2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Erect Wheel-Legged Stair Climbing Robot for Indoor Service Applications

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Abstract— **In this paper, an automatic erect stair climbing mobile robot is developed for indoor service applications. The design of high center of mass, tilt axis near ground, and the triangular wheel-legged structure enable the robot to climb stairs in a dynamic and self-balancing way. The wheel-legged mechanism also keeps the advantages of differential-wheeled mobile platforms when moving on flat ground, such as easy to control, saving power, and zero turning radius. Moreover, the overall mechanical design fits the requirements for a service robot to have proper height and small footprint, which can make human-robot interaction more natural and comfortable in indoor environment. Since the perceptual and control system of the robot are both well integrated, we successfully demonstrate the stair-climbing function and prove that the design and implementation of our work are feasible and efficient. As a result, the robot is expected to be a prototype of universal platform for indoor mobile service robots in the future.**

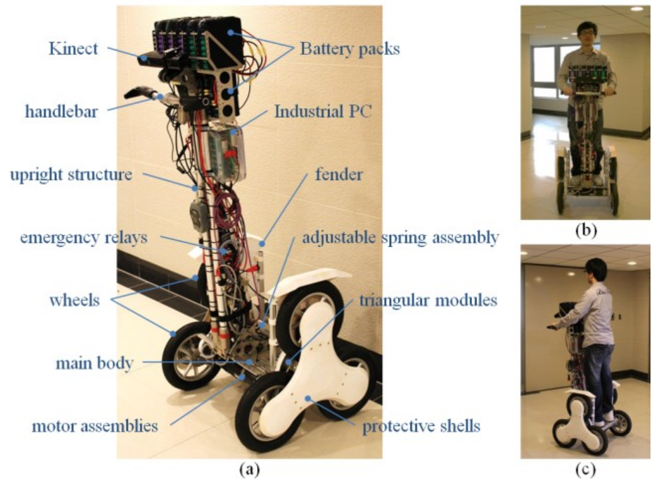

Fig. 1. The general structure of the erect stair-climbing robot and the robot with a human rider standing on it

I. Introduction

A. Motivation and Related Works

Since stair climbing is always a hot topic in robotics, various stair-climbing mechanisms, such as track-based [1][2], wheel-leg [3][4], or humanoid [5][6][7] solutions, are developed. However, for indoor service robots to perform tasks across floors, there are some requirements or limitations that those existed robot platforms cannot match. For example, to interact with human naturally, it is better for a service robot to have similar height as humans. And to move around indoor environment smoothly, the robot should have small footprint and high mobility. Unfortunately, those track-based stair-climbing robots usually lie on the floor, and the wheel-leg stair-climbing robots do not have small footprint or good mobility comparing to basic differential-wheeled platforms. Humanoid robots may be good solutions, but they are too complicated and waste much power for daily usages. Moreover, people would not like a service robot that can scratch or wear the edge of the steps while climbing stairs. As a result, we design a mobile robot (see Fig. 1) with proper locomotion and control strategy to meet all the requirements for stair-climbing service robots.

There are several advantages of our robot. First, the robot can rotate a pair of triangular-shaped structures, each with three power wheels, to ascend or descend stairs step-by-step. Second, the robot can travel on flat ground just like differential-wheeled platforms. Third, the robot is high enough to have natural interaction with people, while the footprint of the robot is also small enough to pass through normal doorways. Moreover, the robot is designed to either move around and climb stairs automatically, or carry a rider who can control the robot. This makes the robot not only an independent mobile platform but also an accessible vehicle that can help a person move around in indoor environment.

B. Structure of the Paper

In this paper, we focus on the design of the robot and the locomotion strategy to ascend stairs. Next section describes the basic ideas and analysis of the robot, which help us to design and implement the mechanism, electrical system, and control strategy of the robot in Section III. Section IV shows the experimental results of the robot ascending stairs with some discussions. Section V is conclusion and future works.

II. Locomotion of Ascending Stairs

A. Concepts

As shown in Fig. 2, the concept of the method of stair climbing locomotion is that the robot can rotate a pair of triangular module (cyan) to climb up stairs and keep balance at the same time. The active wheels (green) on the vertices

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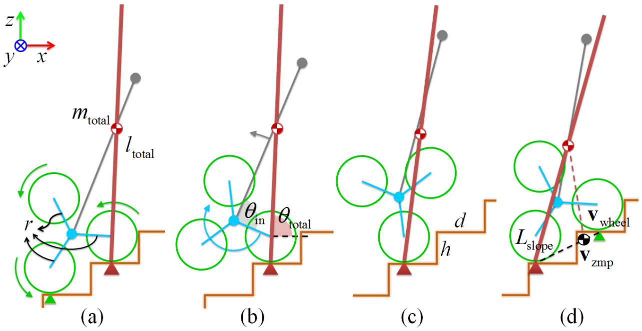

Fig. 2. The dynamic model of stair climbing locomotion

of the triangular module can adjust the position of the robot to the stair steps and also help keeping balance of the robot and the rider (if there is one).

B. Dynamics Analysis

Since the robot and its locomotion are both symmetric, analyzing the dynamics of the robot on the x-z plane is equivalent but simpler, just as shown in Fig. 2. Suppose the total mass of the robot (include the rider if there is one) can be regarded as an uniform mass stick (red bold line) with length l_{total} and mass m_{total}, the climbing process can be modeled as an inverse pendulum falling forward (on the x-z plane) with its fulcrum on the point of contact of the front wheel with the ground. The dynamics of the falling state can be shown as:

$$I_{\text{total}}\ddot{\theta}_{\text{total}} = -m_{\text{total}}g\frac{l_{\text{total}}}{2}\cos\theta_{\text{total}}, \tag{1}$$

where g is the gravitational acceleration constant, θ_{total} is the angle of the rod with respect to horizontal line, and I_{total} is the equivalent rotational inertia of the whole robot (also include the rider if there is one), which can be approximated as a rod of length l_{total} and mass m_{total} with axis of rotation at the end of the rod:

$$I_{\text{total}} = \frac{m_{\text{total}}l_{\text{total}}^2}{3} \tag{2}$$

Actually, I_{total} changes during the climbing procedure since the rotation of the triangular module increases l_{total} until $\theta_{\text{in}} = \pi$ and then decreases it along the climbing procedure. However, the effect help the robot to keep its stability and is too complicated to be analyzed easily. Therefore, we simply use a constant model to describe it. In this model, the x-position of the center of gravity x_{cog} is:

$$x_{\text{cog}} = \frac{l_{\text{total}}}{2}\cos\theta_{\text{total}} \tag{3}$$

The zero-moment point (ZMP) is a key indicator to analyze the balancing situation of an upright robot. Even though the ZMP of our robot during stair climbing cannot be precisely defined as normal biped robots walking on flat ground, we can adopt the idea of virtual ZMP on a virtual slope [7]. The virtual ZMP $\mathbf{v}_{\text{zmp}} = \begin{bmatrix} x_{\text{zmp}} & z_{\text{zmp}} \end{bmatrix}^\top$ is on the slope line $L_{\text{slope}} : z = k_{\text{slope}}x$, where $k_{\text{slope}} = h/\sqrt{3r^2 - h^2}$ is defined according to the distance r from the center of the triangular module to the center of any of the three wheels and the stair rise (height) h. More precisely, the virtual ZMP is the intersection point of the virtual slope line and the "zero-moment line" L_{zmp} [8], which can be shown as:

$$L_{\text{zmp}} : x_{\text{zmp}} = x_{\text{cog}} + \frac{\ddot{x}_{\text{cog}}}{\ddot{z}_{\text{cog}} + g}(z_{\text{zmp}} - z_{\text{cog}}), \tag{4}$$

where

$$\ddot{x}_{\text{cog}} = -\frac{l_{\text{total}}}{2}\ddot{\theta}_{\text{total}}\sin\theta_{\text{total}}, \tag{5}$$

$$z_{\text{cog}} = \frac{l_{\text{total}}}{2}\sin\theta_{\text{total}}, \tag{6}$$

and the acceleration on z-direction ($\ddot{z}_{\text{cog}}$) is regarded much smaller than g and thus its influence to the system can be ignored. We will verify that $\ddot{z}_{\text{cog}}$ has little influence on x_{zmp} in the following simulation.

Since the robot will keep falling if there is no other external force except the normal force and frictional force on the fulcrum, the triangular module has to rotate about $1/3$ circle to make the other wheel touch the higher step of the stair before the robot falls too much to bring itself back to a stable stand. As a result, the virtual ZMP has to be within the range of the touching point $\mathbf{v}_{\text{wheel}}$ of the other wheel with the next step to ensure the stability of the robot:

$$0 < \mathbf{v}_{\text{zmp}} < \mathbf{v}_{\text{wheel}} \tag{7}$$

$\mathbf{v}_{\text{wheel}}$ can be understood as a fixed planar "capture point" [9] and also calculated from the geometric structure of the robot and the stair:

$$\mathbf{v}_{\text{wheel}} = \begin{bmatrix} \sqrt{3r^2 - h^2} & h \end{bmatrix}^\top \tag{8}$$

As a result, the maximum possible rotational speed of the motor which can rotate the triangular module to the required angle in limited time should satisfy:

$$\frac{v_{\max}}{R_{gear}}t_{\text{goal}} > \theta_{\text{rot}}, \tag{9}$$

where R_{gear} is the total reduction gear ratio from the motor to the triangular module. The required time t_{goal}, which must fulfill (7), and the rotation angle θ_{rot} are based on the condition that the triangular module is able to turn and make the other wheel touch the next step of the stair (usually $\theta_{\text{rot}} \approx 2\pi/3$ when climbing normal stairs). However, in the real stair climbing process, θ_{rot} can be decided before each climb of a single step referring to the observation of the structure of the stair.

Moreover, the maximum torque $\tau_{\max}$ of the motor also have to fulfill:

$$\frac{\tau_{\max}R_{\text{gear}}\gamma_{\text{gear}}}{r} - m_{\text{total}}g = m_{\text{total}}\ddot{z}_{\max}, \tag{10}$$

where γ_{gear} is the power transfer ratio of the total reduction gear set. $\ddot{z}_{\max}$ is the largest of all $\ddot{z}_{\text{cog}}$, which usually occurs

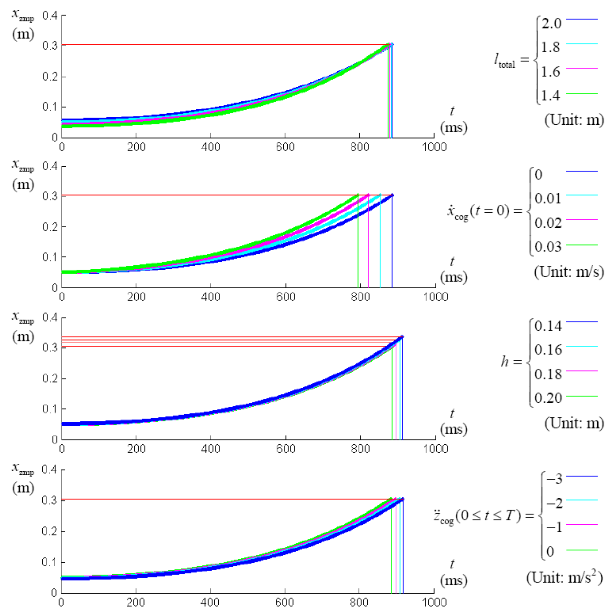

Fig. 3. Simulation results with different variation of parameters (Default: $l_{\text{total}} = 2.0$, $\dot{x}_{\text{cog}}(t=0) = 0$, $h = 0.2$, and $\ddot{z}_{\text{cog}}(0 \le t \le T) = 0$)

at the moment of start climbing, representing the required acceleration for the robot to lift itself and rise in a suitable and comfortable speed to climb stairs. As long as all the above constraints are satisfied, the robot is able to climb up stairs using some control strategies, which will be discussed in the next section.

However, some effects are ignored in the above analysis but should be discussed. First, even though the rotation of the triangular module seems to change the shape of the robot, it is actually an internal change that do not influence the rotary motion of the whole robot too much. That is, the equivalent tilt angle of the whole robot still generally follows the rules of an inverted pendulum. Second, since the above discussion is based on a simplified model, slight rotation of the wheels may be required to adjust the ZMP of the robot during the real ascending procedure.

C. Simulation

A simulation is done with various possible realistic parameter settings using MATLAB, and the results are shown in Fig. 3. $\theta_{\text{total}} = 88^\circ$ is set as the initial state, which can be controlled in the implementation. The red lines mark the x-position of x_{wheel} that the corresponding ZMP should not exceed. Curves with different colors represent different given l_{total}, initial $\dot{x}_{\text{cog}}$, h, and average $\ddot{z}_{\text{cog}}$ in each subfigure respectively, which are the four main changeable parameters in this system. We can find that initial $\dot{x}_{\text{cog}}$ influences the balance range drastically, but the variation of l_{total}, h, and $\ddot{z}_{\text{cog}}$ have little influence to the x-position of ZMP. Therefore, the robot must make sure of its initial speed before start climbing stairs. Also, since all the x_{zmp} stay within the stable range when $t < 700$ms, the average rotation speed of the triangular module during stair climbing have to be larger than $\frac{1/3}{0.7} \times 60 \doteqdot 29(\text{rpm})$.

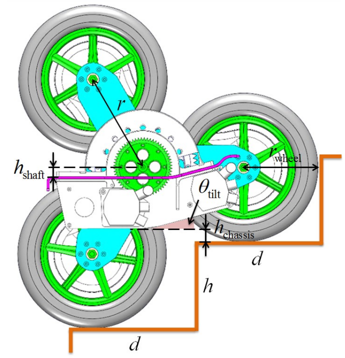

Fig. 4. Design constraints of the main body and the triangular modules

III. Implementation and Control Strategies

To realize the stair climbing locomotion method on an indoor service robot platform, we design every detail of the robot system, including hardware mechanism, actuators, power, sensor, control strategy, and human-robot interaction rules. Following are the description and explanation of how and why we design the robot on each aspect.

A. Mechanism Design

The exterior of the robot is similar to Segway PT [10] in some parts. A human rider can stand on the main body of the robot, where a pair of mechanism for traveling are placed at the two sides of it (see Fig. 1). An upright structure is fixed in the front of the main body with a rotatable handle on the top of it, making the rider easy to control the locomotion of the robot using hand and body motions. However, very different from Segway, the mechanism for traveling is two symmetric motor-driven rotational triangular modules, which enable the robot to climb stairs in a dynamic way. Both triangular modules have three identical and synchronized active wheels. Moreover, the upright structure has to support the computing device, some sensors, and batteries on the top of it. The heavy load on the upright structure not only makes the center of mass higher for the robot to change the position of its center of gravity easily while ascending and descending stairs, but also provides a high viewing point for Kinect to observe the environment like humans do. An adjustable spring assembly is also added to the upright structure so that the center of mass can be adjusted in advance, and the impact of the movement to the devices on the upright structure and the rider can be reduced.

The main body of the robot contains four motors (two for triangular modules and two for wheels) with reduction gears and an IMU in limited space. The structure of the main body is designed as in Fig. 4. For humans to ride a robot comfortably during balance keeping, the up surface plane of the main body for humans to stand on must lower than the rotation center of the triangular modules (h_{shaft}). Also, there should be enough flat area for a person to put his or her feet on. However, to climb up and down stairs, the chassis of the main body has to be high enough so that the main body

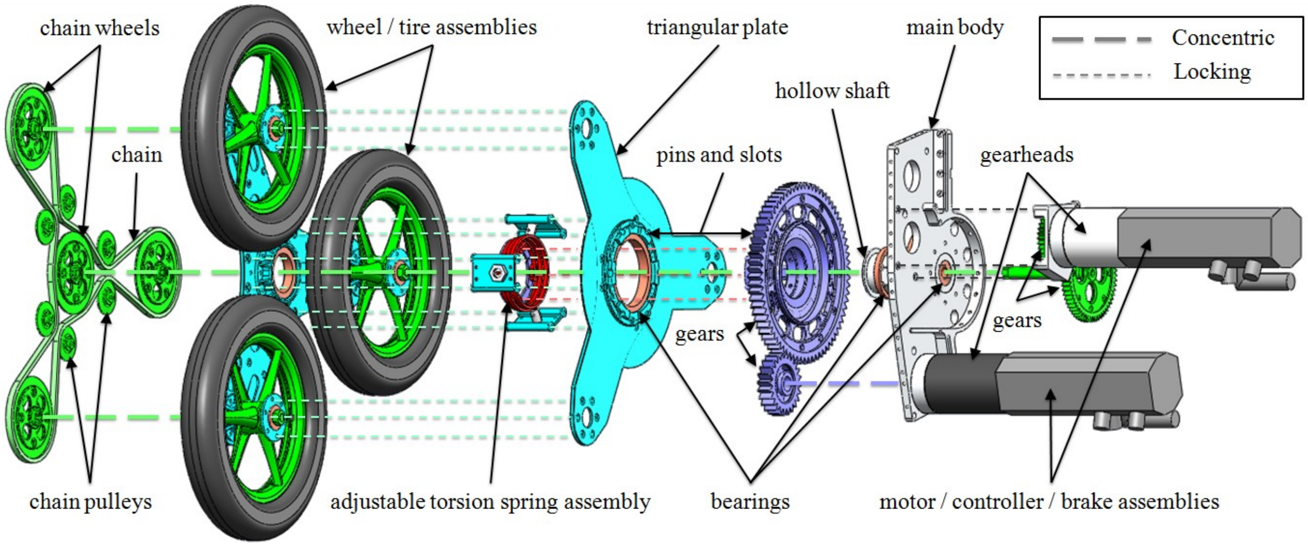

Fig. 5. Exploded diagram of the drive mechanism from bottom view

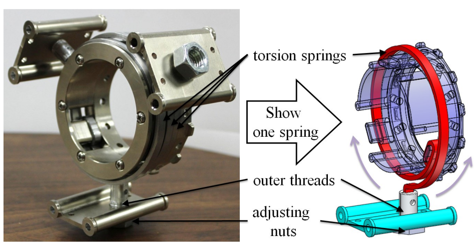

Fig. 6. The adjustable torsion spring assembly

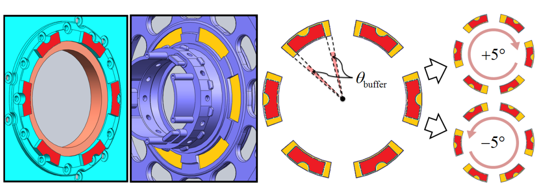

Fig. 7. The pin-and-slot mechanism

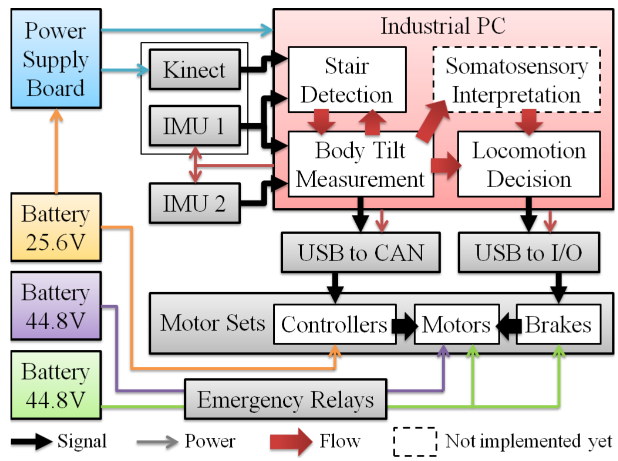

Fig. 8. Block diagram of system structure

would not knock into staircases during the climb (h_{chassis} and θ_{tilt}). Moreover, the triangular modules with the wheels have to match with general stairs, for which we follow the public building codes of our government, which are $h \leq 18$cm and $d \geq 26$cm, to design the size and shape of the triangular modules ($r = 21$cm and $r_{\text{wheel}} = 15.5$cm).

Fig. 5 shows one side of the mechanical transmission system which go over through the hollow shaft fixed on the main body of the robot. The purple, cyan, and red parts are the transmission mechanisms associated with the rotational triangular module, while the green parts are the transmission mechanisms associated with the wheels. Since the four chain wheels on the very left side are the same, pure rotation of the triangular module will not influence the rotation of the wheels, which means that the two motors can drive the triangular module or the wheels respectively and independently. However, in order to make the rider able to control the robot like Segway (using body tilt angles as control commands) and reduce impact, an adjustable spring assembly (see Fig. 6) and a pin-and-slot mechanism (see Fig. 7) are added into the transmission system of the triangular module. The combination of these two designs create flexibility to the drive of the triangular module within a limited range of $\pm 5°$, and their effects will be described later in this section.

B. System Structure

The main computing device of the robot is an industrial personal computer. Four motors with controllers, two inertial measurement units (IMU), and one Kinect are linked to the computer (see Fig. 8). In addition to the different kinds of batteries for the various devices, a special kind of C-LiFePO$_4$ battery, which is designed for high power applications, provides power to the two motors that drive the triangular modules to climb stairs. Following are the descriptions of the important devices.

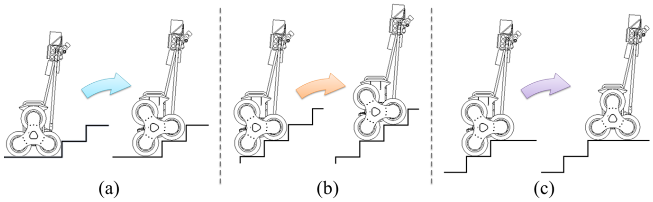

Fig. 9. Three types of procedures of ascending stairs

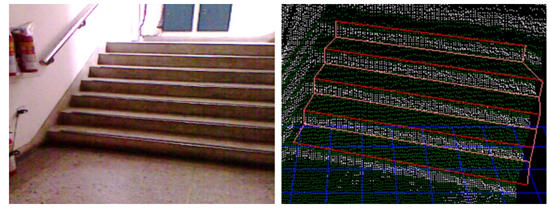

Fig. 10. Using Kinect to recognize and measure the stair

1) Motors: Four BG75CI motors manufactured by Dunkermotoren are used to drive the two triangular modules and two sets of wheels respectively. The selection of the motors follows the rules described in section II. Each motor integrates with controller (position and velocity control only) and encoder all-together and communicate through CAN interface. The motion commands are calculated in the computer and sent to the motors through a high speed USB/CAN converter.

2) Inertial Measurement Units (IMU): MotionNode IMU is an inertial measurement unit with a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer combined together. In the robot system, one IMU is placed in the main body, which is used to find the tilting angle of the robot as a trigger signal to start ascending stairs, while another is attached on the Kinect on the top of the upright structure, which can help to define the main direction of the point cloud data and simplify the algorithm to recognize stairs. The magnetometera are not used in this work at all.

3) Kinect: Kinect [11] is a popular sensor for robotics. Because of its robustness and real-time ability, it is used as our main sensor to recognize and measure stairs. By now, we only use the point cloud generated from the depth image for calculation. The Kinect is placed at the top of the upright structure and heading down a certain angle to cover the front view around the floor, which avoid its range limitation problem and ensure the observation of the nearby situation in the front.

C. Control Strategies

As shown in Fig. 9, the motion of ascending a single step can be divided into three main types: starting from flat floor (a), in the middle of a stair (b), and climbing up to another flat floor (c). Their basic principles are the same, but some control parameters and details are different. The start of (a) can be seem as in the path of (b), while the end of (c) needs extra time to rotate of the triangular module, which cannot assure the stability when the front wheels of the robot touch the flat floor. As a result, the wheel have to rotate forward to compensate the inevitable process. Because of the limitation of the experimental environment, we will only verify the first two types of climbing.

For each climb of a single step, the robot will observe the front view using Kinect and decide which type of climbing procedure should be taken. Once the robot leans forward enough (determined by the sensing results of the IMUs), the wheels on both side will rotate backward a little bit and then immediately the two triangular modules will rotate in the same maximum speed until they reach the target angle. Since the position and velocity control of the motors are available, we just have to design the velocity ramp of the motions of the motors and do not have to control the precise torques of the motors as long as the maximum torque of the motors are large enough to lift the robot and reach the required motion.

From the simulation results in section II, we know that the initial velocity can influence the balance of the robot a lot. As a result, the robot has to stand still before each climbing motion, in order to avoid the initial speed increase too much as the robot is leaning forward and falling.

Since the tires can absorb much of the impact when the robot reaches a new step, no any compliance force control methods are implemented in this work. However, they may be required for more complicated or challenging motions that we will test in the future.

D. Perception of Stairs

The Kinect is placed on the top of the upright structure and facing a certain angle downward to obtain sufficient view of the front terrain. Thus, a heuristic algorithm is developed to recognize and measure the stairs in indoor environment by analyzing the statistic characteristics of the point cloud data from Kinect. The main process of the method is to find the vertical direction of the point cloud sets through sampling and clustering the normal vectors of the 3D points, recognize horizontal planes with similar and reasonable spacing, and detect the near edge lines of the planes to measure the rises and runs of the steps and locate the position and orientation of the whole stair (see Fig. 10). Since the details of the algorithm are not our focus in this paper, we just regard this method as a real-time recognition tool that can measure a stair with error less than 0.5 cm.

IV. Experimental Results

A. Procedures

First, we measure the basic specifications of the robot and test some basic motions on flat ground, including moving forward, backward, and turning with zero radius, for which the robot needs to lean forward to put most of its weight on the front two wheels. And then, we demonstrate the function of climbing up stairs on its own. The testing stair is a normal indoor stair in the building of our laboratory, which matches with the public building codes of our government. In addition, since the testing of the robot climbing up stairs with a human rider can be

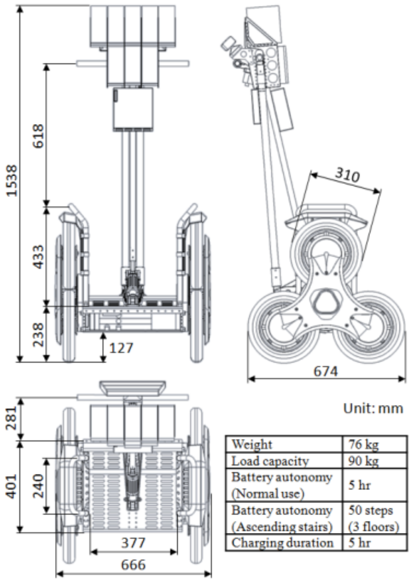

Fig. 11. The dimensions and specification of the robot

dangerous without proper protective measures, we will do the experiment after a specific experimental environment is well built for this robot.

B. Results

The dimensions and specification of the robot is shown in Fig. 11. The total width (about 67 cm) is small enough to pass through normal doorways (about 75 cm in width), and the robot is about the same weight as a person.

Fig. 12 shows the sequential photos of the robot climbing two stair steps on its own. The protective shells on both sides are taken away so that we can observe the transmission situation of the triangular modules and the wheels.

C. Discussions

From the experiment, we find out that the actual moment of inertia of the robot is larger than the rod model, which means that the climbing process is more stable than the simulation. However, the total climbing time of a single step of stair is less than 5 seconds, including the preparation action and the duration of back to complete stationary in the end, which is pretty fast comparing to other stair climbing platforms with similar size and weight. The average rotation speed of the triangular modules during ascending stairs is around 25 rpm, depending on the height of the stair. Last but not least, we also find that bouncy tires can disturb the balance if the robot. As a result, we do not pump the tires too much in the experiment.

V. Conclusions

In this paper, we design and implement an erect mobile robot system and successfully demonstrate its stair climbing ability. The experimental results also prove that the applied concepts and theories are feasible and efficient. Therefore, it is expected that more mobile robots will be integrated with this kind of locomotion system.

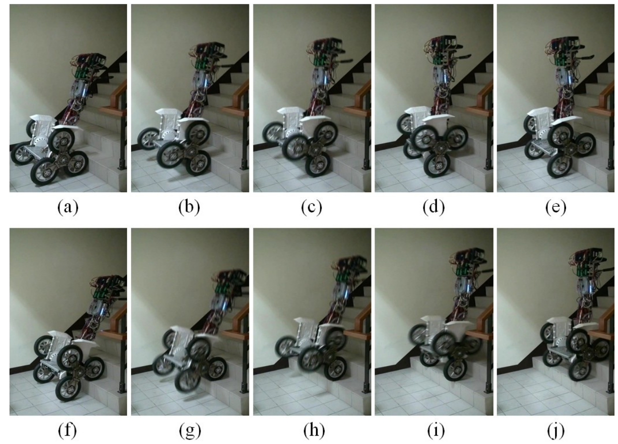

Fig. 12. The sequential photos of the robot climbing up a stairway

In the near future, we will build up a specific experimental environment that enables us to test more challenging motions of the robot under a safer situation, such as somatosensory control on flat ground, going up and down stairs, or even climbing spiral staircases or traveling on other complicated uneven terrains. In addition, integrating more automatic service functions into this robot is also our future goal.

References

[1] N. Li, S. Ma, B. Li, M. Wang, Y. Wang, "an online stair-climbing control method for a transformable tracked robot," *IEEE International Conference on Robotics and Automation (ICRA)*, 2012.

[2] S. Yu, T. Wang, Y. Wang, D. Zhi, C. Yao, X. Li, Z. Wang, Y. Luo, Z. Wang, "A tip-over and slippage stability criterion for stair-climbing of a wheelchair robot with Variable Geometry Single Tracked Mechanism," *International Conference on Information and Automation (ICIA)*, 2012.

[3] Y. Sugahara, N. Yonezawa, K. Kosuge, "A novel stair-climbing wheelchair with transformable wheeled four-bar linkages," *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2010.

[4] S.-C. Chen, K. J. Huang, C.-H. Li, P.-C. Lin, "Trajectory planning for stair climbing in the leg-wheel hybrid mobile robot quattroped," *IEEE International Conference on Robotics and Automation (ICRA)*, 2011.

[5] P. Michel, J. Chestnut, S. Kagami, K. Nishiwaki, J. Kuffner, T. Kanade, "GPU-accelerated real-time 3D tracking for humanoid locomotion and stair climbing," *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2007.

[6] C. Fu, K. Chen, "Gait synthesis and sensory control of stair climbing for a humanoid robot," *IEEE Transactions on Industrial Electronics*, 2008.

[7] T. Sato, S. Sakaino, E. Ohashi, K. Ohnishi, "Walking Trajectory Planning on Stairs Using Virtual Slope for Biped Robots," *IEEE Transactions on Industrial Electronics*, 2011.

[8] K. Mitobe, S. Kaneko, T.Oka, Y. Nasu, G. Capi, "Control of legged robots during the multi supported phase based on the locally defined ZMP" *IEEE/RSJ International Conference on Intelligent Robots and systems (IROS)*, 2004.

[9] J. Pratt, J. Carff, S. Drakunov, A. Goswami, "Capture Point: A Step toward Humanoid Push Recovery," *IEEE-RAS International Conference on Humanoid Robots*, 2006.

[10] Segway Inc. (2013). *The Segway PT: An Overview* [Online]. Available: http://www.segway.com/about-segway/learn-how-PTs-work.php

[11] J. Smisek, M. Jancosek, T. Pajdla, "3D with Kinect," *IEEE International Conference on Computer Vision Workshops (ICCV Workshops)*, 2011.