Controller Design for an Autonomous Wall-climbing Micro-robot Based on TMS320LF2407 DSP Chip

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Abstract

In this paper, a detailed description of the controller design for a wall-climbing micro-robot using LF2407 DSP chip is presented. Because of its high-speed performance, its support for multi-motor control and its low power consumption, LF2407 DSP from TI demonstrates itself as an ideal candidate for a single chip controller for the wall-climbing micro-robot.

Keywords

Digital motor control, micro robot, digital signal processing.

1. Introduction

Nishi [1-3], Backes [4] have built large wall-climbing robots with suction cups. However, designing a micro-robot that can climb walls, walk on ceilings, crawl through pipes and traverse on floors is a challenging task. Autonomous micro-robot system has wide applications include remotely monitoring hazardous environments, reconnaissance, defects inspection, and fire fighting. The restrictions such as small size, light weight, and low power consumption must be satisfied when designing a miniature robot. Such a robot is designed by an interdisciplinary research team at Michigan State University and reported in references [5-8].

The single chip LF2407 DSP is selected as the controller for the micro-robot because of its high-speed performance, its support for multi-motor control and its low power consumption. This paper describes in detail the use of LF2407 DSP chip in the controller design of the wall-climber robot with the dimension less than 9 inches in height and 1.5 inches in width and length.

We first introduce briefly in section 2 the overall structure of the wall-climber micro-robot. The detailed description on how to utilize the DSP resources to control the micro-robot is presented in section 3. In section 4, we discuss the software hierarchy and specific problems related to the micro-robot control. Experimental results are presented in Section 5 which describes the evaluation environment setup and some pictures showing the movement of the micro-robot. Conclusion and further research are discussed in section 6.

2. Wall-climber micro-robot overview

Fig. 1 and Fig. 2 show the image and the mechanical structure of the wall-climber micro-robot. The micro-robot has a biped structure with four joints driven by three motors. This under-actuated kinematic structure reduces both weight and power consumption of robot, since it requires fewer actuators. Motor 3 drives the joint 1 which adjusts the tilt angle of suction foot 2 so that the robot can stick to the floor or wall surface. Motor 2 drives joint 2 as well as joint 3 via a belt drive with a 2:1 reduction. This means joint 2 and joint 3 are coupled with 2:1 relationship between the joint angles. Joint 4 is driven by motor 1 via a differential gear (not shown clearly) intersecting joint 3. Joint 4 angle γ permits steering capabilities for the robot. Due to the existence of differential gear and belt, motor 2 can also drive joint 4 undesirably with ½ of the joint 2 angle. This poses challenges in motion planning and gait control. Our solution to compensate for this side effect is to command motor 1 to turn ½ of motor 2 angle simultaneously but in reverse direction. An additional potentiometer is attached to the joint 4 shaft to get the zero position of joint 4 and to correct the coupling between joint 2 and joint 4.

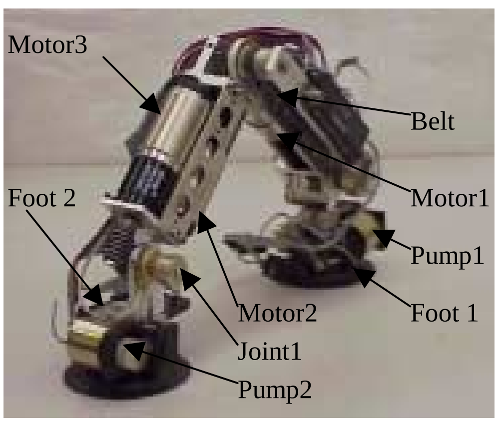

Fig. 1 Picture of wall-climber micro-robot

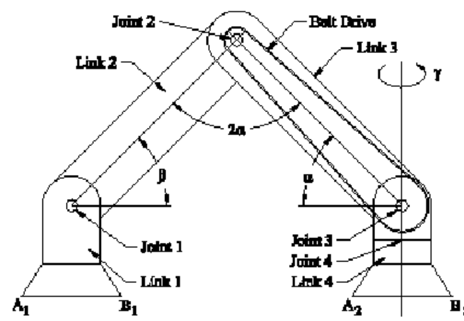

Fig. 2 Structure of wall-climber

The two legs of the micro-robot are supported by the suction feet that provides the robot with the ability to walk on the horizontal surface as well as climb on the vertical wall. Each suction foot of the robot consists of a suction cup, a vacuum pump motor, a micro valve as well as a pressure sensor. The pressure sensor provides information to determine whether the suction foot is securely attached to a flat surface. The micro valve is used to release the cup. In such a way, the robot can walk on flat surfaces step by step and traverse between inclined flat surfaces such as walls and ceilings. Several touch sensors are also attached to the suction cup in different radial directions. This gives information on which part of the suction cup has touched the surface and facilitates the robot in adjusting the suction foot orientation.

Some other components and modules are added to the robot to provide it with sensing and control ability. Those modules include a wireless transmitter/receiver module for remote control, four infrared sensor modules for obstacle avoidance and a pin-hole camera for image detection and transmission.

3. Controller hardware design

The components of the robot such as three DC servomotors, two suction pump motors and two micro valves need to be controlled. The information from sensor components such as two pressure sensors, one potentiometer, six touch sensors and four infrared sensors as well as the decoder output from the wireless transmitter/receiver need to be processed and integrated into the control system.

Due to the limitations of size, weight and power consumption, one of the challenging tasks in designing the controller of the micro-robot is to use as fewer components as possible. The TMS320LF2407 DSP from TI is targeted to provide single chip solution to control the robot. This chip has two event manager modules (EVA & EVB) with two general-purpose timers, three capture units and eight PWM outputs for each module. Other features such as 3.3V power supply, built-in quadrature encoder pulse (QEP) circuits, high speed A/D converter, large number of digital I/O, make it a desirable device to be used in digital motion control. We select this chip to design the controller because of its high-speed performance, its support for multi-motor control and the low power consumption. Fig. 3 illustrates the controller block diagram based on TI LF2407 DSP chip. The resource of the DSP chip is efficiently utilized and the circuit is very concise.

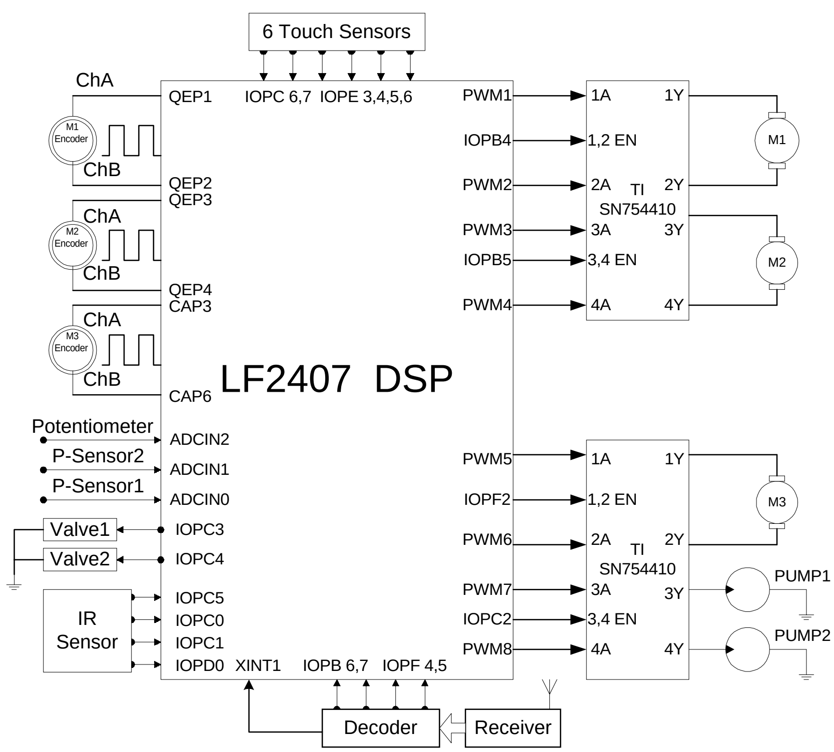

Fig. 3 Block diagram of the controller

Two quadruple half-H driver SN754410 from TI are used to drive the three servomotors and the two pump motors. The servomotors are driven by compare unit outputs PWM1,2, PWM3,4, and PWM5,6 of EVA via the H-bridge driver. Timer 1 is used as the time base to generate PWM signal, with PWM frequency of 20KHz. Timer3 is used to generate the servo-control sampling rate of 1KHz. During each servo sampling period (1ms), compare registers, CMPR1, CMPR2 and CMPR3 are updated for motor1, motor2 and motor3 respectively according to the calculated PID control value. LF2407 DSP has two built-in quadrature encoder pulse (QEP) circuits. The encoder readings of servo Motor1 and Motor2 are easily obtained using the QEP1,2 and QEP4,5 of the Event Manager with Timer2 and Timer4 as the time base respectively. However, for Motor3, we need to employ alternative method to get the encoder reading. The encoder channel A of servo Motor3 is connected to CAP3 pin and the capture unit 3 is enabled to detect the rising edge of the encoder pulse. Channel B is connected to CAP6/IOPF1 pin and this pin is configured as shared pin function of digital input IOPF1. Whenever the capture interrupt is triggered in CAP3, the interrupt service routine detects the digital level of the encoder channel B to determine the rotation direction and adjusts the encoder pulse count value. Apart from serving as the time base for PWM waveform, Timer1 is also used as time base for capture 3 operation. The two functions do not affect each other. We will discuss this method of getting encoder reading using capture unit in detail later.

For the two pump motors, we only need a binary switch. So we configure PWM7/IOPE1 and PWM8/IOPE2 as digital output pins. With the H-bridge driver, we can simply turn on the pump by setting the output as high. The micro valves are also controlled by the digital outputs from DSP via two transistors as the drivers.

The touch sensor consists of an outer tube and an inner super-elastic wire isolated by a silicon tube. When the inner wire touches the outer tube the switch closed. In such a way, the touch sensors provide a set of digital inputs to DSP to facilitate the robot in adjusting the suction foot orientation.

The potentiometer is connected to ADC input pin to generate information about the zero position of the joint 4. This helps to deal with the coupling between joint 2 and joint 4. The analog inputs from the pressure sensors are converted by ADC to determine whether the suction foot is securely attached to a flat surface.

A receiver and a decoder chip are used for remote control purpose. The impulse signal from the decoder triggers the external interrupt pin of the DSP. The interrupt service routine processes the four digital I/O outputs from the decoder and translates the remote control signal into proper command.

Infrared sensor module actually produces high-level or low-level digital signal indicating whether there is an obstacle or not in front of the robot. Those output signal are connected directly to the I/O pin of the DSP.

4 Software development

4.1 Software hierarchy

C compiler from TI is used to generate the control software. Several modules of the software have been written in C language. File Rjoint.c contains low level modules related to servo control and joint movement. File Rsuction.c consists of basic functions to control the suction foot. The responsibility of Robtest.c includes task level scheduling, command interpretation and trajectory generation. File Rsyst.c mainly deals with serial communication with the PC, system settings and wireless communication.

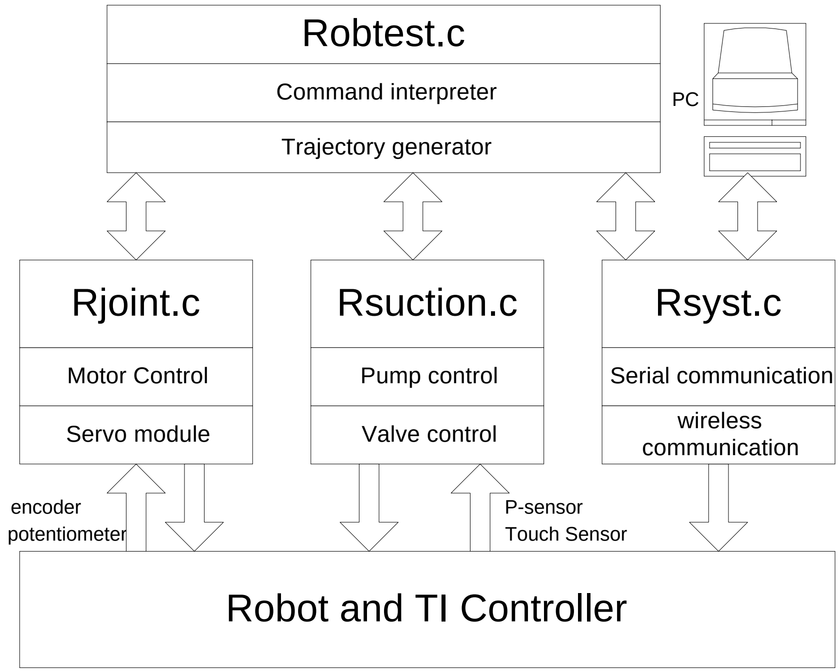

Fig. 4. Software hierarchy

4.2 Encoder feedback

Accurate digital motor control is the basic requirement for the robot to accomplish certain tasks. To achieve this, the servo controller requires position information from the encoder as feedback. As mentioned before, it is easy to obtain encoder reading for motor 1 and motor 2 using the two build-in QEP circuit of DSP. However, for motor 3, software solution is adopted to get the encoder reading because adding additional circuit is not desirable for micro-robot limited in size and weight.

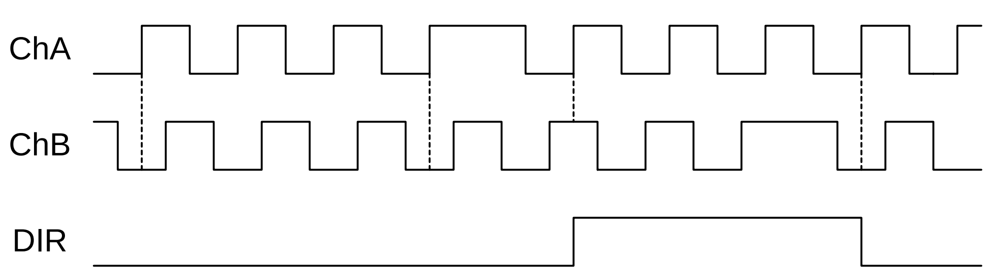

Fig. 5. Encoder pulse and motor direction

The analysis of the magnetic encoder waveform of the servomotor indicates that:

1. The phase shift of channel A and B of the encoder pulse sequences is 90 degree.
2. The logic level of channel B corresponding to the rising edge of channel A changes after the motor changes direction.

These properties are utilized to obtain the encoder reading. The encoder channel A of servo Motor3 is connected to CAP3 pin and the capture unit 3 is enabled to detect the rising edge of the encoder pulse. Channel B is connected to input digital I/O pin IOPF1. Whenever a rising edge is detected, the capture interrupt is triggered. In the interrupt service routine, the logical level of channel B is detected through IOPF1. When channel B is logic low, it means that the motor rotates in positive direction, then the encoder pulse count variable *CAP3_cnt* adds one. When channel B is logic high, it means the motor has changed the rotation direction, then *CAP3_cnt* minus one. In such a way, *CAP3_cnt* updates its value by +1 or -1 according to the rotation direction every time the encoder pulse triggers. It is clear that the value of *CAP3_cnt* indicates the motor angle expressed in encoder counts. *CAP3_cnt* is set as a global variable and its value can be accessed to accomplish feedback control.

4.3 Servo control

Servo control module is the fundamental and most important part for a robot control system. A specific interrupt service routine (ISR) processes the servo control and motion profile calculation. Timer 3 is selected to generate servo control sampling period of 1 ms by setting the associated period register, T3PR, with proper value. Fig. 6 shows the flowchart of the servo ISR.

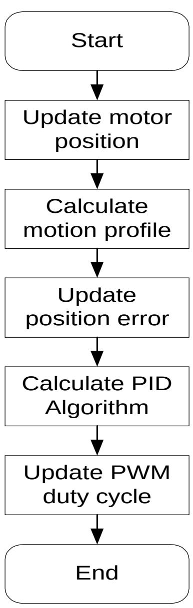

Fig. 6 ISR flowchart

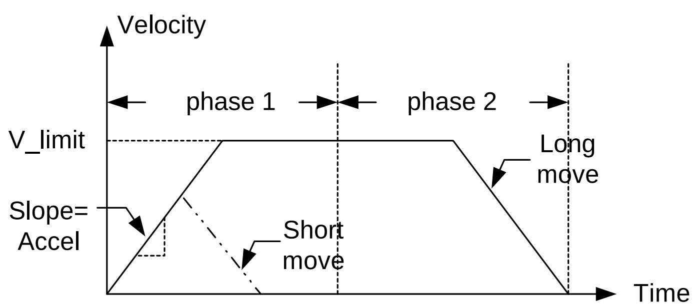

Fig. 7 Velocity trajectory

For smooth motion control, a motion profile is necessary to control the motor acceleration and deceleration. When a motor is commanded to rotate a certain angle, the desired position for each servo step must be calculated by the motion profile routine. Without the motion profile, motion will be abrupt, causing excessive wear on the mechanical components and degrading the performance of the control algorithm. For our application, a linear piecewise trapezoidal/triangular velocity trajectory (Fig. 7) is adopted to implement the motion profile.

The flowchart for the motion profile is shown in Fig. 8. The value of the commanded move distance is divided by two and placed in variable *ph1_dist.* The desired distance, desired velocity and desired position for each servo step is placed in variable, *d_dist*, *d_vel* and *d_pos* respectively. The f*lat_cnt* variable is used to determine when the constant velocity section starts or stops. The *first_half* is the flag indicating whether the motion is in phase 1 or phase 2. The final move destination is stored in *f_pos*. Finally, the *move_in_progress* flag is cleared, ignoring further position commands until the move is completed and this flag is set.

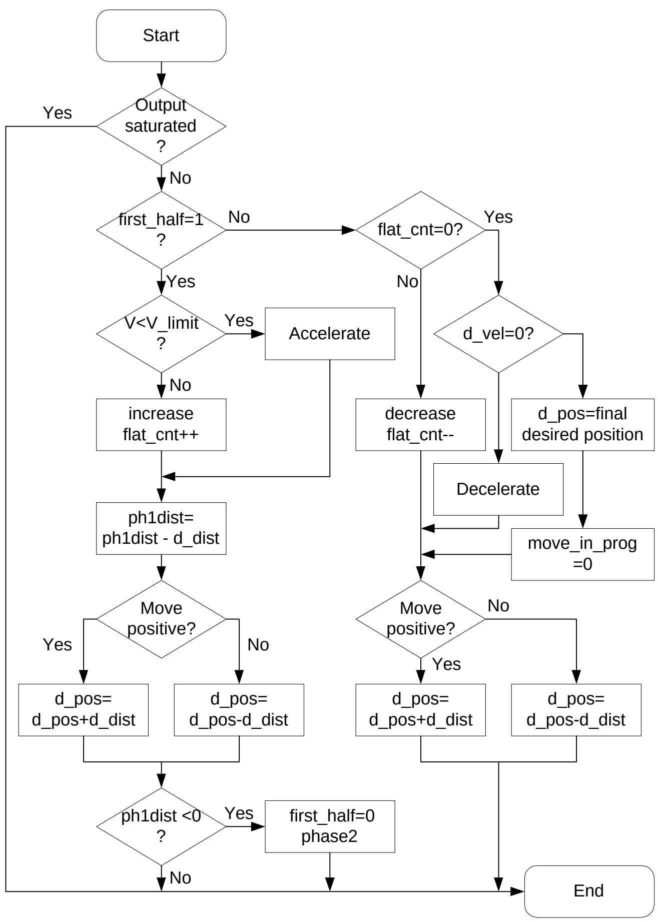

Fig. 8 Motion profile flowchart

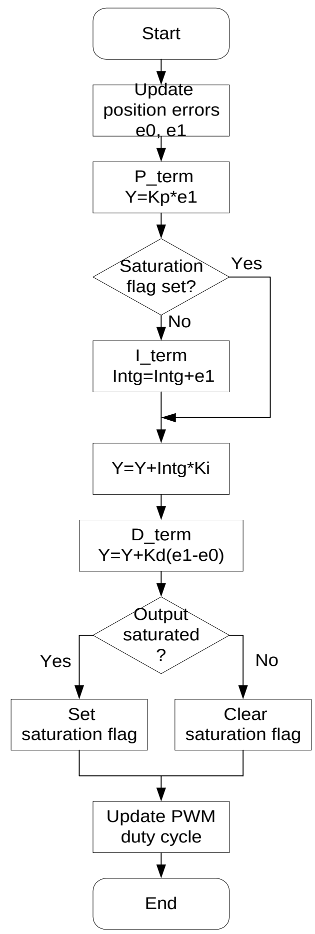

Fig. 9 PID control flowchart

PID algorithm is most widely used for servo motor control [9,10]. It is easy to understand and tune the parameter. The flowchart of the implemented PID algorithm is shown in Fig.9.

5. Experiment and future work

The experiments were conducted on the micro-robot to evaluate the DSP controller. The testing environment includes a computer, our designed controller board and a TMS320LF2407 evaluation board [13] from Spectrum Digital, Inc. The robot is connected via a 40-wire ribbon cable to our controller board. The necessary pins of the DSP chip are connected to the controller board from evaluation board via cables. Computer and evaluation board communicates with each other via RS-232 serial port. Our program code is downloaded to the memory of DSP chip in the evaluation board. Basic functions such as *my_printf*, *my_scanf* have been written so that the DSP can write data to the computer monitor and read data from the keyboard. A command interface is implemented and this facilitates the testing of the robot controller. We input the command from the keyboard of the computer to let robot perform a certain behavior. The parameters and our interested data can be displayed on the computer monitor.

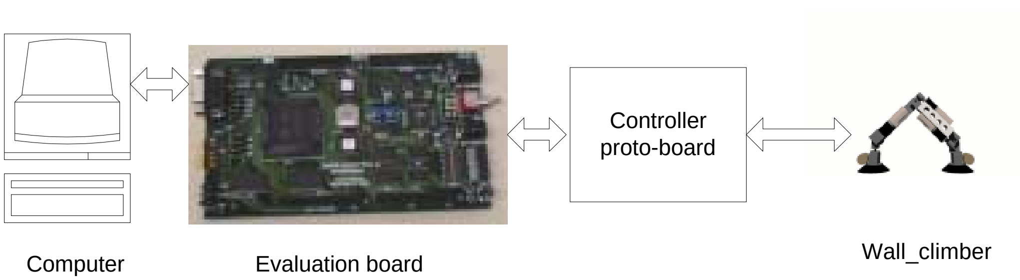

Fig.10 Evaluation setup

Some pictures of the robot climbing the wall are shown in Fig. 11. The experimental results demonstrate that the DSP controller works well.

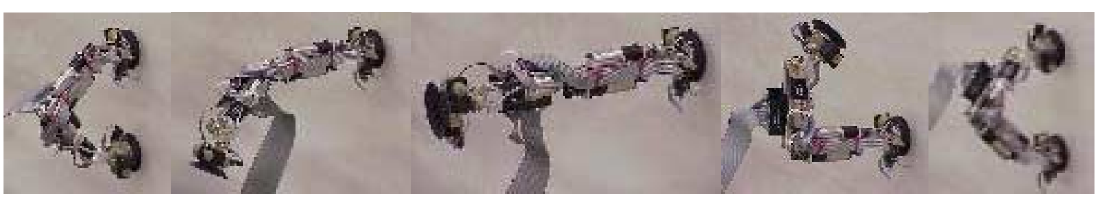

Fig.11. Micro-robot climbing the wall

The next step of our research is to get rid of the evaluation board and combine the DSP chip and necessary peripheral into the controller board. We will build a small PCB board and put it on the robot body. The ultimate goal of our research is to provide the robot with the ability to explore the world autonomously.

6. Conclusion

A controller for a wall-climbing micro robot was designed using TMS320LF2407 DSP chip. Experimental results showed that this chip provides a good DSP solution to control the micro-robot. The robot can accomplish certain tasks such as walking on the ground and climbing the wall successfully. Future improvement of the system is being pursued.

Acknowledgement

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