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An Embedded Controller for a Quadruped Robot Based on ARM and DSP

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***Abstract* - The performance of controllers have deep influence on the capability of the quadruped robot. In this paper, we design and implement an embedded controller, which is made up of two parts: upper layer ARM controller and lower layer DSP controller. The ARM controller, integrated with a WIFI module to facilitate remote control by PC, is responsible for gait planning and sensors information processing. The DSP controller is mainly designed to receive real-time control commands from ARM controller via serial peripheral interfaces (SPI) and communicate with motor drivers through Controller Area Network (CAN) bus. To achieve fairly accurate control of the quadruped robot, four force sensitive resistors (FSRs) and a gyroscope are used on the quadruped robot. The developed embedded controller has been employed to control the quadruped robot Biodog, built at our lab. Using Hopf-based Central Pattern Generator (CPG) algorithm, we conduct experiments on the quadruped robot Biodog to test the embedded controller. The results demonstrate the efficiency of our controller for the rhythmic quadruped locomotion.**

Index Terms - Quadruped robot, Embedded controller, ARM, DSP, CAN bus.

I. Introduction

Regarding walking robots, the quadruped robot and other sorts of legged robots have attracted a great deal of attention in recent years [1] [2]. In contrast with other kinds of robots, the quadruped robot is outstanding for its remarkable ability to step over obstacles and walk through irregular terrains [3]. The choice of the controller decides whether the quadruped robot has robust stability during locomotion. The mainstream design of the quadruped robot controllers utilizes commercial-off-the-shelf products [4], like Boston Dynamics' quadruped robots BigDog and LittleDog, Kimura et al's Patrush and Tekken, MIT's quadruped robot Cheetah. The quadruped robots mentioned above all utilize the commercial-off-the-shelf PC as the controller to complete motion control.

HyQ's all joints are controlled by an onboard Pentium computer connected to motors and valve drivers [5]. The MIT Cheetah, whose control system structure comprises of four layers: Real-Time controller, FPGA, Motor driver, and the PC, utilizes i7 dual-core 1.33 GHz CPU as the Real-Time controller [6]. BigDog, with about 50 sensors, adopts an onboard computer to realize both high-level control of coordinating behavior of legs to regulate velocity, attitude and altitude of the body during locomotion and low-level control of positions and forces at the joints [7]. LittleDog uses an onboard x86 as the controller to process data and plan gaits, and a camera-based localization system for navigation [8].

Recently, the design and implementation of embedded controller for complex industrial control system have drawn a lot of attention from both academia and industry [9]. Compared with the traditional PC-based robot controller, the embedded controller is more compact, flexible and lower in power consumption and it overcomes the shortcomings of MCU in aspect of human-machine interface and network. Along with the development of embedded controllers, the robots will be more miniature, intelligent and at the same time more widely used in the field of industrial control, emergency rescue, robot, military and so on.

There are many researches on embedded controller of ARM and DSP respectively, but few researches concentrate on using them together in the field of robot control. However, the ARM and DSP architecture controller can make full use of high performance of ARM in running operating system and the advantage of DSP in data processing [10].

We develop an embedded controller making up of upper layer ARM controller and lower layer DSP controller to achieve real-time control for the quadruped robot. The ARM controller is responsible for gait planning, sensors information processing and communicating with DSP controller through SPI for its high performance and low power dissipation. Besides, a WIFI module is added to ARM controller to achieve wireless communication with PC. This facilitates remote control for the quadruped robot. Meanwhile the DSP controller, which is extraordinary in calculation, is mainly composed of four DSP microprocessors and two functional interfaces of SPI and CAN. Through SPI, the communication between DSP controller and ARM controller is accomplished. The CAN interfaces of the DSP controller are used to achieve signals transmission with DC motor drivers to realize position control of actuators and guarantee the locomotion of the quadruped robot.

Moreover, we apply four FSRs to the terminals of the quadruped robot limbs to ensure the foot-ground contact. A gyroscope is also installed in the quadruped robot, which is mainly used to measure the rotation angle for the quadruped robot in locomotion.

Stable locomotion is the basic function for a quadruped robot. The traditional kinematics and inverse kinematics is accurate in planning gaits but it is difficult in modeling. To realize fast and easy control, we adopt the control method based on CPG for its advantage in rhythmic motion control.

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II. Architecture of the Embedded Controller

A. *Outline of the Embedded Control System*

The embedded controller designed for the quadruped robot is made up of two complementary controllers: upper layer ARM controller and lower layer DSP controller. ARM controller is mainly used to achieve control algorithms of the quadruped robot and process the information gained by sensors, while DSP controller is responsible for controlling the motors to complete locomotion of the quadruped robot.

The outline of our embedded control system is shown in Fig. 1. It is obvious that the upper layer ARM controller and lower layer DSP controller realize communication through their SPI interfaces and the DSP controller and motor drivers transmit data via CAN bus. By using WIFI module, we can control the quadruped robot by PC through wireless local area network.

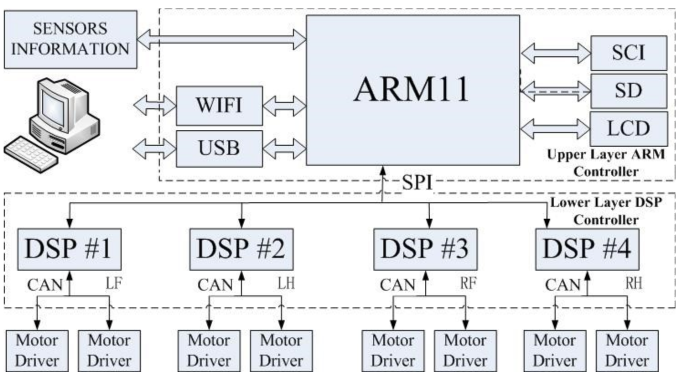

Fig. 1 Outline of control system designed for the quadruped robot.

B. *Upper Layer ARM Controller*

The S3C6410 (ARM11) microprocessor produced by Samsung is used as the core of ARM controller for its high basic frequency and low cost (667 MHz at 1.2 V) [11]. We integrate the ARM controller, shown in Fig. 2, with a series of functional interfaces, which are elaborated as below.

LCD display interface: the interface is connected to a 7 inches LCD with touch screen which facilitates us to run the program.

SD card interface: it is mainly used to boot Linux kernel through SD card. Compared with traditional boot method of Flash, the SD card is more swappable and easier to carry.

WIFI module: for the convenience of remote control by PC, a WIFI module which utilizes USI's WM-G-MR-9-Ref-2 Wireless LAN Module as the core chip is added to the ARM controller. The WIFI module supports IEEE 802.11b/g and its data rate is up to 54Mbps by incorporating Direst Sequence Spread Spectrum (DSSS) and OFDM data modulation.

SPI interface: SPI is a high-speed synchronous serial communication interface that used as the bridge to achieve communication between upper layer ARM controller and lower layer DSP controller [12]. Generally the SPI uses four wires and works at master-slave mode.

Fig. 2 The developed embedded controller of upper layer ARM controller.

C. *Lower Layer DSP Controller*

The DSP controller as shown in Fig. 3, including four TI's TMS320F2812 digital signal processors which are high-performance 32-bit CPU and use the Harvard bus architecture, is used as an assistant controller to coordinate with ARM controller. The two main functional interfaces of DSP controller are introduced in detail as below.

CAN interface: enhanced CAN controller, which is integrated in TMS320F2812 processor, provides its CPU complete CAN2.0B protocol and reduces CPU overhead [13]. In our design, each DSP processor communicates with two motor drivers via CAN bus to accomplish locomotion control of hip and knee joints in one limb of the quadruped robot.

SPI interface: The interface of SPI is used to receive real-time control command from upper layer ARM controller.

Interfaces of SCI and GPIO/PWM are also added in the DSP controller as the spare parts.

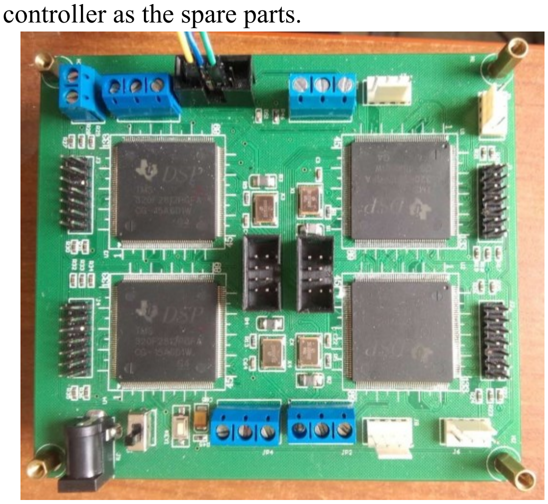

Fig. 3 The developed embedded controller of lower layer DSP controller.

D. *The Sensors*

Sensing for robot is an important part and has been studied on fervently [14]. The quadruped robot is equipped with four FSRs at limbs terminal of the quadruped robot. By using the feedback signals of the sensors, we ensure the foot-ground contact, especially on rough terrains.

A gyroscope is also installed in the quadruped robot, which is mainly used to measure the rotation angle of the quadruped robot in locomotion. Relying on this sensory information, we achieve fairly accurate control of the quadruped robot.

III. Software Design of Communication

A. Remote Communication

Aiming at realizing remote control for the quadruped robot by PC, we designed the WIFI module. The quadruped robot is able to connect to the Internet by using the WIFI module on the ARM controller. Via Transmission Control Protocol (TCP), we achieve the communication between ARM controller and PC while they access to the same local area network (LAN).

TCP can provide a reliable link for applications. Before sending data formally, the communication parts must establish a connection firstly. When the client sends a request to the server, the server processes the request and sends back a response to the client. This process continues till the client sends termination flag.

RT-Linux is imported as an embedded real-time operation system (RTOS) on the basis of ARM [15]. The ARM controller is equipped with Linux system, however it cannot compile code directly. So we build a cross-compiler environment for the development of executable programs.

We realize the design of TCP server application and TCP client application and install them in the terminals of PC and ARM controller. Through this two applications, we realize remote control for the quadruped robot by PC.

B. Communication between Upper Layer ARM Controller and Lower Layer DSP Controller

The DSP controller communicates with ARM controller in the way of master-slave mode through SPI. Each SPI interface of DSP controller contains four wires, which are CS, MOSI, MISO, and CLK. Their functions are shown in Table I.

Fig. 4 shows the communication network structure of SPI. ARM controller works as the SPI master and four DSP processors work as SPI slaves. In order to save the design

TABLE I
Function of SPI Interface Pins

Name	Function
CS	Slave select line
MISO	Master input/Slave output line
MOSI	Master output/Slave input line
CLK	Serial clock line

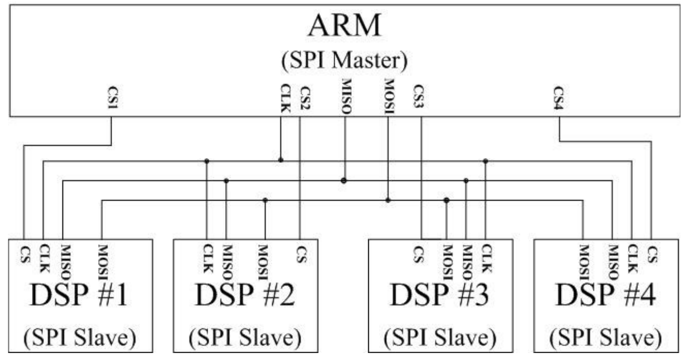

Fig. 4 Hardware connection diagram of SPI communication between upper layer ARM controller and lower layer DSP controller.

space, four DSPs share three wires which are CLK, MISO and MOSI while keep their CS individually. The four chip select wires (CS1-CS4) are connected to GPIOs of The ARM controller and used to confirm which DSP slave processor is selected. When the SPI slave processor is selected, it will start communicating with ARM controller.

It is worth noting that the SPI clock signal can only be provided by SPI master device. When CS outputs lower level, the corresponding chip is selected. The SPI master will send data through MOSI, and the SPI slave will receive data through MOSI, or the SPI slave sends data through SOMI and the SPI master receives data through SOMI. For example, the ARM controller works as the SPI master and CS1 outputs lower level, while other CS pins keep high. The SPI slave DSP #1 will be selected individually. When the CLK signal rises, DSP #1 starts receiving data through MOSI and ARM controller starts receiving data through MISO at the same time. At the following drop of CLK signal, DSP #1 sends data to ARM controller through MISO and ARM controller sends data to DSP #1 through MOSI.

C. Communication between DSP Controller and DC Motor Drivers

As the joints of the quadruped robot must be able to coordinate work with each other, we need to build a communication network to realize real-time control of the quadruped robot.

MAXON's EPOS 70/10 motor drivers are integrated with CAN interfaces that follow the CiA CANopen specification DS-301 Version 4.02 Application Layer communication profile [16-17]. The DSP controller, with eCAN Module that fully complies with CAN protocol, version 2.0B [18], can work at either standard frame mode or extended frame mode. So the DSP controller and the motor drivers can communicate through their CAN interfaces by using standard CAN bus protocol.

The CAN bus network structure in one leg for the quadruped robot is shown in Fig. 5. In addition, at each terminal of CAN network, a resister of 120 Ohm is necessary.

The DSP controller is used as CAN master and two motor drivers in one leg are used as CAN slaves. The signals on

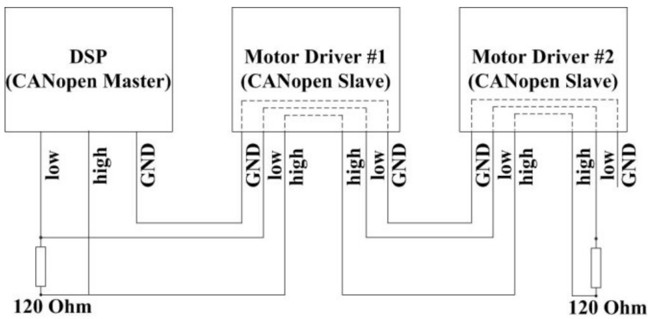

Fig. 5 Hardware connection diagram of CAN bus between DSP controller and motor drivers.

CAN bus are transmitted through differential voltage of CAN_H and CAN_L. When voltage levels of CAN_H and CAN_L are equal, the signal transmitted represent logical '1'. While sending logical '0', the voltage level of CAN_H is higher than the voltage level of CAN_L.

For each motor driver, a unique CAN-ID set by DIP-Switch 1-7 on the drivers is needed to receive messages correctly. During communication, the DSP processor packages the data and CAN-ID of target driver as a "frame", then sends the frame out. The motor drivers will receive command if its CAN-ID is the same as that in the frame on CAN bus.

To control motors, we need to configure the operating mode for the motor drivers firstly. Next we need to set the motors' parameters, including velocity, accelerate, position and so on. Then we can enable the drivers. When we set the target position, the motors will start to move till reaching the set position.

IV. Gait Planning for the Quadruped Robot

Stable locomotion is the basic function for a quadruped robot. Most existing locomotion control methods fall into one of two categories. One category adopts the traditional kinematics and inverse kinematics to plan gaits for quadruped robots. This method is accurate and robust, but it is difficult in modeling and calculating. The other category uses approach based on CPG which widely used in recent years for its advantage in the rhythmic locomotion control for quadruped robots. To realize fast and easy control, we adopt the latter one.

CPG is a neural network which located in the vertebrate spine that can control the movement of animals by generating a periodic signal with multiple phase relationships. The Hopf-based model of CPG is a powerful algorithm to control the rhythmic motion for the quadruped robot [19]. Formulas (1)-(3) show the mathematical model of Hopf oscillators.

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \end{bmatrix} = \begin{bmatrix} \alpha(\mu - r_i^2) & -\omega \\ \omega & \alpha(\mu - r_i^2) \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} + \sum_{i \neq j} R(\theta_i^j) \begin{bmatrix} x_j \\ y_j \end{bmatrix} \quad (1)$$

$$\omega = \omega_{st} / (\exp(-ay_i) + 1) + \omega_{sw} / (\exp(ay_i) + 1) \quad (2)$$

$$r_i = \sqrt{x_i^2 + y_i^2} \quad (3)$$

Where $x$and y are output signals and their relative phase is 0.5π hat they are used to control the hip joint and knee joint, i and j means the i_{th} and j_{th} limb, α and a are constants ω, ω_{st}, and ω_{sw} represent the frequency of oscillator and the frequency of stance and swing durations respectively, μ determines the amplitude of x and y, $R(\theta_j^i)$ is a rotation matrix, θ_j^i is the required relative phase among the i_{th} and j_{th} oscillators to perform the gait.

From formulas (1)-(3), we get the control signals of hip joint and knee joint, shown as formulas (4).

$$\begin{cases} A_{hi} = x_i \\ A_{ki} = \begin{cases} \pm|y_i| & , y_i > 0 \\ 0 & , y_i < 0 \end{cases} \end{cases} \quad (4)$$

In walk gait, they will regulate the legs of the quadruped robot following the motion sequence: Left fore leg - Right hind leg-Right fore leg - Left hind leg. The output walk gait control signals of each joint are shown in Fig. 6 and the control signals of trot gait are shown in Fig. 7, the quadruped robot will follow the motion sequence: Left fore leg and Right hind leg-Right fore leg and Left hind leg.

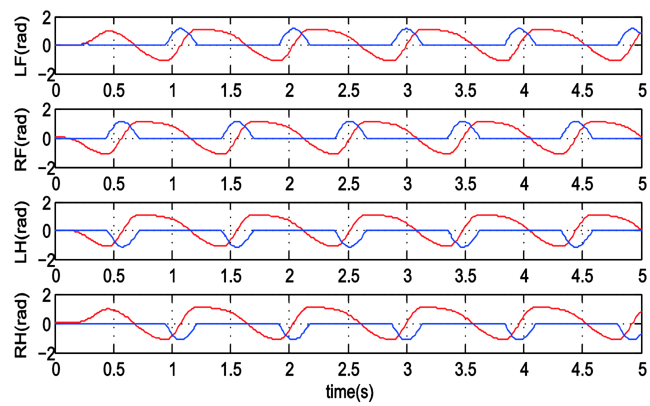

Fig. 6 Output control signals of walk gait for the quadruped robot. The red lines and the blue lines represent control signals of hip joints and knee joints respectively.

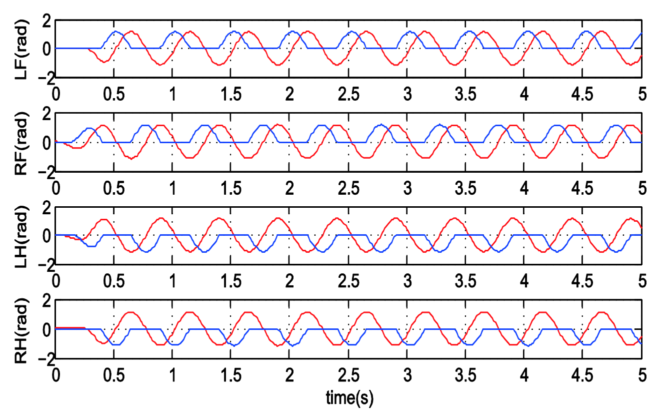

Fig. 7 Output control signals of trot gait for the quadruped robot. The red lines and the blue lines represent control signals hip joints and knee joints respectively.

V. Experiments and Discussion

All the experiments are conducted at a real quadruped robot Biodog built at our laboratory, as shown in Fig. 8. It is a motor driven and position controlled quadruped robot massing about 25kg. The length, width and height of Biodog are: 0.54m, 0.27m and 0.33m. Each limb of the quadruped robot has a hip joint and a knee joint, which two are respectively actuated by one DC motor produced by MAXON.

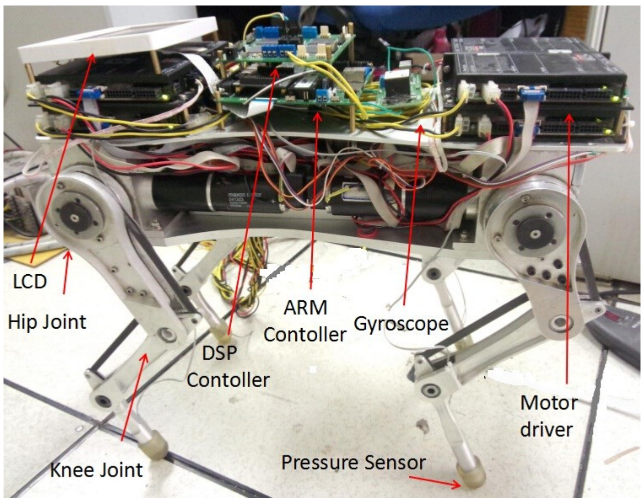

Fig. 8 The Biodog built at our lab, used in the experiment below to test the embedded controller's performance.

The experiment process is depicted in Fig. 9. When the system is powered on, both ARM and DSP controllers initialize their programs firstly. Then ARM controller and DSP controller begin waiting for commands from PC and ARM controller respectively. When we send the remote control signal by PC, ARM controller starts to calculate the related parameters and sends motion commends to DSP controller through SPI. At the moment DSP controller receives data from ARM controller, it executes the appropriate operations to motor drivers via CAN bus immediately. The embedded controller will return to initialization state and wait for the next cycle of remote control command after the quadruped robot moves to the specified location.

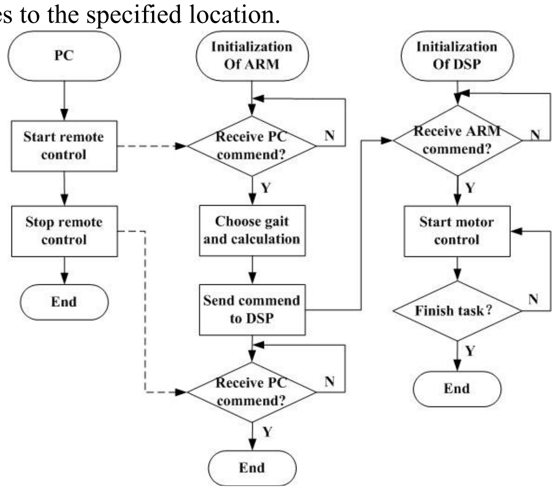

Fig. 9 The control process of the quadruped robot.

(1) Waveforms of SPI signals detected by an oscilloscope are shown in Fig. 10. It is obvious that the ARM controller and DSP controller are configured to capture data on the rising edge of CLK and delivery data on the falling edge of CLK. When CS signal falls down to logic zero and hold on, two controllers of ARM and DSP start to communicate. At the rising edge of CLK, ARM controller and DSP controller capture data separately. On the following falling edge of CLK, they will send data to each other. As shown in Fig. 10, ARM controller sends data 0x0A and receives 0x0F, conversely, DSP controller sends data 0x0F and receives data 0x0A.

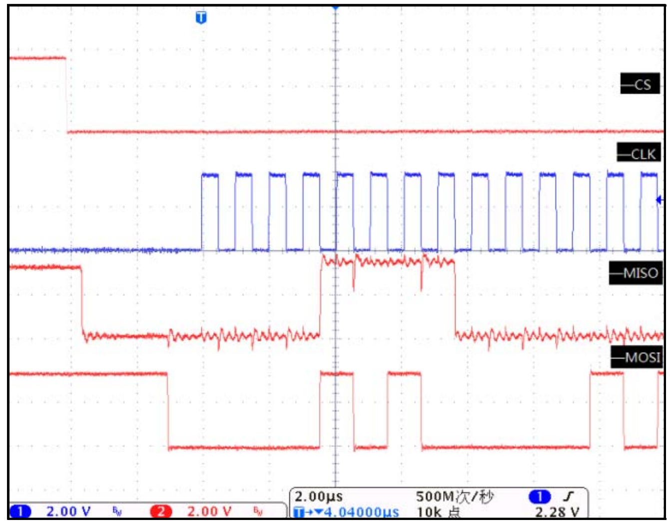

Fig. 10 Waveforms of SPI signals detected by an oscilloscope. They are CS, CLK, MISO, MOSI, from top to bottom.

(2) As shown in Fig. 11, we detect the waveforms of CAN signals between DSP controller and motor drivers. The blue line and red line represent signal CAN_H and CAN_L. The green line represents the value of (CAN_H - CAN_L). During communication, the state of equal voltage levels of CAN_H and CAN_L represents logical '1'. When CAN_H's voltage level is higher than CAN_L's voltage level, logical '0' is transmitted.

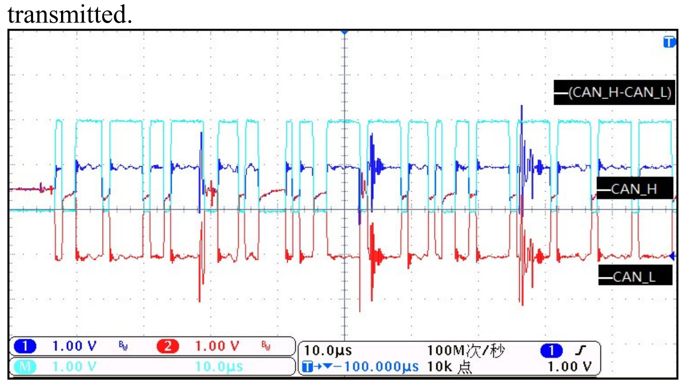

Fig. 11 Waveforms of CAN signals between DSP controller and motor driver. They are (CAN_H-CAN_L), CAN_H, CAN_L, from top to bottom.

(3) The Hopf-based gait control algorithm of CPG is realized using our embedded controller which mounted on the quadruped robot. We present the snapshots of trot gait in Fig. 12. As shown in Fig. 12 (a), the quadruped robot is ready to start. In Fig. 12 (b), the quadruped robot takes the first step. It

is clear that the right fore leg and left hind leg move forward. The quadruped robot takes the second step in Fig. 12 (c) that the left fore leg and right hind leg are in front relatively. The quadruped robot keeps on going step by step in Fig. 12 (d) (e). Finally, the quadruped robot stops at initial position in Fig .12 (f).

Fig. 12 Snapshots of the experiment video. In the experiment, we test the developed embedded controller.

VI. CONCLUSION AND FUTURE WORK

This paper introduces the design of the embedded controller based on ARM and DSP microprocessors for the quadruped robot. ARM controller is made up of S3C6410 microprocessor and some peripheral interfaces like USB, SPI, SD and WIFI. It is responsible for rhythmic motion control of the quadruped robot and communication with DSP controller and PC. DSP controller is consisted of four TMS320F2812 digital signal processors and functional interfaces of SPI and CAN. SPI is used to achieve the communication between ARM controller and DSP controller and CAN is applied to transport commends from DSP controller to DC motor drivers. In order to achieve remote control for the quadruped robot by PC, we add a WIFI module to ARM controller.

To test the performance of the embedded controller designed above, we conduct experiments on the quadruped robot Biodog. By adopting the powerful algorithm of CPG which based on Hopf model, we realize stable rhythmic locomotion of the real quadruped robot. The results verify the effectiveness of our embedded controller to provide reliable control performance.

Future work will concentrate on developing the remote control platform on PC. Through this platform, we can achieve gait selection, velocity regulation, position control of the quadruped robot conveniently.

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