. Later, Wang Tianmiao, and Su Baiquan from the University of Aeronautics and Astronautics, Beijing, studied the kinematic mechanism and path planning of Essboard [13][14][15]. However, they did not study the self-balance of Essboard further.

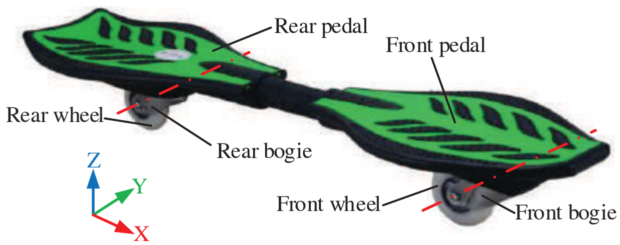


Fig. 1. A commercial version of Essboard.

In conclusion, although many scholars have studied Essboard, there is still a lack of research on its balance control so that at present, it cannot be developed into a self-balanced two-wheeled mobile robot. To solve this problem, this paper studies the motion mechanism of Essboard, decomposes its motion, and decouples its balance control and motion control for the first time. Further, a two-wheeled self-balanced mobile robot, named the Essbot, without auxiliary supporting wheels, is developed, and it is shown in Fig. 4.

II. CONCEPTIONAL DESIGN

The Essboard is a special entertainment and transportation tool. Its flexible structure and sports form make it applicable to various sports and entertainment types. Therefore, it is challenging and interesting to develop it into a two-wheeled self-balanced mobile robot, and compared with the traditional two-wheeled self-balanced mobile robot, Essbot developed from Essboard has better flexibility and more motion forms (e.g., winding forward).

The control problem of a two-wheeled self-balanced mobile robot relates to the two aspects, "balance," that is, the attitude control, and "motion," that is, the trajectory control. Although the Essboard is an incomplete and underactuated system, its attitude balance and trajectory are still controllable and operable. By observing and analyzing the operation of people who are riding Essboards, it is found that the movement of Essboard can be decomposed into a balance in left and right directions and a movement in front and back directions.

A. Basic Principle of Attitude Balance Control

As presented in Fig. 1, the two wheels of the Essboard are arranged in the front and back directions, so it has inherent stability in the front and back directions and instability in the left and right directions. Further, it can be found that the motion of Essboard in the left and right directions (i.e., along the $z-y$ plane) can be equivalent to the inverted pendulum model, as shown in Fig. 2(a). Inspired by the fact that acrobats keep balance by rotating the balance rod in their hands while walking on a wire rope, we design an inertial flywheel device to adjust the balance of Essboard in both left and right directions, as shown in Fig. 2(b). By adopting the inertial flywheel device, we achieve the self-balance of Essboard for the first time, and further develop it into a two-wheel self-balanced robot without auxiliary supporting wheels, named the Essbot.

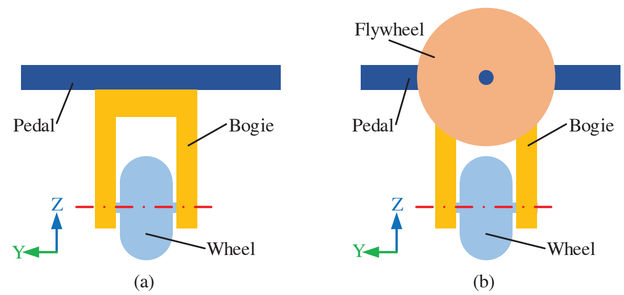


Fig. 2. Balance control of the Essbot.

The Essbot's attitude in the left and right directions can be controlled by adjusting the rotation of the inertial flywheel. Further, the balance control principle can be explained by Newton's third law. Namely, when the Essbot's attitude increases in the left or right direction, the inertial flywheel can be accelerated by controlling the motor fixed on the pedal to drive the inertial flywheel in the inclined direction, which means that the pedal imposes a moment in the inclined direction on the inertial flywheel. Meantime, according to Newton's third law, the inertial flywheel also imposes a moment on the pedal which is equal in size but opposite to the tilt direction, which counteracts the Essbot's tilt and restores it to balance.

B. Basic Principle of Motion Trajectory Control

We study the problem of the Essbot's motion control, that is, the control of its travel speed and direction, as shown in Fig. 3.

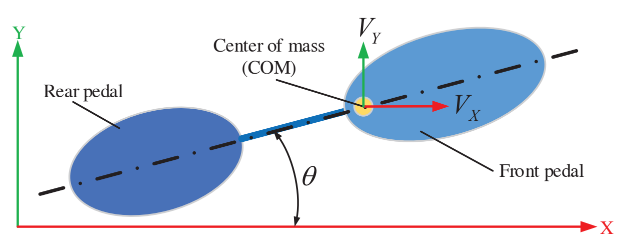


Fig. 3. Motion control of the Essbot.

It is worth mentioning that Essboard is a non-holonomic constraint and underactuated system. Its two wheels do not have power, and they represent driven wheels. By observing and analyzing the operation of rider riding Essboard, it can be found that the regular twist of the pedal is the key to realize Essboard's motion, and the relative twist angle between the front pedal and the rear pedal is the key to adjust Essboard's turn. To sum up, the motion speed and direction of the Essbot can be controlled by regularly controlling the rotation angle of Essbot's pedal.

III. SYSTEM DESIGN

According to the Essbot design concept described in Section II, the specific design of the Essbot is introduced in this section. It mainly includes the design of its mechanical, electrical, and control systems.

A. Mechanical System

The mechanical design of the Essbot should ensure that the mechanical structure and mass distribution are reasonable enough to meet the main requirements of self-balanced control. The Essbot we designed is shown in Fig. 4.

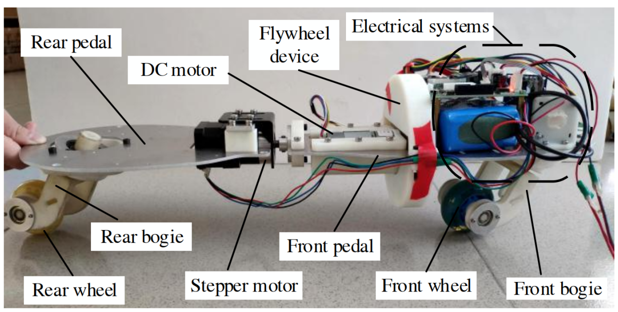


Fig. 4. A self-balanced Essboard-like mobile robot – Essbot.

The Essbot's movement in the front or back direction is achieved by controlling the pedal to rotate according to specific rules, while the balance attitude in the left and right directions is mainly controlled by controlling the rotation of the inertial flywheel. It should be noted that in order to prevent the fast-rotating flywheel from harming people, a protective cover is designed.

In theory, the inertial flywheel device that adjusts Essbot's balance in both left and right directions can be installed on either front pedal or rear pedal. However, considering that in future, the corresponding environmental sensors such as depth cameras or lidars can be installed on the Essbot to enable it to have environmental awareness function to achieve an automatic obstacle-avoidance driving, we install the inertial flywheel on the front pedal.

B. Electrical System

According to the requirements for the Essbot's control, the corresponding electrical system is designed, and it is shown in Fig. 5. The MCU is the main component of the electrical system. It is mainly responsible for calculating the control quantity of each motor so that the output of each motor can meet the balance and movement requirements of Essbot. The IMU is installed on the front pedal to detect the inclination of the front pedal in real-time and transmit the measured data to the MCU. The wireless communication module is responsible for the wireless communication between the MCU and a host computer, that is, it either receives the control commands or data from a host computer or transmits the Essbot related data to the host computer.

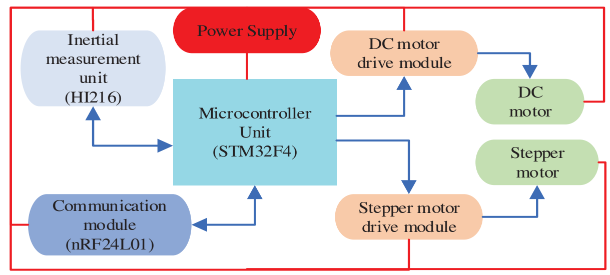


Fig. 5. The electrical system of the Essbot.

In order to make the electrical system more suitable for the Essbot's function and size, the PCB board is designed and welded as the Essbot's main board, as shown in Fig. 6.

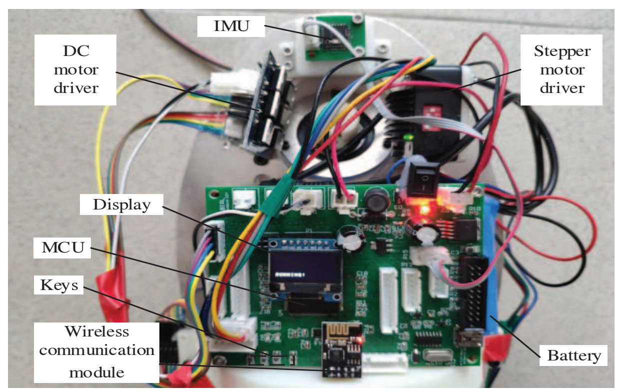


Fig. 6. The PCB motherboard of the Essbot.

C. Control System

The Essbot's control system is shown in Fig. 7. In Fig. 7, the host computer as an upper level is responsible for providing the man-machine interface, data and control command input, and other functions. The MCU as an intermediate layer runs the main control program, which mainly includes reading the control commands (e.g., turning or advancing) and data (e.g., PD controller parameters) sent by the upper computer. By calculating the attitude data measured by the IMU and executing the balance and motion algorithms, the motor control quantity of the balance and motion control is calculated, and the corresponding control quantity is output to the motor control module. The bottom layer is each executive unit, including the motors.

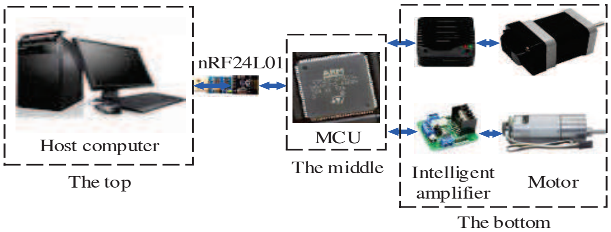


Fig. 7. The control system of the Essbot.

IV. ESSBOT CONTROL

In Section II, the problems of balance control in the left and right directions and motion control in the front and back directions of the Essbot are solved by motion decomposition. In this section, specific control methods are described.

A. Balance Control

The key problem of the two-wheeled self-balanced robot is balance control. According to the motion analysis that is presented in Section II and the mechanical structure design of the Essbot that is presented in Section III, the balance of Essbot is to keep the inclination of Essbot's front pedal in the horizontal plane near to 0°.

In order to control the Essbot balance, the deviation angle of the Essbot's front pedal from the horizontal balance position is considered as a deviation, and the deviation is kept close to zero by the negative feedback control. Specifically, the magnitude and direction of the acceleration of the flywheel are controlled by measuring the angle deviation and angular velocity of the front pedal, and then the magnitude and direction of the torque of the front pedal are controlled to achieve the balance control of the front pedal. The schematic diagram of the balance control of Essbot is shown in Fig. 8.

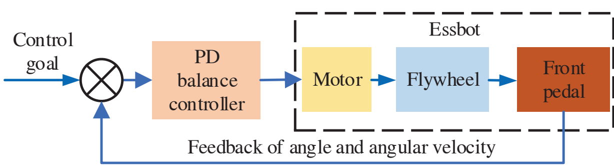


Fig. 8. The schematic diagram of the Essbot balance control.

B. Motion Control

Based on the analysis provided in Section II, to control the Essbot's motion is to control the pedal's angle regularly. The tilt angle of the Essbot's front pedal is controlled by the flywheel device, and its angle is maintained near 0°. Therefore, the Essbot motion control can be achieved by regularly controlling the angle of the rear pedal relative to the front pedal. The control law of rotation angle of the rear pedal is set to:

$$\phi_{RearPedal} = Asin(2\pi/T * t) + B \tag{1}$$

where A is the amplitude (degree), T is the period (s), and B is the average of oscillation (degree).

Based on the riding experience of Essboard, B determines the direction of the Essbot's movement. When $B = 0$, Essbot keeps straight, when $B < 0$, Essbot turns clockwise, and when $B > 0$, Essbot turns counterclockwise.

V. SIMULATION

According to the above, we designed a new two-wheeled self-balanced mobile robot named the Essbot. However, tuning the parameters of the Essbot's PD balanced controller in practice is a challenging and experienced task. Therefore, we verified the correctness and effectiveness of Essbot and the proposed control methods using virtual prototyping technology. In the near future, we plan to use a physical prototype of the Essbot to verify the correctness and effectiveness of our work.

ADAMS is a professional commercial software developed for the simulation and analysis of mechanical systems, and it has excellent and professional virtual prototype simulation and analysis capabilities. Using ADAMS, we build a virtual Essbot prototype to simulate and analyze it, and the built model is shown in Fig. 9.

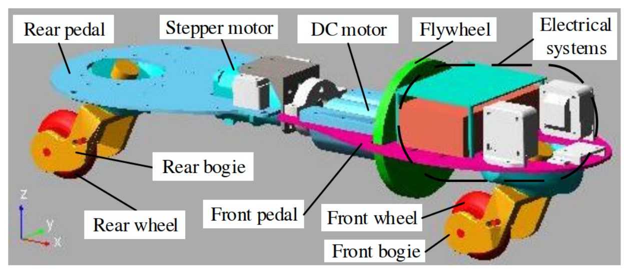
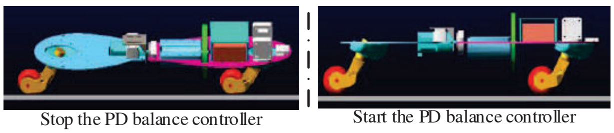


Fig. 9. The Essbot model built using ADAMS.

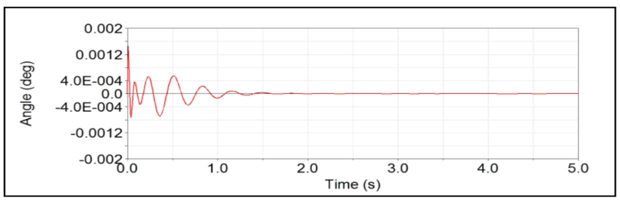
A. Balance Control

According to the method for Essbot balance control that is presented in Section IV, the PD controller was designed in ADAMS. The input of the PD controller was the deviation of the angle of the front pedal relative to the balance position and its angular speed, and the output was the torque of the motor driving the flywheel.

The Essbot balance control included two situations: (1) the angle of the rear pedal relative to the front pedal remained 0°, that is, $\phi_{RearPedal} = 0$; (2) the angle of the rear pedal relative to the front pedal changed according to a certain rule. In case (1), we first kept the angle between the rear pedal and the front pedal at 0°, then the Essbot balance controller was started, and the inclination of the front pedal was measured in real-time. The simulation results are shown in Fig. 10, where it can be seen that using the PD balance controller, the tilt angle of the front pedal was kept stabile near the balance position of 0°. In case (2), we first set the angular motion law of the rear pedal as $\phi_{RearPedal} = 20 * sin(2\pi/1 * t)$, and then run the PD balance controller and measured the inclination of the front pedal in real-time. The simulation results are shown in Fig. 11, where it can be seen that using the PD balance controller, the inclination angle of the front pedal was also kept stable near the balance position of $0°$.

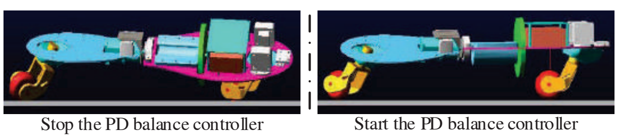


(a) Attitude of the Essbot

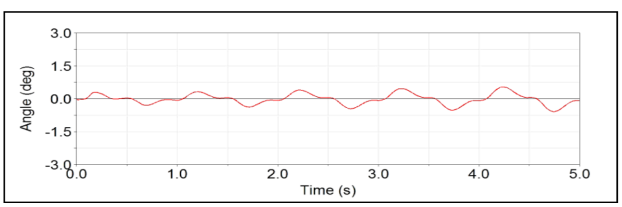


(b) Inclination of front pedal

Fig. 10. Balance simulation of the Essbot in case (1).



(a) Attitude of the Essbot



(b) Inclination of front pedal

Fig. 11. Balance simulation of the Essbot in case (2).

The simulation results prove the correctness and validity of the flywheel balanced device and the proposed balance control method, which can well control the Essbot balance in the left and right directions.

B. Motion Control

According to the motion control method proposed in Section IV, while keeping the Essbot balance, we can control the Essbot's motion by controlling the rotation law of the rear pedal.

Setting the rotation law of the rear pedal to $\phi_{RearPedal} = 20sin(2\pi/1 * t) + 0$, that is, $B = 0$, the Essbot was winding forward, as shown in Fig. 12(a). Further, by setting the rotation law of the rear pedal to $\phi_{RearPedal} = 20 * sin(2\pi/1 * t) - 5$, that is $B < 0$, the Essbot was turning clockwise, as shown in Fig. 12(b). Lastly, by setting the rotation law of the rear pedal to $\phi_{RearPedal} = 20 * sin(2\pi/1 * t) + 5$, that is $B > 0$, the Essbot was turning anticlockwise, as shown in Fig. 12(c).

The simulation results presented in Fig. 12 show that the proposed Essbot motion control method is correct and effective. Thus, the Essbot's motion can be controlled by controlling the rotation of the rear pedal.

VI. INFLUENCES OF CONTROL PARAMETERS

This section mainly studies the influence of different control parameters in Eq. (1), namely, parameters A, T, and B on the Essbot's motion.

The analysis was based on the control law given by Eq. (1). First, we set T to 1 s and B to $0°$, and then we studied the influence of A on the forward speed of Essbot by changing its value; the obtained results are shown in Fig. 13(a). Then, we set A to $20°$ and B to $0°$, and then studied the influence of T on the forward speed of Essbot by changing its value; the results are shown in Fig. 13(b). Finally, we set A to $20°$, and T to 1 s, and then studied the influence of B on the turning radius of Essbot by changing its value; the results are shown in Fig. 13(c).

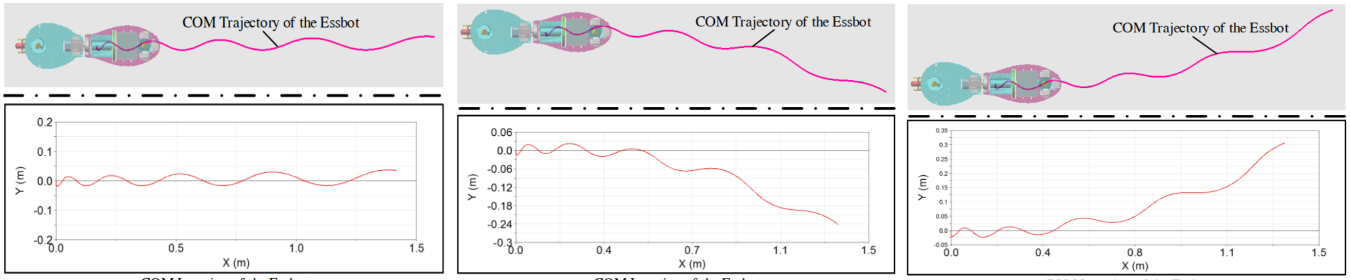
As can be seen in Fig. 13(a), the Essbot speed in the forward direction along the x-axis increased with the increase in the value of A when A was in the range $0 \sim 35°$. In Fig. 13(b), it can be seen that the Essbot speed in the forward direction along the x-axis decreased with the increase in cycle T when T was in the range $1 \sim 1.6$ s, that is, it increased with the increase in the pedal rotation frequency. In Fig. 13(c), it can be seen that the turning radius of Essbot increased with the increase in the average amplitude B when B was in the range $0 \sim 5°$. Therefore, based on Eq. (1), the forward speed of Essbot can be controlled by adjusting the value of parameters A and T, whereas the turning radius can be controlled by adjusting the value of parameter B.

It is worth mentioning that the simulation parameters were set such that to be in agreement with the rider's riding skills and experience in the actual operation of Essboard, which further proves the correctness and effectiveness of the developed Essbot and the proposed control methods.

VII. CONCLUSIONS AND FUTURE WORK

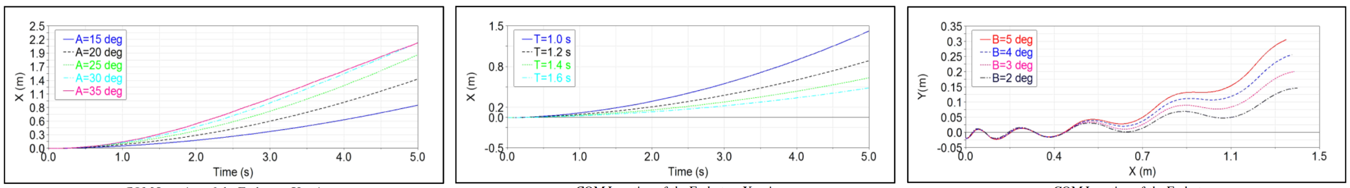
In this paper, by studying the motion mechanism of Essboard, its motion is decomposed into a balance in the left and right directions and a movement in the front and back directions for the first time, and the design concept of Essbot is put forward. On this basis, a two-wheeled self-balanced mobile robot named the Essbot is developed, and its balance and motion control methods are introduced. Furthermore, the influence of different control parameters on the Essbot's motion is studied.

Thus, this paper realizes the motion decomposition and self-balanced control of the Essboard for the first time, and



(a) Winding forward (b) Turning clockwise (c) Turning anticlockwise

Fig. 12. Motion simulation of the Essbot.

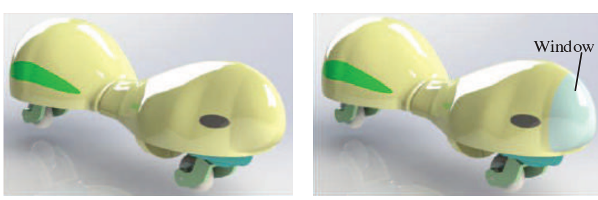


(a) Forward motion (b) Forward motion (c) Turning motion

Fig. 13. Influences of control parameters.

further develops it into a new two-wheel self-balanced mobile robot, named the Essbot, and realizes its balance and motion control. The presented research results denote significant progress in the field of wheeled self-balanced robots and Essboard.

In the future, we will optimize the structural design of the Essbot and install environmental sensors on it to equip it with the obstacle-avoidance driving ability. By the way, our ultimate goal is to transform the Essbot into a new multi-functional two-wheeled self-balanced mobile robot, which is shown in Fig. 14.



Without environmental sensors With environmental sensors

Fig. 14. Future Essbot.

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