Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

System Design and Balance Control of a Bipedal Leg-wheeled Robot

Chao Zhang[1], Tangyou Liu[1], Shuang Song[1]*, Max Q.-H. Meng[2], *Fellow, IEEE*

***Abstract*—The combination of wheels and humanoid robots is a promising way to improve the performance of bipedal robots in agility, moving speed, and energy efficiency. This combination enables the robot to move faster on flat ground, which can effectively improve the adaptability of the biped robot in application scenarios such as logistic distribution, inspection and home services. This paper introduces a 6-DOF bipedal leg-wheeled robot *SR600*, which has two actuated wheels at the end of the robot shanks, and achieves its balance and locomotion through wheel-driven approach. *SR600* is mainly composed of five parts: a waist, two thighs, and two shanks with wheels. It is modeled as a variable-structure wheeled inverted pendulum and we derived its kinematics model based on the center of gravity constraint. Control strategies for balance and locomotion of *SR600* are handled by proportional integral differential (PID) controllers. Finally, several practical experiments are conducted to validate the feasibility of the robot mechatronic system and the balance control strategies.**

***Index Terms*—bipedal leg-wheeled robot, robot design, balance control, velocity control.**

I. Introduction

As an important sub-class of legged robots, biped robots have been extensively studied to clarify the principles of human locomotion and manipulation, so as to make such kind of robots better serve humans in living environment. However, they have many inherent disadvantages, such as natural instability, poor flexibility, slow moving speed and low energy efficiency, which limit them from research fields to practical applications. Robots with driven wheels generally move faster and more efficient than legged locomotion on a continuous flat ground [1]–[3]. Therefore, many studies have tried to combine wheels with bipedal robots to overcome some shortcomings of humanoid robots [4]–[6]. These bipedal leg-wheeled robots have the potential to demonstrate a better performance in agility, moving speed and energy efficiency that makes them more suitable for indoor and outdoor inspection and logistics distribution tasks.

[1]Chao Zhang, Tangyou Liu, Shuang Song are with School of Mechanical Engineering and Automation, Harbin Institute of Technology(Shenzhen), Shenzhen, China, 518055.

[2]Max Q.-H. Meng is with Department of Electronic Engineering, the Chinese University of Hong Kong, Hong Kong, China, and affiliated with the State Key Laboratory of Robotics and Systems (HIT), Harbin Institute of Technology, China.

*Corresponding author: Shuang Song, mail: songshuang@hit.edu.cn

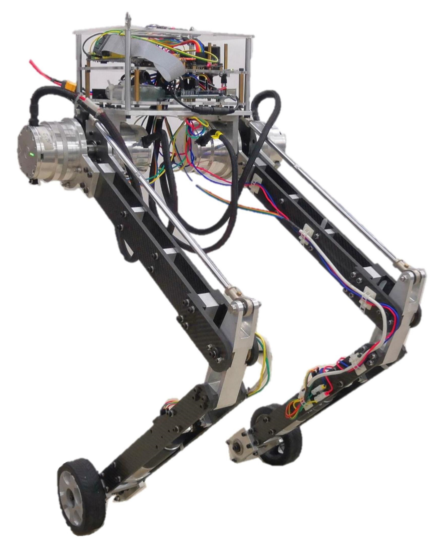


Fig. 1. Current prototype of our bipedal leg-wheeled robot *SR600*.

Robots that combine wheels and legs are common to see while wheels combined with humanoid robots are not too many [7]. In 1998, Osamu Matsumoto in Japan developed a biped type leg-wheeled robot with the ability to negotiate the stairs dynamically [8]. In the 2015 DARPA Robotics Challenge, a humanoid robot called *DRC-HuBo* attached two driving wheels to its knee and two passive wheels to its foot, and it can move with its four wheels by the kneeling posture [9]. Boston Dynamics introduced *Handle* in 2017, a robot that used legs and wheels to provide highly agile and small-footprint material handing solution for logistics [10]. *Handle* has a powerful electro-hydraulic drive system and exhibits excellent mobility, but the hydraulic elements are less energy efficient and the robot is a little oversized (up to 1.9m in height), so it is not suitable for working in human settlement. The State Key Laboratory of Robotics and System in Harbin Institute of Technology also presented a hydraulic wheel-legged humanoid robot called *WLR* in 2018, *WLR* is 1.6m tall and has 16 actuated degree of freedoms, it is highly inspired from *Handle* and has achieved the abilities of ground moving, squatting, picking up the box and avoiding obstacle [11]. As far as we know, *Ascento*, a two-wheeled

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

jumping robot developed by ETH Zurich is the most similar to our *SR600* in structure. It used topology optimized leg mechanism to decouple stabilizing and jumping control and can navigate quickly on flat surfaces and pass over obstacles by jumping [12]. However, it is difficult for the robot to negotiate continuous obstacles such as stairs, meanwhile the size of robot is too small (less than 660mm in height) that makes it lack of interaction with people.

In our work, we have developed a compact and lightweight bipedal leg-wheeled robot named *SR600* and conducted some research on it. *SR600* is a 6-DOF robot that consists of five parts and achieves its balance and locomotion through wheel-driven approach. Four high power density motors with precision absolute encoders are installed at the hip of the robot to control the movement of the hip and knee joints. The driving wheels at the end of the shanks are actuated by two DC brush motors. In terms of robot control, we modeled the robot as a variable structure wheeled inverted pendulum [13] and used PID control method to achieve the balance control of the robot in a specific pose.

In the rest of this paper, we first describe the design of robot mechatronics system including mechanism and hardware in section II. Next, the kinematics model of the robot based on the center of gravity constraint is derived in section III. After that, in section IV, we introduce the control strategies used for balance. In section V, we verify the feasibility of system design and the balance control effect through multiple experiments. Finally, we summarize this article and briefly introduce the future work.

II. Mechatronics System Design

A. Mechanism

The robot is designed to be used in application scenarios such as logistics distribution, inspection and home services. Therefore, its dimensions are selected with reference to the proportion of the human leg [14], which can achieve complete squatting and when it fully extends its knee joints, the height of the robot can reach about 900mm. *SR600* is mainly composed of five parts: a waist, two thighs, and two shanks with actuated wheels at the end. It is a 6-DOF robot, each hip and knee joint are actuated by a joint servo motor and each wheel is actuated by a DC brush motor. This configuration allows the robot to balance itself dynamically and locomote quickly on a flat ground by means of wheels, and changes the height of the robot by the hip and knee joint motors. The design speed of the robot is about 1.5m/s which is capable of meeting most indoor movement requirements. According to the design principle of making the robot compact and lightweight, the entire mechanical structure is completed, as shown in Figure 2.

The waist is mainly equipped with two hip joint motors and most of the robot hardware like IMU, battery, motor drivers and controller boards. The hip joint motor can drive the thigh

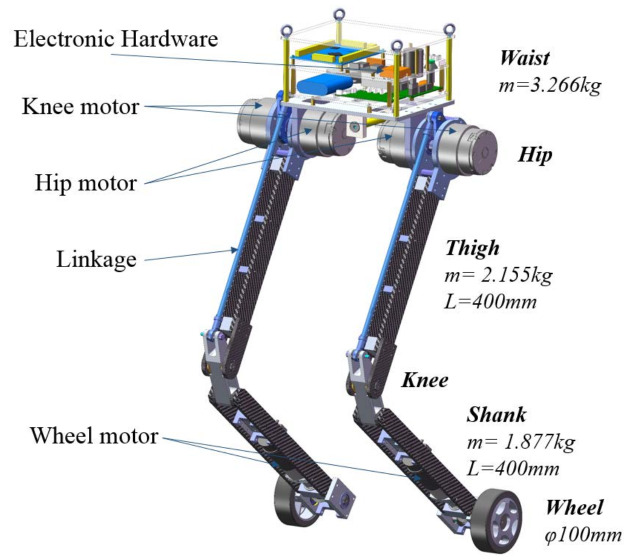


Fig. 2. The CAD model of the robot.

to rotate relative to the pitch axis. On each leg, the knee joint motor is installed opposite to the hip motor, and transmits the power to the knee joint through a four-bar linkage mechanism (Figure 3a) to realize the flexion and extension movement of the knee joint. This transmission mechanism design has the functions to make the center of mass (COM) of the robot closer to the waist and reduce the inertia of the legs. The knee joint revolute pairs use copper alloy graphite bushing instead of the traditional rolling bearings, which helps to reduce the size of the knee joint and improve its ability to withstand radial forces. The driving wheel is installed at the end of the shanks by leg-wheel-fusion type [15], and a 90W DC brush motor is arranged along the shank. The power of the motor is transmitted to the bevel gear through the coupling and finally outputs to the wheel which makes the shank has a compact structure,as shown in Figure 3b.

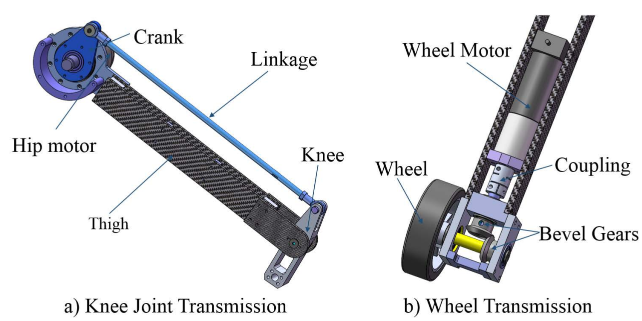


Fig. 3. Knee joint and wheel transmission mechanism of the robot.

In the mechanical design, we use a large number of carbon fiber sheets and aluminum alloy materials, and the key parts under high stress are made of materials such as steel and copper alloy to ensure sufficient strength and rigidity of the robot as well as light weight (the actual weight of the robot is about 11kg). The main structural parameters of the robot are listed in Table I:

TABLE I
PHYSICAL PROPERTIES OF THE ROBOT

Category	Value	Unit
Initial height	300	mm
Max width	900	mm
Waist width	350	mm
Thigh length	400	mm
Shank length	400	mm
Wheel diameter	100	mm
Mass	11	kg
Max speed	1.5	m/s

B. Hardware

In the selection of the hip and knee joint actuators, we use the virtual prototype simulation tool SolidWorks Motion [16] based on the ADAMS dynamics solving engine to simulate the torque and velocity of these joints. The knee joints usually work in a bended condition, which requires the motor to provide sufficient holding torque. According to the simulation results, we select the INNFOS QDD-6010-64 joint motor with 500W rated power and rated torque up to 40Nm. The motor uses a two-stage planetary gear reducer with a reduction ratio of 64, yet it only weights 0.72kg and has a certain back drive capability. Besides, the joint motor integrates a precision encoder and has built-in control modes such as torque, speed and position and supports controller area network (CAN) bus communication.

The wheel driving motor requires the ability to balance and drive the robot; that is, the motor should provide sufficient power and torque to meet the designed speed (1.5m/s) and minimum acceleration (2.5m/s^2) requirements. In addition, the wheel driving motor and the transmission mechanism should be able to withstand frequent direction changes and acceleration of the wheels and have small rotation backlash to improve the control response performance. So, we chose the RM35 DC brush motor with a gear reducer of 16 reduction ratio and a 500-line photoelectric encoder; moreover, we selected an appropriate driver for the wheel motor, which controls the motor through the logic IO and PWM inputs.

A 6-axis inertial measurement unit (IMU) is mounted at the waist of the robot to measure the waist posture as well as the tilt angle of the robot. The robot uses a control board based on STM32F407 as the main control unit, processing the main computational tasks for the robot. It mainly undertakes CAN communication with the joint motors, generates PWM signal to control the wheel motors, collects and processes data from sensors, and finishes the calculation of feedback control algorithm. The IMU is mounted on the waist and connected to an Arduino Mega 2560 by inter-integrated circuit (I2C) interface. The Arduino runs a program to process the original data from IMU by Kalman Filter algorithm and transfers the final data to the STM32 master through the serial port in real time. In addition, we have added a high-speed Bluetooth module for wireless communication between the robot and the external PC to monitor the state of the robot and control it remotely. The list of robot hardware is as follows:

TABLE II
HARDWARE OF THE ROBOT

Name	Specifications
Joint motor	INNFOS QDD-6010-64
Joint motor hub	INNFOS HUB
Wheel motor	DJI RM35
Wheel motor driver	Mini Balance WSDC2412D
Main controller	QMXX STM32F407ZGT6
IMU	Mini Balance GY-521
Microcontroller	Arduino Mega 2560
Bluetooth module	DOFLY LY-BL001
Battery for control circuit	MCOBEAM 12V 3200mAh 3S
External power supply	MEANWELL RSP-3000-48

The control circuit of the robot uses a 12V Li-ion battery to provide needed power. Up to now, we utilize an external power supply(48V3000W) to provide power for motors which need high current. It ensures that we can do experiments continuously without considering about charging battery frequently.

The hardware connection diagram of SR60 is shown in the figure bellow.

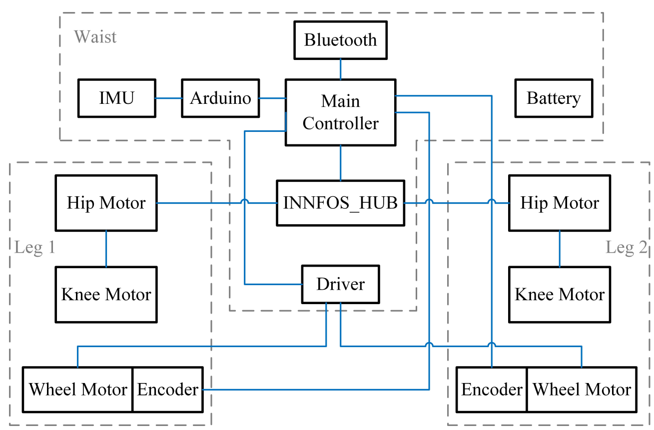


Fig. 4. Hardware connection diagram of the robot.

III. KINEMATICS MODELING

As our bipedal leg-wheeled robot has actuated motors on its hip and knee joints and we assume that the left and right joints move synchronously, we can abstract the robot as a structurally variable wheel inverted pendulum (WIP) model [17]. At one hand, we should derive the pose of each link relative to the base frame of reference by means of forward kinematics modeling method, and then calculate the position of the center of mass (COM) of the robot using the multibody

COM equation [18]. At another hand, according to the WIP static balance constraint, the vertical projection of COM position of the robot should locate at the axes of the two drive wheels, we can calculate the required joint angles under the giving robot height.

A. COM Calculator

In order to derive the COM position and the tilt angle of the robot, we first give the general formula to calculate COM of a multi-body system.

$$X_{full-body}(q) = \frac{\sum m_i X_i^w(q)}{\sum m_i} \tag{1}$$

Where $X_{full-body}(q)$ indicates the COM of the robot (except for two wheels) relative to the base frame in current pose q, and q is a vector about the joint angles. m_i stands for the mass of the *i-th* link. $X_i^w(q)$ denotes the COM position of *i-th* link relative to the base frame in pose q and it can be calculated by multiplying the links transformation matrix and the COM position of each link in its local frame, that is

$$X_i^w(q) = T_i^w(q) X_i^i. \tag{2}$$

For getting the transformation matrix of the robot, we established the reference coordinate system. The base frame $\{0\}$ is attached at the midpoint of the line segment connecting the two driving wheel centers, and the waist frame $\{4\}$ at the center of upper surface of the waist.

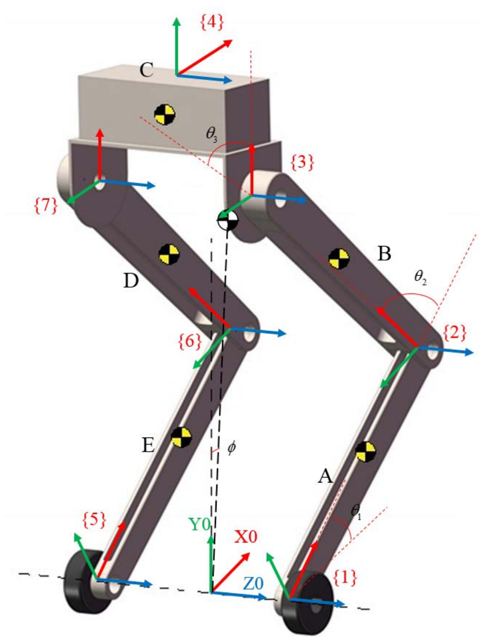


Fig. 5. Schematic diagram of the robot coordinate system.

According to the structural parameters of robot links, we can list the Denavit-Hartenberg (D-H) parameters of the robot [19]. The D-H parameters describe the pose relationship of adjacent links by four parameters, wherein the link length a, the link twist α, the link offset d and the joint angle θ. According to the robot CAD model, the D-H parameters is shown in table III.

TABLE III
D-H PARAMETERS OF *SR600*

i	$\alpha_{i-1}\,(^\circ)$	$a_{i-1}\,(mm)$	$d_i\,(mm)$	$\theta_i\,(^\circ)$
1	0	0	$a/2$	θ_1
2	0	L_1	0	θ_2
3	0	L_2	$-b/2$	θ_3
4	0	L_3	$-c/2$	-90

In the table III, a denotes the distance between two driving wheels, b the shoulder width at $\{3\}$, and c the waist width. The individual transformation matrix of each link is obtained by the transformation matrix formula of the adjacent links; further, we can get the transformation matrix of each link relative to $\{0\}$. Among them, ${}^0_4T$ denotes the waist frame $\{4\}$ relative to the base frame $\{0\}$.

$${}^0_4T = \begin{bmatrix} s_{123} & c_{123} & 0 & L_1c_1 + L_2c_{12} + L_3c_{123} \\ -c_{123} & s_{123} & 0 & L_1s_1 + L_2s_{12} + L_3s_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Next, we measure the mass of each link and the COM position relative to its local frame. Substituting the measured results into equations (1) and (2), we can solve the robot COM position $[p_x, p_y, p_z]$ relative to the base frame.

$$X_{full-body}(q) = \frac{m_A{}^0X_A + m_B{}^0X_B + m_C{}^0X_C + m_D{}^0X_D + m_E{}^0X_E}{m_A + m_B + m_C + m_D + m_E} \tag{4}$$

From the equation above, the COM position $[p_x, p_y, p_z]$ is a vector with respect to the robot current pose q, and the tilt angle of the robot can be obtained as

$$\phi = \arctan(p_x/p_y). \tag{5}$$

B. Balance Inverse Kinematics

In III-A, we have obtained the COM position and the tilt angle of the robot, which makes it possible to adopt proper control strategies to eliminate the tilt angle and achieve balance. Next, we focus on the problem that by giving the pose of the waist relative to base frame, how to solve out the desired joint angles satisfying the wheel inverted pendulum (WIP) static balance constraint. It is of great significance for controlling the twist to reach a specified pose.

When the WIP is dynamically balancing, the COM of the robot (exclude the wheels) should satisfy the balance constraint; that is, the COM should lie right above the wheel axis and make the tilt angle of the robot

$$\phi = f(\theta_1, \theta_2, \theta_3) = 0 \tag{6}$$

In addition, we want to keep the waist of the robot in a horizontal position so that we can easily install some additional equipments such as manipulator on it in the future. So, we introduce a second constraint for the robot pose.

$$\theta_1+\theta_2+\theta_3=\pi/2 \tag{7}$$

We also want to control the robot waist to a specified height h; that is, the vertical distance from frame $\{4\}$ to frame $\{0\}$ equals to h.

$$L_1s_1+L_2s_{12}+L_3s_{123}=h \tag{8}$$

From above three equations, we can get the joint angles θ_1, θ_2, θ_3 satisfying the WIP static balance constraint and the desired waist pose. For our robot, θ_2 and θ_3 can be actively controlled by the knee motor and the hip motor; but θ_1 is the angle of the shank relative to the horizontal plane, which is underactuated. A straightforward idea is to eliminate the bias between the target θ_1 and the actual measured value by PID operation to achieve balance of the robot. However, considering the inconvenient installation of the IMU on the calf, we chose to mount the IMU on the waist. According to the geometric relationship, the angle measured by the IMU is equal to the tilt angle of our robot. Therefore, we can directly measure the tilt angle of the robot by the IMU, and eliminate the tilt angle bias to achieve the balance of the robot at a given height.

IV. Balance Control

SR600 replaces the feet of a bipedal robot in traditional sense with two actuated wheels. In this paper, we mainly focus on the balance control as well as locomotion of this type of robot, thus introducing the advantages of wheeled motion into bipedal robots. The wheel-driven locomotion control of the robot can be mainly decomposed into two problems - balance control and velocity control. The overall structure of control system is shown in Figure 6.

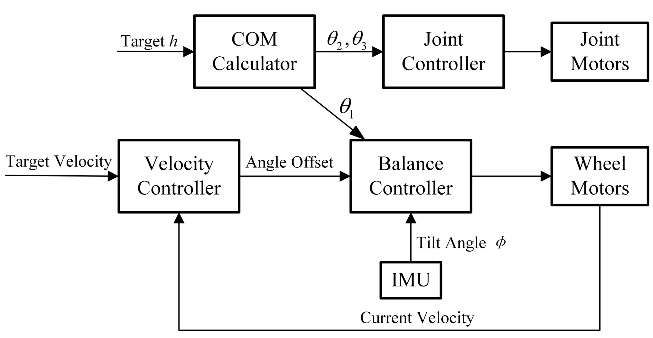


Fig. 6. Diagram of the control system.

A. Balance Controller

As a two-wheeled robot is inherently unstable, achieving self-balance is the basis for the robot to implement other tasks. At present, we have achieved the balance control of our bipedal leg-wheeled robot based on the PID control strategy. From the derivation in section III, we modeled the robot as a variable structure wheeled inverted pendulum and the robot should put its COM right above the wheel axis to keep its balance. The height of the robot waist h is a variable and we want the waist orientation always keep horizontal. When giving a specific height h, we can calculate the desired joint angles θ_1, θ_2, θ_3 satisfying the balance constraint. The tilt angle of the robot ϕ can be directly measured by the IMU according to the geometry relationship between the COM position and the pose of robot waist. Then, we can use proportional differential (PD) controller to eliminate the tilt angle bias to achieve the balance of the robot.

According to our hardware, the output torque of wheel motor is nearly proportional to the voltage applied to it by motor driver, and we can adjust the voltage by changing the PWM duty cycle added to motor driver.

B. Velocity Controller

After realizing the balance control of our robot, we designed a velocity controller to control the speed of the robot. The velocity controller is implemented by a cascade PID strategy. That is, the balance controller is placed in the inner loop of the velocity controller to ensure the priority of the balance control, and the speed is controlled by changing the target tilt angle of the balance controller. When we set a target speed for velocity controller, the velocity controller will transform the input velocity value into a specific tilt angle and send it to the balance controller, then the balance controller will actively drive the robot to keep the given tilt angle, which leads to the robot move at the target speed.

The velocity controller has another important function. When the robot carries an unknown load or the IMU has an installation error, there will be an error between the actual COM position and the calculated or measured one. If only the balance controller is used, the robot may get out of control due to the error. After adding the velocity controller, when the robot tends to drift due to the COM position error, the velocity PI controller can effectively eliminate the influence of the error by calculating a new balance inclination, making the system more robust and reliable.

V. Experiments

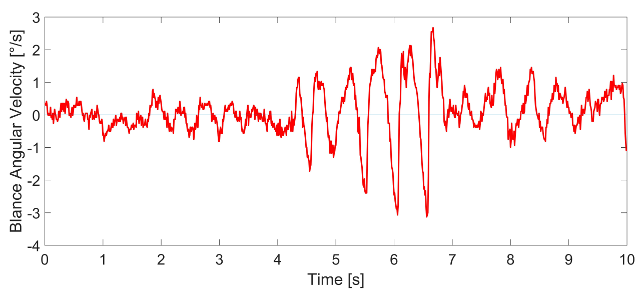
This section introduces several balance control experiments carried out on the robot prototype to test the rationality of the *SR600* mechatronics design and the performance of the control strategies.

In the experiment, we selected three different robot waist heights, and realized the balance control of the robot(Figure 7) by adjusting the balance PD and velocity PI parameters. When only the balance controller was used, we found that the robot had the trend to balance but hardly to stand for a long time. However, when we added the velocity controller to the system and set the target velocity equal to zero, the robot balanced well. Besides, we also found that the PID parameters were not sensitive to the height change.

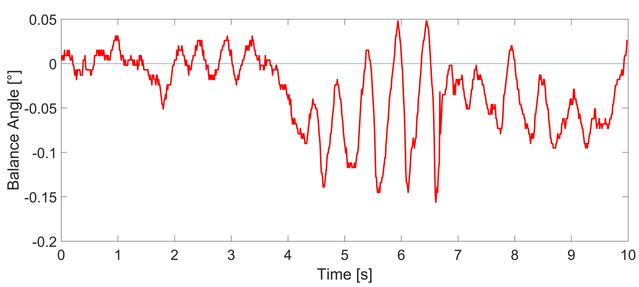
We recorded the balance angle and angular velocity of the robot in Figure 7b, and the results are shown is Figure 8. From the curves, we can see that the balance angle and angular velocity fluctuate around 0; when we added an external disturbance in 4s, the robot was able to quickly restore balance.

(a) (b) (c)

Fig. 7. *SR600* achieved balance at 3 different heights.



(a) Balance angle



(b) Balance angular velocity

Fig. 8. Balance angle and angular velocity of the robot.

VI. Conclusion

In this paper, we presented a bipedal leg-wheeled robot *SR600* which aims at improving the speed of traditional biped robot on the flat ground by installing actuated wheels at the end of the shanks. The mechatronics system of the robot has proved to be stable, compact and lightweight. We designed the PID controller based on the kinematics model and achieved balance control of the robot in actual experiments which further validated the feasibility of the system design and the control strategies. In the short term, we plan to further optimize the mechatronics system and adopt more optimized control method to realize the wheel-driven locomotion control of the robot. The long-term goal is to add feet to the robot so that it has two kinds of locomotion modes - navigating by wheel on flat ground and negotiating obstacles by foot - which makes bipedal leg-wheeled robot truly an all-terrain mobile robot.

References

[1] S. Jeong and T. Takahashi, "Stable and quick standing-sitting motion of i-pentar by whole-body motion with force control," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2008, pp. 199–204.

[2] M. Stilman, J. Olson, and W. Gloss, "Golem krang: Dynamically stable humanoid robot for mobile manipulation," in *2010 IEEE International Conference on Robotics and Automation*. IEEE, 2010, pp. 3304–3309.

[3] D. Ruiken, J. P. Cummings, U. R. Savaria, F. C. Sup, and R. A. Grupen, "ubot-7: A dynamically balancing mobile manipulator with series elastic actuators," pp. 676–682, 2017.

[4] O. Matsumoto, S. Kajita, and K. Komoriya, "Flexible locomotion control of a self-contained biped leg-wheeled system," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3. IEEE, 2002, pp. 2599–2604.

[5] Ascento. Accessed: 25.09.2019. [Online]. Available: https://www.ascento.ethz.ch.

[6] S. Chen, J. Rogers, B. Zhang, and K. Sreenath, "Feedback control for autonomous riding of hovershoes by a cassie bipedal robot," *arXiv preprint arXiv:1907.11353*, 2019.

[7] B. Siciliano and O. Khatib, *Springer handbook of robotics*. Springer, 2016.

[8] O. Matsumoto, S. Kajita, M. Saigo, and K. Tani, "Dynamic trajectory control of passing over stairs by a biped type leg-wheeled robot with nominal reference of static gait," *Journal of the Robotics Society of Japan*, vol. 16, no. 6, pp. 868–875, 1998.

[9] J. Lim, I. Lee, I. Shim, H. Jung, H. M. Joe, H. Bae, O. Sim, J. Oh, T. Jung, S. Shin *et al.*, "Robot system of drc-hubo+ and control strategy of team kaist in darpa robotics challenge finals," *Journal of Field Robotics*, vol. 34, no. 4, pp. 802–829, 2017.

[10] Handle. Accessed: 25.09.2019. [Online]. Available: https://www.bostondynamics.com/handle.

[11] X. Li, H. Zhou, H. Feng, S. Zhang, and Y. Fu, "Design and experiments of a novel hydraulic wheel-legged robot (wlr)," pp. 3292–3297, 2018.

[12] V. Klemm, A. Morra, C. Salzmann, F. Tschopp, K. Bodie, L. Gulich, N. Küng, D. Mannhart, C. Pfister, M. Vierneisel *et al.*, "Ascento: A two-wheeled jumping robot," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 7515–7521.

[13] S. Jeong and T. Takahashi, "Wheeled inverted pendulum type assistant robot: inverted mobile, standing, and sitting motions," in *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2007, pp. 1932–1937.

[14] M. Kouchi, M. Mochimaru, H. Iwasawa, and S. Mitani, "Anthropometric database for japanese population," *Japanese Industrial Standards Center 1997–98 (AIST, MITI)*, 2000.

[15] N. Eiji and N. Sei, "Leg-wheel robot: a futuristic mobile platform for forestry industry," in *Proceedings of 1993 IEEE/Tsukuba International Workshop on Advanced Robotics*. IEEE, 1993, pp. 109–112.

[16] K.-H. Chang, *Motion Simulation and Mechanism Design with SOLIDWORKS Motion 2019*, 2019.

[17] Z. Li, C. Yang, and L. Fan, *Advanced control of wheeled inverted pendulum systems*. Springer Science & Business Media, 2012.

[18] M. Zafar, C. Erdogan, K. Volle, and M. Stilman, "Krang: Center of mass estimation," Georgia Institute of Technology, Tech. Rep., 2014.

[19] J. J. Craig, *Introduction to robotics: mechanics and control, 3/E*. Pearson Education India, 2009.