Abstract

In the paper, a robot is designed to move up-and-down stairs for providing service. This robot consists of a main body, actuating system, roller chains, a front arm and a rear arm for assisting in moving up and down stairs. The actuating system includes two brushless DC motors for locomotion, two worm gears for torque magnification, and two DC motors to control arms. A DSP-based board acts as control center. Some rubber blocks attached to the roller chains are used to generate friction with ground and stairs for moving. A fuzzy logic controller integrates the outputs of DC bus current sensor and an inclinometer to steer the robot. Two walking experiments of moving up and down stairs with the rise/depth of 120/400 mm and 175/280 mm are shown in the taped pictures from videos to verify the proposed design.

Keywords: Stair-climbing robot, fuzzy logic control, brushless DC motor.

1. Introduction

With growing aging population and decreasing working population and birth rate, the number of home-caring workers will soon surpass that of available working force. Taiwan and other developed countries have been experiencing such suffering. Furthermore, the expense of home-caring elders will substantially increase. It is therefore necessary to develop a future substitute for the human work force. Home-caring robot is an excellent candidate capable of supporting such an aging society. Especially, the elders can control the robots directly to move up-and-down stairs for service.

The robots designed in two types to carry elders up and down stairs [1-7] consist of the stick type and the biped type, which use the handrail to assist the elders while walking and moving up-and-down stairs. The former uses tires and rubber belts, and the latter uses two legs to assist walking and moving up-and-down stairs [1]. A control bar is attached to the robot waist to assist the aged person by stepping onto the feet of the robot. The robot “Zero Walker-1” [2] focused on ascending and descending stairs. An electric wheelchair named “iBOT” [3], capable of ascending and descending stairs and slopes was released by a Japanese company. In [4], a bipedal robot was developed to provide only lower-limbs and a waist, named “WL-16RII”, which can walk independently and allow users to build the upper body based on their requirements. This biped locomotor would be applicable as a walking wheelchair or as a walking support machine that is able to walk up and down stairs carrying or assisting an elder. The developed biped locomotor with Stewart Platform Legs successfully achieved walking up and down on stairs for 250 mm continuously and carrying 60-kg man on it. Additionally, Nishiwaki, et al. [5] successfully controlled their robot “H6” to walk up stairs for 250 mm by utilizing toe joints; and the robot “HRP-2” from Harada successfully climbed up 280 mm stairs by grasping the stair rail [6]. A self-standing type eight-wheeled robot in [7] is able to climb up and down stairs and is supported by a mechanism with a planetary gear without an inner gear to eliminate the disadvantages of a wheeled system. However, the height of climbing an obstacle generally is the same as the diameter of the robot's wheel. The aforementioned robots generally need tremendous effect on expense and time. Furthermore, it is very difficult to lift an aged person by human force; and it is not very easy to have a large and heavy-weight lift machine in a normal house.

In the paper, a cheap and simple stair-climbing robot will be designed to provide the service of carrying objects up and down stairs or patrolling for security. It is well-known that the most effective style of movement of a robot on a plane field is the wheel type. As obstacles and stairs exist, crawler-type and leg-type robots become better candidates for application. However, the proposed robot is equipped with roller chains which are attached with polyurethane rubber blocks to generate friction with ground and stairs for climbing up and down.

The main difference between a fuzzy logic control (FLC) and the conventional control is that the former is not based on a properly defined model of the system but instead implements the same control “rules” that a skilled expert would operate. FLC has been applied to
robot applications, such as mobile robots [8-10], humanoid robots [11], and soccer robots [12], and also to chaos synchronization [13, 14]. In the paper, the FLC will steer the robot based on the outputs of DC bus current sensor and an inclinometer. A control board including a digital signal processor (DSP) TMS320F28335 realizes the fuzzy rules.

The paper is organized as follows for further discussion. Section 2 describes the robot mechanism design and each component, the ways of climbing up and going down stairs, and the friction during motion. Section 3 states the fundamental theory of fuzzy logic control. Section 4 presents the experimental results of two kinds of stair-motion. Finally, section 5 claims our conclusions.

2. Robot Mechanism

The stair-climbing robot consists of a main body, roller chains, a front arm, and a rear arm. The lateral-view and vertical-view sketches of the robot by AutoCAD are shown in Figs. 1 and 2. The main body is equipped with two brushless DC motors (BLDCMs) and their drives for locomotion, worm gears for torque magnification, two DC motors to control two arms, and DSP-based board as control center. The chassis size of the main body is 58.5cm ×53cm and each arm is 48cm × 40cm, such that the maximum and minimum lengths of the moving robot will be 154.5cm and 58.5cm, respectively. There are 3 pairs of roller chains in the main body and two arms, respectively. Some polyurethane rubber blocks, each with size of 3cm×2cm×1cm, attached to the roller chains are applied for generating friction with ground and stairs for moving. There are 40 blocks for each arm and 56 for the main body. The distance between any two plastic blocks is properly arranged to fix the stair brink. A sensor network in the main body including one DC bus current sensor and one inclinometer provides the information for the robot to steer two motors.

The robot lifts two arms for saving space and energy dissipation when it moves in a plane field. At the instant of climbing up, the front arm will be pushed down to flat top so that the main body is lifted and will be pulled up for the next stair-climbing. The rear arm keeps flat while the robot climbs up. Fig. 3 shows the way of climbing up stairs based on the physical constraint. Fig. 4 displays summary of climbing-up motion step by step. While climbing, two forces have to be overcome. One is the force along the inclined plane due to the gravity force of the robot system, \( mg \cdot \sin \theta_m \), and the other is the frictional force, \( mg \cdot \cos \theta_m \cdot \mu \), where \( m \) is the total mass of the robot system, \( g \) is the gravity acceleration, \( \theta_m \) is the inclination angle of the stair, and \( \mu \) is the frictional coefficient.
The total output torque of the motor, $T_e$, has to satisfy the following inequality,
\[2T_e \geq (mg \cdot \sin \theta_m + mg \cdot \cos \theta_m \cdot \mu) \times l_m \tag{1}\]
where $l_m$ is the operating radius.

Comparing with induction motors, the BLDCMs with more considerable energy density have replaced conventional field excitations and eliminated windings and the requirement of external electrical sources. They use an electronic inverter to improve deficiencies of the brushed DC motors with mechanical commutator prone to malfunctioning and high copper loss. These merits result in the prevalence of BLDCMs. In order to reduce the electrical specifications and volume size of the motor, gears are considered for torque magnification. As a result, (1) can be modified as
\[2T_e \times S_1 \times \eta_1 \times S_2 \times \eta_2 \geq (mg \cdot \sin \theta_m + mg \cdot \cos \theta_m \cdot \mu) \times l_m \tag{2}\]
where $S_1(S_2)$ and $\eta_1(\eta_2)$ are the gear ratio and the efficiency of the first (second) gear, respectively. Consequently, the motor types of low rated input voltage and high rated speed are primary selection.

Similarly, Fig. 5 shows the way of going down stairs and Fig. 6 displays summary of going-down motion step by step. During going down, the output torque from motors can be reduced since it is in the same direction of gravity force of the robot system.

Fig. 7 displays the picture of the 45-Kg stair-climbing robot with one 5-kg arm for loading and future research. Its operating radius is $l_m = 0.25m$. Worm gears and the charger are then shown in Fig. 8. Since the batteries are prerequisite for the robot, an inbuilt charger is considered for convenience in charging.

### 3. Fuzzy Logic Control

A fuzzy logic controller may be viewed as a real-time expert system since it aims to incorporate expert human knowledge in the control algorithm. The fuzzy logic control (FLC) system consists of FI (fuzzification interface), DML (decision making logic), KLB (knowledge base), and DFI (defuzzification interface), shown in Fig. 9. The triangle-shape membership functions of DC bus current $I$, inclination angle $\theta_m$, and fuzzy output $y$ are shown in Fig. 10, where there are seven linguistic variables, PB (positive big), PM (positive medium), PS (positive small), ZO (zero), NS (negative small), NM (negative medium), and NB (negative big) used in the paper.

Some of the most successful applications by fuzzy control have been highly related with conventional controllers, such as proportional-integral-derivative (PID) controller. Especially, the PD-like fuzzy control is widely adopted in many applications. In the system,
Then the output will be
\[ y = \frac{\sum_{i=1}^{n} \mu_i w_i}{\sum_{i=1}^{n} \mu_i} \]  
(6)

Summarily, Table 1 lists the linguistic control rules and Fig. 12 displays design scheme of fuzzy logic control.

4. Experimental Results

The specifications of the stair-climbing robot are given as follows. The gear ratio and efficiency of the first (second) gear are \( S_1 = 66 \) \( (S_2 = 20) \) and \( \eta_1 = 0.7 \) \( (\eta_2 = 0.55) \), respectively. The static frictional coefficient of polyurethane rubber blocks is about 0.6. Fig. 13 presents the characteristic curve of an inclinometer in the system. The output voltage depending on the voltage source is almost linear with the inclination angle. The rated specifications of BLDCM are: 200 W, 24 V, 9600 rpm, and \( T_e = 0.1336 \text{Nm} \). Since the waveforms of back electromagnetic forces (EMFs) and the armature currents of a BLDCM are trapezoidal alike, not perfectly sinusoidal, the six-step driving algorithm is adopted on speed control rather than the vector control. The popular PI control is adopted for speed regulation. Fig. 14 depicts the fast responsiveness of BLDCM characteristics at 7000 rpm by PI control.

A preliminary experiment that the unloaded robot climbs up and goes down a gradual stair with the rise of 120 mm and depth of 400 mm (\( \theta = 7.16^\circ \)) by wired control is proceeded. It is firstly easy to check the validity of (2). The results of every motion in Figs. 3 and 5 are shown in Figs. 15 and 16, respectively [15]. It qualifies the designed robot. Then we conduct the second experiment that the robot with loading of one arm moves up and down a steeper stair with the rise of
175 mm and depth of 280 mm (θ_m = 32°) by FLC and (1) still holds. The taped pictures of the experiment and every motion in Figs. 3 and 5 are shown in Figs. 17 and 18, respectively. Even lack of any gyroscope, there is little variation in proceeding direction happened during motion due to high friction force between rubber blocks and stairs. The designed robot performs very well during the trip even there are damaged parts on the up-and-down way shown in Fig. 19. The FLC prevents the robot abruptly going down to the ground and damaging itself.

5. Conclusions

In the paper, we have developed a stair-climbing robot to provide service for the elders and completed two walking experiments of moving up and down stairs with the rise/depth of 120/400 mm and 175/280 mm. In fact, the arm as load may capture the specific object during trip in the future research. In addition, if a CCD camera is mounted on it, the robot will patrol for security around the house.

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Figure 15. Realized motion of climbing up by wired control.

Figure 16. Realized motion of going down by wired control.
Figure 17. Realized motion of climbing up by FLC.

Figure 18. Realized motion of going down by FLC.
References


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