FPGA-based Hexapod Robot Spider

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***Abstract*—This paper describes a FPGA-based hexapod robot spider, which is used for student education purposes. In the paper mechanical design, kinematic analysis, electro-mechanical device and FPGA system are introduced. Some key points about gait mode, non-stop PWM signal，filter of reflex ultrasonic wave and Bluetooth control are given in detail. At the end of the paper a discussion section gives some technical opinions about FPGA-based system, gait mode, filter of sonar echo and remote control.**

***Index Terms*—FPGA, robot spider, mini-sever, PWM , Bluetooth Control**

I. Introduction

Robot spiders are widely built and researched for a variety of purposes, including space exploration, mine cleaning in battle fields and rescue work in disasters. Robot spiders can be used in such application situations because of their special leg-walking mode. Compared with wheel mode robot, the efficiency of robot spider is not higher, but a robot spider can easily cross over obstacles.

The hexapod robot spider CC-Balck5 described in the paper is used for educational purposes for college students. They can take it as an experiment platform, and write their own VHDL program to realize varieties of movements.

II. Mechanical Design

The robot spider CC-Black5 consists of 6 legs, which are located on both sides of the body, as shown in Fig.1. Each leg has 2 joints, i.e. each leg includes 2 freedoms. One freedom is rotating around lengthways axis. This is defined as the small-leg joint. Another freedom is rotating around the crosswise axis and it is defined as the big-leg joint. The whole structure includes 12 freedoms. Some mechanical data are listed in TABLE I.

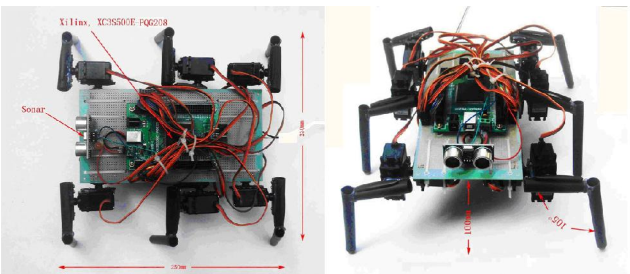


Fig.1 Top view and front view of CC-Black5

TABLE I. MECHANICAL CHARACTERISTICS

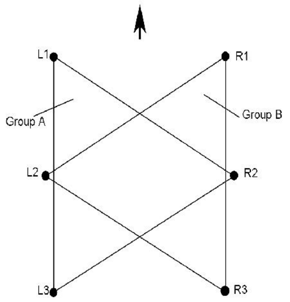
length	250(mm)
width	230(mm)
height	130(mm)
Height of bottom space	100(mm)
Total mass	615(g)
mass of each leg including 2 joints	82(g)
stride	50(mm)
speed	50(mm/s)

III. Kinematics Analysis

A. Gait Mode

A robot spider with six legs could have a lot of gait modes. The gait mode of CC-Black5 is similar to the mode of coxswainles-six-oar rowboat. With the rowboat mode the movement of all six paddles are same at the same time, but for CC-Black5 there are some differences. All six legs of CC-Black5 are divided into two groups: Group A and Group B, as shown in Fig.2. Group A includes two left legs, L1,L3 and one right leg, R2. Group B includes two right legs, R1,R3 and one left leg, L2.Each group forms a triangle. All three legs which are in one group will make the same movement at the same time. The main consideration is that, when the legs of one group leave from the ground, then the other three legs of the other group keep standing on the ground. This can keep CC-Black5's movement stable.

In term of kinematics design, the movement of each leg includes four beats: leg rising→return stroke→leg descending →paddling. The movement is like as human arm in free style swim, or like as paddle in a rowboat. The positions of one right leg of CC-Black5 during 4 beats is shown in Fig.3, where in states 3 and 4, the leg contacts the ground, in states 1 and 2, the leg leaves the ground. In state 4, the leg carries CC-Black5 forwards. At this moment, the three joints of the three big legs in one group output the maximum power. The CC-Black5 takes 250ms for one beat. Four beasts form a loop, which takes one second. A stride length of a loop is 50mm.



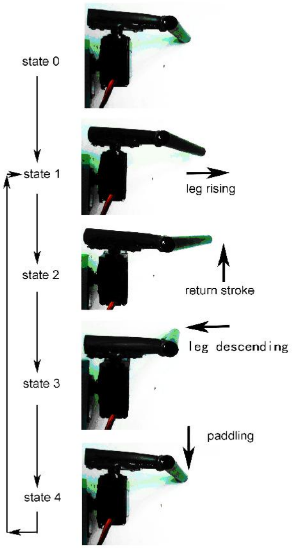


Fig.2 Two groups of legs Fig.3 Four-beat movement mode

B. Eight-beat gait or four-beat gait mode

The experimental program has been tested for two ways of gait: 8-beat gait and 4-beat gait.

In the 8-beat gait program, Group B is standing on the ground until 4-beat movement of Group A is completed, and vice versa. The 8-beat sequence is: Group A leg rising→return stroke→leg descending→paddling→Group B leg rising→return stroke→leg descending→paddling. In this way CC-Black5 moves very stably. But the efficiency is lower. One loop of walking costs 2 seconds, and because there are always 3 legs standing on the ground, a bigger friction occurs.

In the 4-beat gait program, Group A and Group B move simultaneously following 4-beat mode, but two groups have 2-beat phase difference. The 4-beat sequence is: Group A leg rising and Group B leg descending→Group A return stroke and Group B paddling→Group A leg decending and Group B leg rising→Group A paddling and Group B return stroke. In this way the movement of CC-Black5 is faster and more lively. One loop of walking takes 1 second.

However it is very important to notice that, in 4-beat gait program beat 1 and beat 3 demand 3 legs rising and 3 legs descending simultaneously. In fact it leads to a strongly harmful push-up movement. A fine adjustment of time sequence during beat 1 and beat 3 must be made. With adjustment every time leg-rising allways occurs a little bit later than leg-descending. This adjustment makes the walking of CC-Black5 more stable and stronger.

C. Basic Status

The basic statuses of CC-Black5 are: standing, going forward, going backward, turning left and turning right. The standing status is the most important one, and all joints of CC-Black5 are located in their middle position. Because of mechanical deviation, the duty values of each PWM signal for each jiont is not in the same. These initialization values must be carefully adjusted. All other statuses need only off-set parameters based on standing status. All off-set parameters are nearly the same. Other additional statuses, such as hand-waving, body up-down, swing dance are also possible to configurate.

IV. ELECTRO-MECHANICAL DEVICE

The electro-mechanical device used as a joint of legs is a mini-server, as shown in Fig.4. Its electrical and mechnical characteristics are listed in the TABLE II.

A mini-server consists of an IC for control-drive, a DC motor, a gear set and a proportional potentiometer, as shown in Fig.4 and Fig.5. Control-drive module can detect a specific PWM signal and drive the DC motor. The gear set reduces the rotating speed of the motor. According to the duty time of a signal the control module fixes the axis of the mini-server to a certain position. The proportional potentiometer outputs an electrical level to the control module to correct this position. So the mini-server then rotates to a fixed position between 0 and 180 degree according to the duty of PWM signal(see Fig.7). Because the gear set has no self-lock characterristics, the mini-server can not keep this position if the signal disappears, or is broken. Fig.6 shows the control conception of a mini-server.

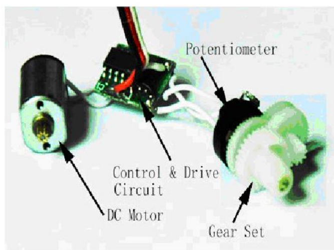


Fig.4 Mini-server Fig.5 Structure of mini-server

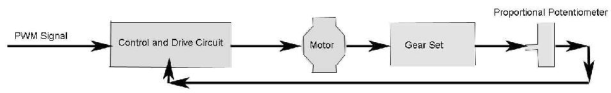


Fig.6 Control conception of a mini-server

TABLE II. ELECTRICAL AND MECHANICAL CHARACTERISTICS OF MINI-SERVER

power	5(V DC)
Max. current	100(mA)
Control signal	50(Hz), PWM with duty 0.5(ms) – 2.5(ms), LVTTL
Rotating angle	0 – 180(degree)
torque	≥20(N-cm)
weight	35(g)

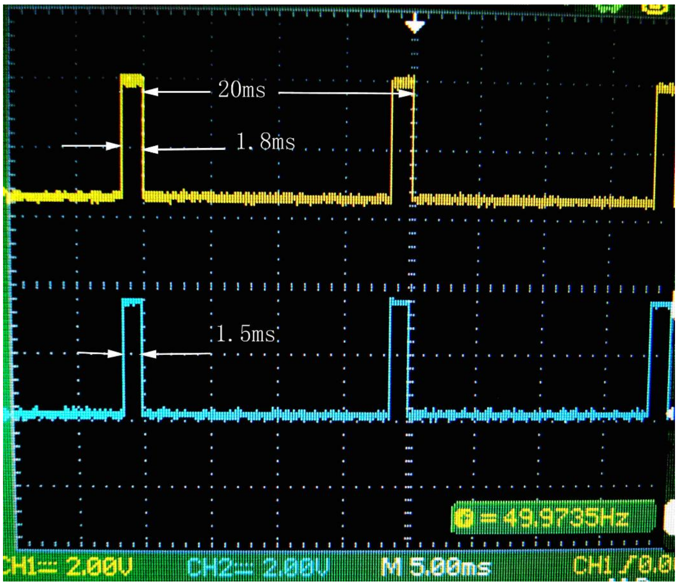


Fig.7 PWM signals of 2 mini-servers

V. FPGA SYSTEM

A. Minimum System of FPGA

The movement of CC-Black5 is all under the control of a FPGA(Field-Programmable Gate Array) system. A standard minimum system of FPGA is used in CC-Black5, according to the system recommended by Xilinx Inc. Other than this minimum system no other additional components and devices are used. The hardware design is based on the Master Serial Mode as shown in Fig.8. It is a low cost, high-performance solution for a robot spider.

The system consists of two ICs only. The main one is FPGA, which type is XC3S500E-PQ208. It belongs to Spartan-3E FPGA family of Xilinx Inc. Inside of the chip 500K system gates, 158 I/O pins are integrated. The run speed of FPGA is high up to 300MHz. Another chip in Fig.8 is a flash memory, which type is XCF04S of Platform PROM family of Xilinx Inc. The size of XCF04S is 4 Mb. It is used to keep the configuration data of FPGA. The configuration data is programmed with VHDL(Very high speed Hardware Description Language), and is down loaded into the flash memory through JTAG interface.

B. Sonar device

A sonar device as shown in Fig.9 is used to measure the distance between CC-Black5 and a wall. If the distance is smaller than 10cm, CC-Black5 will turn back and change forward direction. A speaker of the device sends 40kHz ultrasonic wave. The receiver has the same size as the speaker. Both of them are resonated under 40kHz ultrasonic wave. The transmission speed of ultrasonic wave in the air is 340m/s. A counter in FPGA measure the response time of the echo, and gives a signal to change the the walking direction when the response time is shorter than 0.59ms.

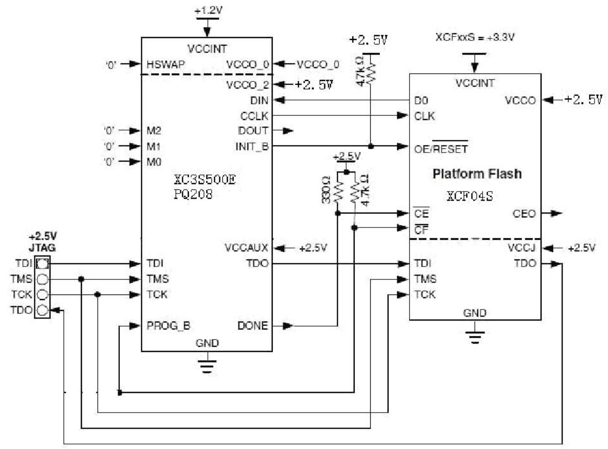


Fig.8 FPGA system based on Master Serial Mode

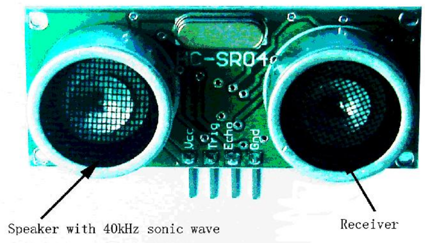


Fig.9 Sonar device

C. Bluetooth Module

A Bluetooth module as shown in Fig.10 is used to control CC-Black5.Through it man can use a mobile phone or a laptop to remote control movements of CC-Black5. The control distance is more than 50m. The frequency of the Bluetooth module is 2.4GHz. The control commands include “stop”, “forward”, “backward”, “turn right”, “turn left”, and “hand waving”. The communication between the host and the Bluetooth module is on the basis of protocol V2.1+ EDR. The interface between Bluetooth module and FPGA is LVTTL-UART with 115,200 Baud rate. The Bluetooth module consists of the chip BlueCore4-Ext (CSR Ltd.) and a MCU. The functional block diagram is shown in Fig.11.

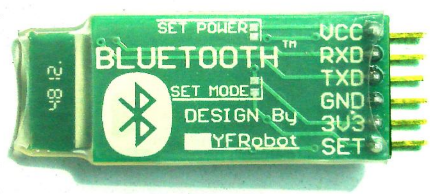


Fig.10 Bluetooth Module

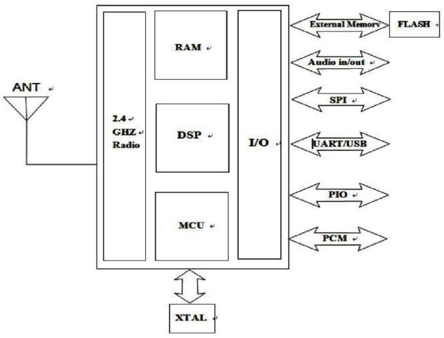


Fig.11 Functional Blocks of The Bluetooth

D. I/O Port Assignments

The I/O resourece of FPGA, XC3S500E is very rich. It has 158 I/O pins on the chip. CC-Black5 has 12 joints, which need 12 I/O ports. The sonar device needs one input to get the response of the echo and one output to trigger ultrasonic wave. The Bluetooth module needs one output pin to connect its RXD, and one input pin to connect its TXD. Additional 2 outputs are used for LEDs as indicators. All 18 I/O ports occupy only a small part of the I/O resource of FPGA. Fig.12 shows the I/O assignment of FPGA.

E. Synchronous and Non-Stop PWM Signal

The all 12 PWM signals are synchronous. Fig.7 shows only 2 signals of the 12 signals, and they are exactly synchronous. The FPGA is clocked with an external 50MHz crystal oscillator. Through frequency divides it results in some basic clocks: 50Hz for PWM signal, 4Hz for beats of walking, and other clocks for the Sonar and for UART of the Bluetooth module. Because of concurrent characteristics of FPGA it is easy to keep all 12 PWM signals non-stop and synchronous. It means that during the whole running cycle of CC-Black5 all 12 PWM signals will never be broken, but can be changed. It is important for mini-server. If the PWM signal stops, the rotate position of mini-server will be easily changed under a load. It will make a robot spider weaker and instable.

Using Xilinx hardware design tool ISE it is easy to create the schematic of the FPGA system of CC-Black5, as shown in Fig.13 and Fig.14. Fig.13 shows that the FPGA system becomes an ASIC(Application Specific IC), having three input pins on the left side of the IC: clk pin, echo pin and txd pin, and 16 output pins on the right side of the IC: led, led1, 12 mini-server signals, trig and rxd pins.

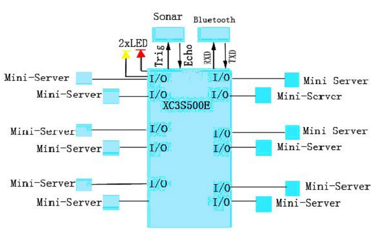
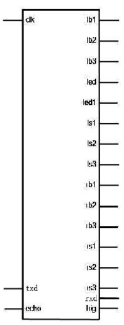


Fig.12. Assignment of I/O pins



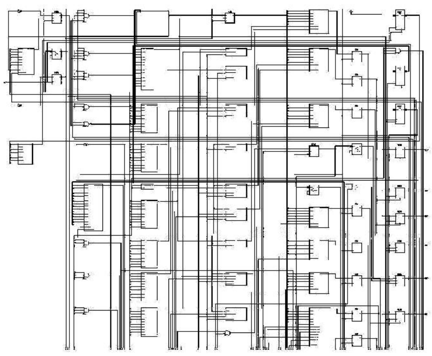


Fig.13 Schematic of FPGA Fig.14 Fine schematic

The input clk pin gets external 50MHz clock, the input echo pin gets a reflex ultrasonic wave signal, and the input txd pin gets signals from Bluetooth module, which form a 8-bit command. The signal type of the three input pins is rising-edge of externals. Both led pin and led1 pin output high level (3.3V) or low level (0V). 12 mini-server signal pins output synchronous non-stop PWM signals, which control movements of spider legs. The trig pin outputs a rising-edge signal to start the sonar device. The rxd pin outputs an acknowledge to the Bluetooth module after the command is implemented. Fig.14 shows a detail of schematic, which includes a lot of counters to divide frequency and FFs(flip-flop) to capture rising-edge of signals and output synchronous signals.

In the field of robot spider, some of them have been built based on the 32-bit embedded system. For these kind of robot spider to keep all PWM signals synchronous and non-stop is not so easy. Compared with control by the embedded system, the FPGA-base robot spider CC-Black5 walks more stably.

F. Communication of the Bluetooth Module

Between the host and Bluetooth module the communication is 2.4GHz RF according to the protocol V2.1+ EDR. The host can be an android mobile phone, or a windows laptop. The App for Bluetooth on the mobile phone must support UART format. The communication between the Bluetooth module and FPGA is LVTTL-UART. The Baudrate for both of them are set as 115,200.

For example, if the host sends a character “r”, the Bluetooth module gets it, then transmits it to FPGA through its TXD pin. According to “r” FPGA changes its moving status into “turning right”, and gives a response character back to RXD pin of the Bluetooth module. The Bluetooth module sends the response back to the host. It is a complete transaction.

VI. DISCUSSION

By the concurrent feature of FPGA and its rich resources of I/O, the demand for more synchronous and non-stop PWM signals can be easily met. In the authors’ point of view, FPGA system is more suitable to such loading case than the 32-bit embedded system.

CC-Black5 uses 12 mini-servers, which can be drived by FPGA XC3S500E directly. If more powerful big servers are used, then additional drive modules are needed to insert between output pins of FPGA and servers.

Because the gait mode is not as stable as the wheel mode, it causes instable reflex ultrasonic waves. A filter design for sonar device in FPGA is then necessary. In CC-Black5 , when a reflex echo continues more than 2 seconds, it can be confirmed that there is a real obstacle wall in front. Sometimes when a reflex ultrasonic wave from the floor reaches to the receiver of the device, the filter will ignore it.

The UART interface as a process in FPGA has been programmed. The remote control can be easily realized with various devices. Except of the Bluetooth module, the GSM base-band module SIM300S, or SIM900A(Siemens) are successfully constructed in CC-Black5. A Man-Spider communication through a mobile phone can be set up.

The battery is always a problem just like in other kind of robots. Here, CC-Black5 needs 5V and maximum 1.5A power supply.

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