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A Fuzzy Control Based Stair-Climbing Service Robot

Ming-Shyan Wang

*Department of Electrical Engineering, Southern Taiwan University
Taiwan, R.O.C.*

1. Introduction

Recently, Taiwan and many developed countries have been experienced an emergence of growing aging population and decreasing working population and birth rate. The number of home-caring workers in need has surpassed that of available working force. Furthermore, the expense of home-caring elders will substantially increase. The employment of foreign workers is just a temporary solution. 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.

It is well-known that the most effective style of movement of a robot on a plane field is the wheel type. However, as obstacles and stairs exist, crawler-type and leg-type robots become better candidates for application. The robots of the stick type and the biped type are generally designed to carry elders up and down stairs. The former uses tires, rubber belts, and the handrail to assist the elders while walking and moving up-and-down stairs, and the latter uses two legs and the handrail to assist walking and moving up-and-down stairs (Takahashi et al., 1998). 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” (Konuma and Hirose, 2001) focused on ascending and descending stairs. An electric wheelchair named “iBOT” (Independence Technology, 2009), capable of ascending and descending stairs and slopes was released by a Japanese company. In (Sugahara, 2005), 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 one 60-kg man on it. Additionally, the authors (Nishiwaki et al., 2002) 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 (Harada et al., 2002). A self-standing type eight-wheeled robot in (Takita et al., 2004) 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 effort on expense and time. Furthermore, it is very difficult to lift an aged person by human force and not very easy to have a large and heavy-weight lift machine in a normal house.

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 (Malima et al., 2006; Chen et al., 2004; Song & Wu, 1999), humanoid robots (Wang et al., 2004), and soccer robots (Wang & Tu, 2008). In the chapter, 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 chapter is organized in 6 sections including introduction 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. The image processing for the CMOS camera and FPGA and the tracking, capturing, and putting back the target object by the arm based on results of image processing are introduced in section 3. Section 4 states the fundamental theory of fuzzy logic control. Section 5 presents the experimental results of two kinds of stair-motion and the image processing. Finally, section 6 claims the conclusion and future work.

2. Stair-Climbing Robot

The designed 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. One DC bus current sensor and one inclinometer provide the information for the robot to steer two motors.

Fig. 3 shows the way of climbing up stairs based on the physical constraint. 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. 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 robot system force of gravity, $mg \cdot \sin \theta$, and the other is the frictional force, $mg \cdot \cos \theta \cdot \mu$, where m is the total mass of the robot system, g is the gravity acceleration, θ is the inclination angle of the stair, and μ is the frictional coefficient. In order to reduce the electrical specifications and volume size of

Fig. 1. A lateral view of the robot

Fig. 2. A vertical view of the robot

Fig. 3. Motion of climbing up

Fig. 4. Summary of climbing-up motion

the motor, gears are considered for torque magnification. The total output torque of the motor, T_e , has to satisfy the following inequality,

$$2T_e \times S_1 \times \eta_1 \times S_2 \times \eta_2 \geq (mg \cdot \sin \theta + mg \cdot \cos \theta \cdot \mu) \times l_m \tag{1}$$

where l_m is the operating radius, $S_1(S_2)$ 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 force of gravity of the robot system.

Fig. 5. Motion of going down

Fig. 7 displays the picture of the 45-Kg stair-climbing robot with one 5-kg arm for service. 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.

Fig. 6. Summary of going-down motion

Fig. 7. Picture of the stair-climbing robot with its arm

Fig. 8. Worm gear and charger

3. Robot Arm and Image Processing

3.1 Robot arm

The top view of the multi-link arm is shown in Fig. 9. It consists of three couples of gears, three DC motors, four links, and one clamper. Referring to Fig. 9, the first DC motor steers the diving gear S_3 and driven gear S_4 to determine the rotating angle. Gear S_3 links S_4 directly. Due to the limit of four stalls at corners, the span angle is within $(-30^\circ, 30^\circ)$. The second motor controls the gear couples of $S_5 - S_{6d}$ and $S_{6u} - S_7$ together with belts to stretch the length of the arm. S_{6d} and S_{6u} are mounted in the same shaft and with same number of gears. The lengths of the four links are l_1, l_2, l_2 and l_3 , respectively.

Fig. 9. The multi-link arm

The pixel array of CMOS camera THDB-D5M used in the robot consists of a matrix of 2752×2004 pixels addressed by column and row (Terasic, 2008). The address (column 0, row 0) represents the upper-right corner of the entire array. The 2592×1944 array in the centre called active region represents the default output image, surrounded by an active boundary region and a border of dark pixels, shown in Fig. 10. The boundary region can be used to avoid edge effects when achieving colour processing the result image of the active region, while the optically black columns and rows can be used to monitor the black level.

Pixels of active region are output in a Bayer pattern format consisting of four “colours”, Green1, Green2, Red, and Blue (G1, G2, R, B) to represent three filter colours (Terasic, 2008). The first row output alternates between G1 and R pixels, and the second row output alternates between B and G2 pixels, shown in Fig. 11. The Green1 and Green2 pixels have the same colour filter, but they are treated as separate colours by the data path and analogue signal chain.

The image raw data is sent from D5M to DE2-70 board (Terasic, 2008) where the FPGA on DE2-70 board will handle image processing and convert the data to RGB format to display on the VGA display. As a result, we first capture the image of experiment background to find the ranges of colours of RGB, and then define their location regions for colour discrimination, shown in Fig. 12.

The target object in the experiment is a cola can with the weight of 330 g and red color surface. Referring to Fig. 12, the ranges of RGB intensities locate at (50, 70), (25, 30), and (23, 28), respectively. In order to reduce the effect of light variation, the image in RGB space will

be converted into YC_bC_r space (Benkhalil et al., 1998; Hamamoto et al., 2002). In addition, the ranges of RGB from D5M are four times of the general image.

Fig. 10. Pixel array description (Terasic, 2008)

Fig. 11. Pixel Color Pattern Detail (Top Right Corner) (Terasic, 2008)

Fig. 12. Image of experiment background

4. 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. 13. The triangle-shape membership functions of DC bus current I , inclination angle θ_m , and fuzzy output y are shown in Fig. 14, 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 chapter.

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, variables of DC bus current and inclination angle are fed back to determine the control action. The inclination angle of the stairs is fixed so that there is little variation on it during motion. In addition, the motion speed of the robot is too slow to need predicting the change of the next states of the sensor signals. As a result, for easily programming, the simplest P control algorithm is employed to achieve the motion control while the robot climbs up and goes down stairs.

The i th fuzzy rule in the fuzzy rule-base system is described as

$$R_i : \text{If } x_1 \text{ is } A_{i1} \text{ and } x_2 \text{ is } A_{i2}, \text{ then } y \text{ is } w_i \quad (2)$$

where $w_i, x_j, A_{ij}, j = 1, 2, i = 1, 2, \dots, n$ are fuzzy output variables, input fuzzy variables and linguistic variables, respectively. Referring to Fig. 15 for i th membership function with isosceles triangle shape, b_{ij} means the length of the base, and a_{ij} stands for the abscissa of the centre of the base. The membership grade of input x_j is calculated by

$$A_{ij}(x_j) = 1 - \frac{2 \cdot |x_j - a_{ij}|}{b_{ij}}, \quad j = 1, 2 \quad (3)$$

The bases of triangular membership function keep same for easily programming. By product operation, the membership grade of the antecedent proposition is calculated as

$$\mu_i = A_{i1}(x_1) \cdot A_{i2}(x_2) \quad (4)$$

Then the output will be

$$y = \left(\sum_{i=1}^n \mu_i w_i \right) / \left(\sum_{i=1}^n \mu_i \right) \quad (5)$$

Summarily, Table 1 lists the linguistic control rules.

Fig. 13. Block diagram of fuzzy logic control system

Fig. 14. Membership functions of current sensor, inclinometer, and fuzzy control output

Fig. 15. i th membership function with isosceles triangle shape

5. Experimental Results

The specifications of the stair-climbing robot are as following. The gear ratio and the 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. 16 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 $T_e = 0.1336 Nm$. 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 rather than the vector control is adopted on speed control. The popular PI control is adopted for speed regulation.

$\theta_m \backslash I$	ZO	PS	PM	PB
NB	ZO	PS	PM	PB
NM	ZO	PM	PM	PM
NS	ZO	PB	PS	ZO
ZO	ZO	PB	PS	ZO
PS	ZO	PB	PS	ZO
PM	ZO	PS	PM	PM
PB	ZO	PS	PM	PB

Table 1. Linguistic control rule table

Fig. 16. Characteristic curve of an inclinometer

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 ($\theta = 16.7^\circ$) by wired control is proceeded. It is firstly easy to check the validness of (1). The results of every motion in Figs. 3 and 5 are shown in Figs. 17 and 18, respectively (Wang & Tu, 2008). 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 ($\theta = 32^\circ$) by FLC

and (1) still holds. The taped pictures of the experiment and every motion in Figs. 3 and 5 are shown in Figs.19 and 20, 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. The FLC prevents the robot abruptly going down to the ground and damaging itself.

The third experiment contains image processing and arm motion. In order to prevent target damage while clamping, one pressure sensor is installed inside the clasper. The pressure output after calibrating is sent to DSP for reference. Fig. 21 displays the sequentially taped pictures from videos of capturing the cola can and putting it back by the robot arm (Tu, 2009). As the can shifting left or right, the arm can correctly track to the corresponding direction.

Fig. 17. Realized motion of climbing up by wired control

Fig. 18. Realized motion of going down by wired control

6. Conclusion and Future Work

In the chapter, 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. The third experiment of object tracking, capturing, and loading by the arm have been shown in the taped pictures from videos to verify the proposed design. In fact, we will show the arm may capture the specific object during climbing up and down in the future. In addition, the robot will patrol for security by the CCD camera around the house while more image processing functions are provided.

Fig. 19. Realized motion of climbing up

Fig. 20. Realized motion of going down

Fig. 21. The taped pictures of the experimental results of image processing and arm motion

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Climbing and Walking Robots

Edited by Behnam Miripour

ISBN 978-953-307-030-8

Hard cover, 508 pages

Publisher InTech

Published online 01, March, 2010

Published in print edition March, 2010

Nowadays robotics is one of the most dynamic fields of scientific researches. The shift of robotics researches from manufacturing to services applications is clear. During the last decades interest in studying climbing and walking robots has been increased. This increasing interest has been in many areas that most important ones of them are: mechanics, electronics, medical engineering, cybernetics, controls, and computers. Today's climbing and walking robots are a combination of manipulative, perceptive, communicative, and cognitive abilities and they are capable of performing many tasks in industrial and non- industrial environments. Surveillance, planetary exploration, emergence rescue operations, reconnaissance, petrochemical applications, construction, entertainment, personal services, intervention in severe environments, transportation, medical and etc are some applications from a very diverse application fields of climbing and walking robots. By great progress in this area of robotics it is anticipated that next generation climbing and walking robots will enhance lives and will change the way the human works, thinks and makes decisions. This book presents the state of the art achievements, recent developments, applications and future challenges of climbing and walking robots. These are presented in 24 chapters by authors throughout the world. The book serves as a reference especially for the researchers who are interested in mobile robots. It also is useful for industrial engineers and graduate students in advanced study.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Ming-Shyan Wang (2010). A Fuzzy Control Based Stair-Climbing Service Robot, Climbing and Walking Robots, Behnam Miripour (Ed.), ISBN: 978-953-307-030-8, InTech, Available from:

<http://www.intechopen.com/books/climbing-and-walking-robots/a-fuzzy-control-based-stair-climbing-service-robot>

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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