Conceptual Design of Spherical Vehicle System for Future Transportation

Chun-Hsien Ho, Chen-Kai Wu, Jia-Ying Tu, and Shang-Kai Hsu
Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan
Email: {steveho183532, markwu0410, shangkaihsu}@gmail.com, jytu@pme.nthu.edu.tw

Abstract*—A conceptual design of spherical vehicle system for future transportation is proposed and experimentally verified in this paper. This uses the concepts of rolling motion, spherical structure, change of center of gravity and dynamic stability to realize planar locomotion. Modern wheeled automotive designs, which rely on sophisticated steering systems and multiple wheels to make physical contact with ground, inevitably increase the total weight and degrade the energy efficiency. In addition, the current designs of skeleton and body shell are relatively vulnerable to lateral impact, endangering the passengers' safety in accidents. Thus, the proposed design completely removes the wheel and tire devices: a spherical shell is used as the vehicle body for locomotion. Additionally, a pendulum device is developed for the purpose of steering and balancing. Ideally, the spherical structure can release the impact energy in a more rapid and even way in a collision, improving the vehicle safety; the pendulum mechanism can reduce the mechanical complexity and improve transmission efficiency. A prototype of the vehicle system and the associated remote control systems using the Arduino units are developed. Numerical and experimental studies are presented to demonstrate the proposed concepts.

***Index Terms*—spherical robot, future transportation system**

I. Introduction

Many modern automotive systems use wheel and tire devices to make physical contact with ground in order to realize in-plane motion and maintain stability. In addition, the all-wheel steering mechanism and chassis structures are important in order to take control of the wheels, transfer mechanical energy and achieve directional change. However, the lateral mobility of the vehicle is constrained by the wheel kinematics; the tires can provide with traction for turning but also result in the loss of mechanical energy. In addition, the modern automotive systems rely on sophisticated steering systems to connect and transfer power energy to wheels and tires. However, the complicated mechanical mechanisms and frames usually inevitably increase the weight and degrade energy efficiency.

In terms of safety issue, the existing designs of skeleton, body shell and chassis of wheeled vehicles are relatively vulnerable to lateral impact, sometimes resulting in significant shell deformation and endangering the passengers' safety in traffic accidents. This issue is hardly to be improved because the automotive exterior and interior designs are significantly constrained by the all-wheel framework.

Figure 1. The monowheeledrobot of[1]

Figure 2. Thediwheeled vehicle of[2]

Considering future transportation systems beyond current designs, mono wheel vehicle [1] ordiwheel vehicles [2], single-wheel robots [3]-[5], and cylindrical robots [6] are developed. Two examples of the references are presented in Fig. 1 and Fig. 2. The mono wheel and diwheelvehicle systems show the common advantages that the wheel and tires devices are enlarged and become the main body frames. In this way, the steering mechanism is simplified and power consumption during locomotion is minimized. However, the mono wheel device is relatively difficult to control and stabilize. Although the diwheel vehicle provides better stability, the lateral mobility may require further improvement.

The above observation on the existing automotive systems motives a possible new vehicle design in this paper. This uses the combined concepts of rolling motion, spherical structure, change of center of gravity and

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dynamic stability to develop a spherical vehicle. The concept can be similar to the design of spherical robots, e.g., [7]-[9]; their work may emphasize more on the functionality of exploring, monitoring and entertainment. In the long term, the development of spherical vehicle is transportation-oriented, and thus the energy consumption, safety, robustness and strength of the mechanical structures and control systems will be very important.

The next section of this paper will introduce the mechanical design of the spherical vehicle prototype, followed by the introduction to the control system development based on the Arduino devices and PI techniques. The third section conducts the ADAMS numerical simulation in order to validate the proposed mechanism. System identification and implementation results will be shown in the fourth section. Finally, the conclusion of this work is provided.

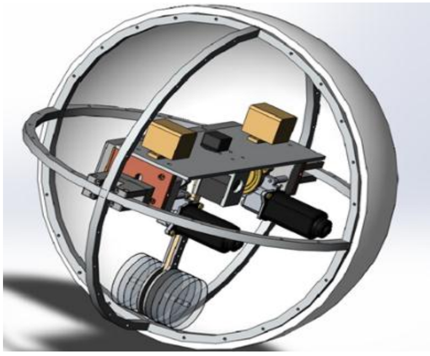

Figure 3. The scheme of the spherical vehicle system.

Figure 4. The rig of the spherical vehicle system.

II. The Design of Spherical Vehicle System

The proposed scheme of the spherical vehicle system is illustrated in Fig. 3, including an exterior spherical shell acting as the main body and functioning like a three-dimensional flywheel. A pendulum device for the purpose of balancing and steering is added, and an interior platform equipped with power devices and three servo motors is installed. Fig. 4 shows the prototype of the vehicle rig. The detail mechanical and control system design are introduced in the following subsections.

A. Conceptual Design

Compared with wheeled vehicle systems, which depend on multiple wheels and tires to maintain in-plane stability and to achieve forward/backward locomotion, the proposed vehicle is equipped with a spherical shell as the exterior structure; the planar wheel/tire devices are completely removed and only a single point is in contact with ground. Accordingly, assuming that the exterior spherical shell is ideally rigid relying on no traction force, the system is rendered to be neutrally stable, such that the required locomotion energy can be minimized without the energy loss due to overcoming the static friction and dynamic traction. In addition, on facing unwanted collision, ideally assuming an elastic collision, the impact force at any point can be dissipated via free rotation of the vehicle and spread around the entire spherical structure rapidly and averagely, avoiding significant local deformation; this improves the safety design.

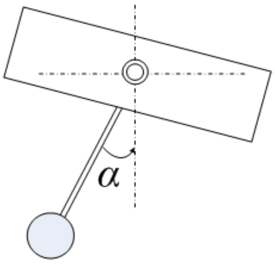

Figure 5. The platform front view to show the pendulum vibration angle.

Furthermore, because the exterior design is based on a neutrally-stable spherical structure, the vehicle can be driven and steered with higher mobility via a straightforward concept of altering the interior center of gravity. The engine/motor systems are mounted to the vehicle center platform in line with the spherical axis; thus, complicated transmission components are unnecessary. Here, pendulum devices are added to the vehicle interior space, which function like dynamic balancers and a steering system. When the vehicle tends to roll and lose the stability, the pendulum vibrations can provide inertial force to cancel the kinetic energy. This concept is similar to the ideal of [10]. However, in comparison with the work of [10], an more positive objective of the pendulum design in this study is to achieve active steering control. When the pendulum is oscillated with a certain angle α, as shown in Fig. 5 for example, which change the center of gravity of the vehicle body, directional change can be made rapidly and efficiently. Thus, the steering and stabilization purposes are met simultaneously via a common and straightforward mechanism. Promisingly, the pendulum-type steering mechanism would reduce the complexity of the interior mechanical design, providing omnidirectional mobility and promote the energy transmission efficiency, which are hardly to be achieved by current automotive designs.

B. Mechatronics and Control system design

According to the aforementioned ideas, the conceptual spherical vehicle rig is illustrated and developed in Fig. 3 and Fig. 4, respectively. Here, the entire spherical shell is made by combining two hemispherical shells, which are fixed to a two- ring-cross frame. Two of the intersection points of the frame are in connection with two electric servo motors via revolute joints, which provide torque to rotate the spherical shell. An interior rigid platform is also connected to the frame, with all the motors, control units, sensors and batteries fixed to it. Underneath the platform, a servo motor and a pendulum device are installed; this motor controls the pendulum vibration angle. At present paper, only a pendulum is considered for the purpose of demonstration and an initial investigation. In future work, the multiple pendulum steering-balancing system will be considered.

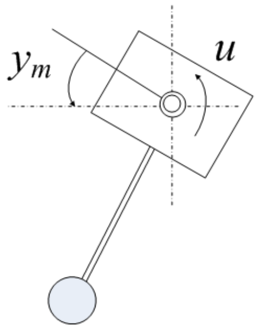

Figure 6. The platform lateral view to show the measuredtilting angle and motor Speed signals.

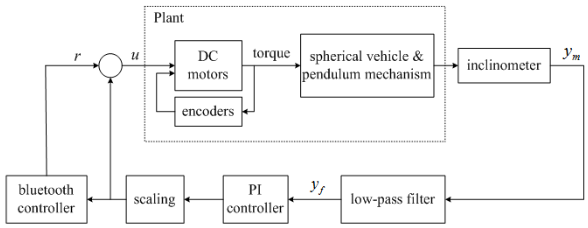

Figure 7. Control block diagram of the spherical vehicle.

The vehicle control system is realized by using Arduino boards to modulate the motor speed and torque. The motors have their own encoders and built-in controllers. In addition, an inclinometer is attached to the center of the platform to provide feedback signals of the tilting/rocking angle, denoted as *ym* and shown in Fig. 6. The control block diagram of the spherical vehicle is collectively depicted in Fig. 7.

During the test, the measured inclinometer signal, *ym*, is sent back to the Arduino-based control system. Because the ym signal inevitably includes high-frequency sensor noises, a low-pass filter is applied, which preserves the main low-frequency response characteristics and remove the high-frequency noise effects. The filtered inclinometer signal is labeled *yf* in Fig. 7. A general form of low-pass filter in Laplace domain is written as

$$y_f = \frac{\omega}{s+\omega} y_m \tag{1}$$

where s is the Laplace variable and ω determines the cut-off frequency. In order to realize the filter design using the Arduino units, (1) is transformed to discrete domain as follows

$$y_f(k) = a y_m(k-1) + y_m(1-a) \tag{2}$$

where a is given by

$$a = e^{(-\omega T)} \tag{3}$$

In (2) and (3), k denotes the number of time step and T represents the sampling interval.

The classical PI algorithm is applied to modulate the motor speed. Here, the control equation in continuous-time domain is given by

$$u(t) = K_P y_f(t) + K_I \int_0^t y_f(\tau) \mathrm{d}\tau \tag{4}$$

where KP and KI are the proportional and integral gains, respectively. The control objective is to maintain the motor speed during forward rotation while the platform remains horizontal. Thus, the stabilization of the platform position can be classified as a regulation problem, i.e., the rocking angle should be zero. Accordingly, the gains are directly multiplied by the feedback signal *yf* and (4) is transformed to discrete form as follows

$$\begin{aligned} u(k) &= r(k) + u(k-1) + \\ &K_P y_f(k) + K_P y_m(k-1) \end{aligned} \tag{5}$$

where r is the reference signal of the motor speed and u is the discrete control signal sent to the motor in proportional to the speed. Equation (5) is coded to the Arduino system for control implementation. The on-line signals *yf* is fed back to the Bluetooth device, such that the remote user can on-line adjust the reference signal.

III. Simulation Validation

This section uses the commercial software ADAMS to valid the design and investigate the vehicle dynamics for parameterization. The ADAMS model of Fig. 8 includes three main components: a partial spherical shell, a platform and a pendulum system. The platform plus pendulum devices are presented in Fig. 9 in detail, where the numerical torque is applied to the two ends of the platform to simulate the motor driving torque. In addition, a torque to vibrate the pendulum device and produce the oscillation angle α is also included in the study. From our simulation investigation, in the case of forward roll locomotion, the vehicle stability is constrained by the pendulum oscillation angle α. The pendulum vibration enables the entire vehicle to slide and tile with a certain angle to make turn. The weight and the original position of the center of gravity all affect the permissible maximal tilting angle of the vehicle. When the angle reaches the limit, the roll locomotion will become unstable and out of control. Therefore, the pendulum vibration control plays an important role on the steering stabilization Moreover, it is noticed that the platform generates reaction force in response to the motor torque and likely rocks the back and forth. In order to keep the platform stable and horizontal, sophisticated mechanical and control system design for modulating the center of gravity to counteract the reaction force should be considered. To this end, a preliminary controller is developed in (4) and (5). From the ADAMS simulation results, the main parts of the spherical vehicle mechanism are verified.

Figure 8. The ADAMS model of the entire spherical vehicle

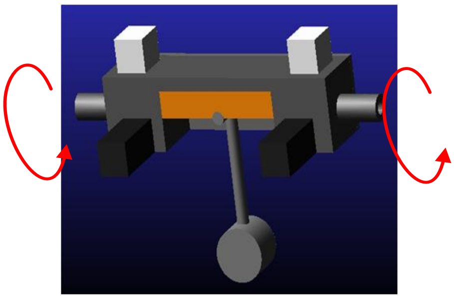

Figure 9. The platform and pendulum steering system.

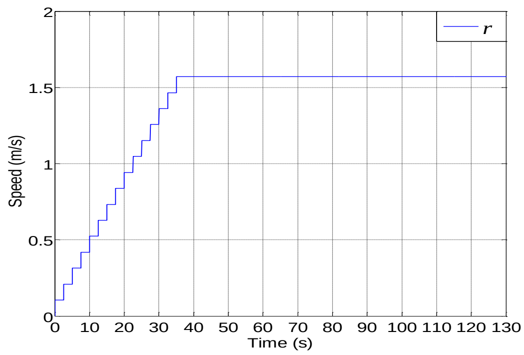

Figure 10. The ramped step reference signal of the motor speed.

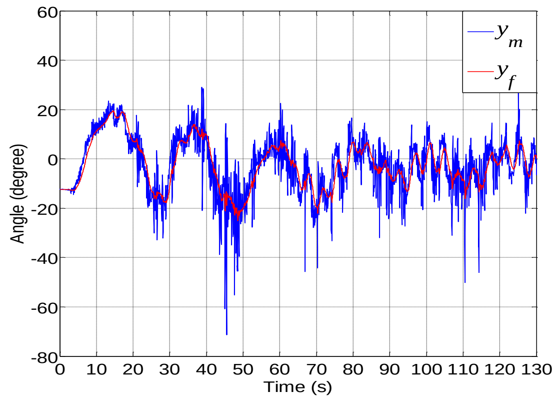

Figure 11. Comparisons of the inclinometer signals with and without filtering.

IV. Implementation Study

The system identification, synthesis of filter parameters and PI control gains and real-time experimental results are presented in this section. With an identification process and statistic computation in the Matlab environment, the low-pass filter parameters in (1)-(3) are determined as ω = 30 rad/sand a = 0.97, while $T = 0.001$ s is set to the Arduino controller. In the identification test, step-function reference signals are sent to the two main motors, which are proportional to the motor speed. An initial ramp of 35s is given in order to ensure smooth and stable locomotion in the settling state. The testing time span is set to 130 s. According to the mentioned experimental setting, the reference signal r is drawn in Fig. 10 and the corresponding uncontrolled responses are displayed in Fig. 11. The two signals, y_m and y_f, are compared, showing that the low-pass filter design effectively obviated the high-frequency noise and preserved the important dynamic information at low frequencies.

On the basis of the input and output data in Fig. 10 and Fig. 11, the transfer function between the motor speed and platform tilting angle was identified as

$$\frac{y_f(s)}{u(s)} = \frac{-8.56s^2 + 1.22s - 0.01}{s^3 + 0.88s^2 + 0.11s + 0.08} \tag{6}$$

exhibiting a third-order dynamic system. The frequency response of the spherical vehicle is presented in Fig. 12, which indicates a resonance frequency at about 0.3 rad/s and a low DC gain. According to the analysis of Bode diagram and root locus, the PI control gains are parameterized as K_P = 0.018 and K_I = -0.04. The control object is to reduce the rocking angle of the platform.

Fig. 13 compares the uncontrolled and PI-controlled implementation results, which are represented by the yf and yc signals, respectively. Here, the time after the 35th second is considered to be the steady state of the vehicle locomotion. In the uncontrolled case, the platform oscillated in the range of ±10° in the steady state. With the application of PI controller, the vibration was effectively reduced to ±5°. In addition, the platform vibration reaches to steady state in a more rapid way, as seen in the yc plot. However, it is also noted from Fig. 13 that the PI controller may excite the unwanted high-frequency dynamics of the system; a phenomenon that will require further attention in future control system design. In summary, the implementation work demonstrates: (i) the feasibility of the proposed spherical vehicle system; (ii) the effectiveness of using a control system design to counteract the reaction force due to the motor torque.

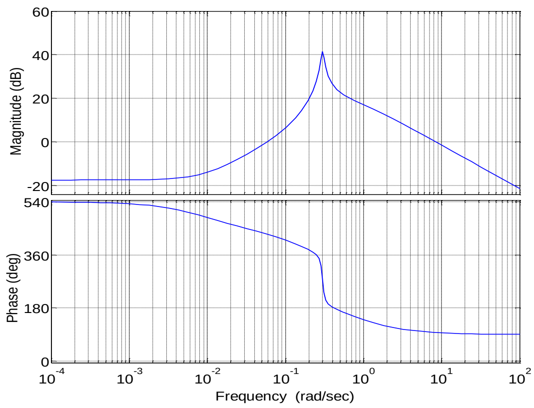

Figure 12. The frequency response of the spherical vehicle.

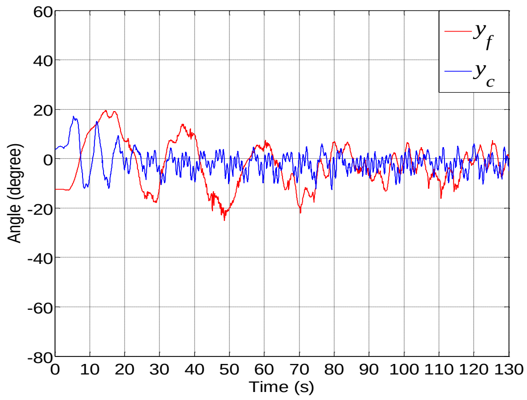

Figure 13. The uncontrolled and PI-controlled responses, showing that the PI controller effectively reduces the platform rocking angle.

V. Conclusion and Future Work

In this paper, a new design of future vehicle system is proposed and verified via numerical and experimental studies in this work. The new vehicle system uses the combined concepts of spherical structure, change of center of gravity and dynamic stability to realize the planar locomotion. A spherical shell is adopted for the exterior design, which is a part of the body structure and can be analogous to a three-dimensional flywheel. In this manner, the two-dimensional wheel and tire components are completely removed. In addition, a pendulum device is added to the vehicle interior space for the purpose of steering and stabilization

A prototype of the sphere vehicle is developed. The Arduino board, Bluetooth devices and tilt sensors are installed and integrated in order to form the remote feedback control systems. The control objective is to modulate the motor speed, thus achieving the desired vehicle locomotion while the interior platform remains horizontal and stable. Preliminary numerical studies verify the spherical and pendulum mechanisms; the implementation results also demonstrate the proposed mechanism and control systems.

In future work, the multivariable pendulum control system and the vehicle mathematical model will be developed. The pendulum controller aims at providing dynamic stability and rapid steering. The mathematical model is important for investigation into the critical stability and for the design of advanced control systems.

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Chun-Hsien Ho.was born in August in 1991 in Taiwan. He graduated from Department of Power Mechanical Engineering at National Tsing Hua University in 2014.
His current research interests include Robotics,modelingand identification of dynamic systems, and transportation.

Chen Kai Wu was born in May 1992in Kaohsiung, Taiwan. He graduated from Department of Power Mechanical Engineering at National Tsing Hua University in 2014.
His current research includes Robotics, transportations, automobile control systems, modeling and identification of dynamic systems, and embedded systems.

Shang-Kai Hsu was born in 1990 in Taipei, Taiwan. He graduated from Department of Power Mechanical Engineering at National Tsing Hua University in 2014.
His current research interests in mechanial design.

Jia-Ying Tu was born in Kaohsiung, Taiwan. She received the PhD degree in mechanical engineering from University of Bristol, UK in 2010. Since August 2010, she joined the Department of Power Mechanical Engineering at National Tsing Hua University, Hsinchu, Taiwan, where she is currently an assistant professor. Her research interests include dynamic analysis and design of dynamically substructured systems and control system applications.