A Spherical Robot based on all Programmable SoC and 3-D Printing

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Abstract - As the competition and exploration on marine is going more intense, intelligent underwater robots or autonomous underwater vehicles have become important tools to accomplish tasks such as ocean geologic survey, mineral exploration, victims rescue, military reconnaissance, etc. The mechanical structure and electronic control module design, which have long been research hotspots in this field, are in direct relation to the performance, reliability, maintainability and deployment ability of underwater robots. Existing designs commonly develop the body of robots with a large quantity of components or parts and realize information processing and motion control by using multiple kinds of electronic devices. This paper proposed a novel technical solution for underwater robots design. 3-D printing technology was adopted to construct the body of our spherical amphibious robots directly, which eliminated manufacturing difficulty, shortened the production cycle and improved water-tightness. Xilinx Zynq-7000 All Programmable SoC was used to integrate motor control, sensor management, data acquisition and other functional units or circuits into a single chip. Moreover, a universal FMC slot for high speed board and four PMod sockets for low speed modules were provided on the mother board of the electronic control module to expand functions, upgrade hardware or install scientific instruments for special missions. By introducing 3-D printing and latest SoC technologies, the system complexity of the spherical robot was significantly reduced, which improved reliability. Meanwhile, the design room for intelligent robots was broadened with modular design and all programmable SoC. The design in this paper may have reference value for multipurpose underwater robots or vehicles.

Index Terms - Spherical robot. Amphibious/underwater robot. 3-D printing. All programmable SoC. Xilinx Zynq-7000.

I. INTRODUCTION

As the competition and exploration on marine is going more intense, concerns on underwater operation tools have been raised. Unmanned underwater robots and vehicles, which are major tools for observation, investigation, development or rescue missions in underwater environment, can be divided into remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) [1]. A ROV is connect to the mother ship with an umbilical cable which provides power source and transfer data, while an AUV has no physical connection with the mother ship and cruises fully automatically relying on the source power and electronic devices carried by itself. Compared with ROVs, AUVs have the advantages of larger movement range, lower maintenance charge, greater diving depth and no risk of umbilical cord [2]. As an aggregate of intelligent control strategies and advanced scientific instruments, AUVs have abilities to acquire high quality data and execute special tasks. Since the 1990s, more and more AUVs or intelligent underwater robots with mature technologies have been used to accomplish tasks such as marine specimens collection, ocean geologic survey, mineral exploration, victims rescue, military reconnaissance, etc.[3]-[6]

A spherical robot is a kind of robot in ball shape and packs electronic devices, scientific instruments, sensors and batteries inside its spherical shell. The rigid spherical shell can protect interior mechanical units and electronic devices and provide the largest room for equipment installation [7]-[8]. Moreover, a robot with symmetrical shape generates less turbulence and does little disturbance to the surroundings, which improves its concealment and may be meaningful to military applications [9].

Because of the above characteristics, interest in spherical robots has increased in recent years. The spherical amphibious robot Groundbot, which was developed by Rotundus AB in Stockholm, Sweden, tried to serve as an alternative design instead of wheel-based rover Spirit for a Mars rover [10]. With a diameter of 60 cm, the Groundbot was driven by displacement of its mass center and can roll in water or soft soil at speeds up to 3 m/s. Its improved versions were able to climb slopes up to 15-18 degrees and cooperate for airport reconnaissance and surveilance with embedded navigation and vision system. The BYQ-series robots, developed by the research team led by Sun Han-Xu in Beijing University of Posts and Telecommunications, had functions of climbing, jumping, stereo vision and autonomous location navigation and can work in multiple scenarios including underwater environment [11]-[12]. Besides, research teams in University of Delaware, Azad University of Qazvin, King Mongkut’s University, etc. also had their own various spherical robots which faced different applications [13]-[15].

We started researching on spherical robots/AUV in 2008. By 2013, a spherical underwater robot driven by 3 vectored water jets [16] and a spherical amphibious robot inspired by turtles [17] have been successfully designed. To combine the flexibility of micro-robots and mobility of amphibious robots, a mother-son robot system was proposed in 2012 [17]. However, all the designs mentioned above commonly adopted a large quantity of non-standard components and parts to build the body of robots. Limited by spherical robots’ particularity in shape, the part manufacture and quality control are very difficult, which leads to a longer production cycle and a higher cost. In addition, as a greater emphasis has been placed on the...
intelligence and automation of underwater robots or AUVs, a stronger and more flexible electronic platform is needed to replace traditional MCU, DSP or on board computer and realize advanced PID algorithm, swarm-robot management, autonomous object tracking and other intelligence features.

This paper proposed a novel technical solution for underwater robots design. 3-D printing technology was adopted to construct the body of our spherical amphibious robots directly, which eliminated manufacturing difficulty, shortened the production cycle and improved water-tightness. Xilinx Zynq-7000 All Programmable SoC (System on Chip) was used to integrate motor control, sensor management, data acquisition and other functional units or circuits into a single chip. Moreover, a universal FMC slot for high speed board and four PMod sockets for low speed modules were provided on the mother board of the electronic control module to expand functions, upgrade hardware or install third part scientific instruments for special mission. By introducing 3-D printing and latest SoC technologies, the system complexity of the spherical robot was significantly reduced, which improved reliability. Meanwhile, the design room for intelligent robots was broadened with modular design and all programmable SoC.

The rest of this paper is organized as follows. An overview on features and functions of our spherical amphibious robot and mother-son robot system will be introduced in Section II. The mechanical structure design with 3-D printing and the electronic control module design based on Zynq-7000 will be described in Section III and Section IV in turn. Section V will be conclusion and follow-up relevant research work.

II. GENERAL DESIGN OF THE SPHERICAL ROBOT

A. Principle of the Spherical Amphibious Robot

As the design has been introduced in the reference [17], we proposed a spherical amphibious robot which was used for covert missions or tasks in narrow room that normal AUV could not complete. As shown in Fig. 1, the shell of the spherical robot consisted of a hemisphere upper hull (250 mm in diameter) and two quarter-sphere lower hulls (266 mm in diameter) which can open and close. The hard upper hull was waterproof and can protect electronic devices and batteries inside it from collision. Four actuating units, each of which was equipped with two servo motors and a water jet motor, were installed under the upper hull. When the robot was in underwater mode, the lower hulls closed and four water jet motors in the actuating units provided vectored thrust though the holes in the lower hulls to realize 6 DOFs motion. When the robot was in land mode, the lower hulls opened and the actuating units stretched out to quadruped walk under the driven of eight servo motors.

![Fig. 1 Diagram of the spherical amphibious robot](image)

Fig. 1 Diagram of the spherical amphibious robot

As shown in Fig. 2, the electronic control module of the spherical robot was centered with an AVR MCU (ATmega2560) which provided pulse width modulation (PWM) signals to motors and acquired location and environmental information with various sensors. Two 7.4V/3600mAh LiPo batteries and two 8.4V/200mAh NiMH batteries were used as build-in power supply.

B. Mother-Son Robot System

Though the spherical robot was much more flexible and compact than most of underwater robots or AUVs, there are still some mission area that it cannot reach (e.g. a very narrow pipe). New material (e.g. ionic conducting polymer film and shape memory alloy) based micro-robots in centimeter scale provide a solution to those delicate work. Unfortunately, most of existing micro-robots are in simple structure and equipped with little power, which results in a very limited range of activity [18]. A mother-son robot system based on the spherical robot was proposed to deal with this problem [19]. As shown in Fig. 3, the spherical robot acted as a carrier to expand the motion range of the micro-robots based on ionic conducting polymer film. After the micro-robots were sent out, the spherical robot provided power and control signals through an umbilical cable connected to the tail of the micro-robots.

![Fig. 3 Mother-son robot system](image)

Fig. 3 Mother-son robot system

C. Requirements for Intelligent Application

Limited by information science and electronic technologies, intelligent underwater robots or AUVs were not widely used until 1990s [2]. Ever since 21st century, to meet the requirements of missions in some extreme environments or even substitute manual-controlled ROVs, some functions or tech-
nologies (as rounds in Fig. 4) are essential to intelligent underwater robots.

1) Intelligence or Automation: An intelligent underwater robot should be a node of the information network which is able to acquire, store, transmit/receive and process data. On this basis, the robot should have functions of artificial intelligence such as autonomous navigation, path planning, swarm-robot or robot-network management, object tracking and etc.

2) Motion Performance: The motion of the robot should be fast, precise and stable. Under the influence of turbulence, water pressure and ocean currents, the system function of the robot varies over time and adaptive control algorithms are needed. Given the limitations of robots’ power, low-power actuators and advanced power systems are also essential.

3) Viability or Robustness: The recycle of an underwater robot may be difficult or even impossible, so the abilities of self-diagnosis and health management are expected.

4) Generalization or Interchangeability: The robot should be low-cost and easy to produce, maintain and update, so standard parts and modular design should be adopted.

Given the above, most of existing designs, including our spherical robot, cannot adapt to the development of intelligent underwater robot: non-standard mechanical part are used heavily, which results in high-cost, long production cycle and worse reliability. Meanwhile, application specific integrated circuits (ASICs) are major parts of the electronic control module of a robot, which increase power consumption and the design/update difficulty. 3-D printing technology and all programmable SoC provide a novel solution to these problems, in which both the mechanical structure and electronic module can be designed, simulated and updated with software.

III. MECHANICAL STRUCTURE DESIGN WITH 3-D PRINTING

A. Technology and Materials Selection

As previously introduced, because of spherical robots’ particularity in shape, a high proportion of non-standard or customized mechanical parts and components were used to construct the spherical robot, which significantly increased the prototype cost and production cycle and deceased the mate

precision and waterproofness. For instance, the hemispherical upper hull was produced through injection molding, which was very expensive in small batch production. And a commercial steel bar was machined into the bracket of an actuating unit which needed a lot of bolts, nuts and gasket to fix motors, jets and axles.

3-D printing is an infant technology which prints products on a layer-by-layer basis with material powder or beads. Compared with injection molding and cutting-based machinery, 3-D printing is able to produce custom products at relatively low prices and need no tools or molds, therefore it is more suitable for prototype production and function verification [20]. More importantly, 3-D printing is a manufacturing process which transforms mechanical drawings in computer-assisted design (CAD) software to products directly, so designers can focus on designing products rather than managing production process.

Existing commercial 3-D printers currently use various materials including aluminum, steel, titanium, ceramics, resins and plastics. But the major mature materials are engineering plastics such as acrylonitrile butadiene styrene copolymers (ABS), polylactic acid (PLA) and photocurable resin. TABLE I gives a brief performance comparison between current major materials for 3-D printing. As internally threaded parts and axles demand for better fit precision and wearability, we adopted photocurable resin, which is based on stereo lithography apparatus (SLA), to manufacture these precise parts. And we adopted ABS, which is based on fused deposition modeling (FDM), to manufacture most of the structural parts. As to gears and other driving parts, we adopted standard metal parts.

TABLE I

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<tr>
<th>Material or Craft</th>
<th>Performance</th>
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<tr>
<td></td>
<td>Strength</td>
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<tr>
<td>ABS</td>
<td>High</td>
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<td>PLA</td>
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<td>SLA</td>
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B. Mechanical Structure Design

The modified version of the spherical robot kept the original spherical shape and the amphibious motion mode. To improve the water-tightness and increase the diving depth of the robot, a double-insurance waterproof structure was designed in the upper hull. As shown in Fig. 5, the electronic control module and batteries were wrapped by the outer hemisphere hull and the inner square hull, in the margin of which notches were curved to install seal washers. Slots and notches were built on the round chassises to insert the printed circuit board (PCB), batteries and servo motors. And snap hooks and mounting bosses on the chassises were used to fix these devices or components, which facilitated assembly/disassembly and enhanced the shock resistance of the entire robot.

As shown in Fig. 6, to simplify the assembly of the actuating units, slots and elastic connectors were used on the bracket of an actuating unit to fix servo motors and water jets. And a simple gear
set, which contained two standard bevel gears, was equipped to transmit the torque provided by the servo motor to the axle which was vertical to the motor rotor. Slots and elastic connectors were used to fix servo motors and water jets. When install a motor, all need to do was to insert the motor just like sliding a clip. No bolts or nuts were used for assembly and the mechanical reliability is improved.

C. Simulation and Optimization

The bracket of an actuating unit, the material of which was ABS, was a key part which supported the weight of the whole robot. To test its mechanical properties, a simulation has been done with SolidWorks SimulationXpress. As shown in Fig.7, the flank of the bracket and the mounting holes for servo motor were selected as the fixtures. Given the weight of the robot was approximately 2.11 kg, a force of 30 N was applied on support surface. Figure 7 (a) showed that the maximum displacement was 2.994×10⁻¹ mm and the maximum von mises stress was 5.353×10⁶ N/m². The intersecting area of two vertical planes was the area of stress concentration. To reduce stress concentration and displacement, we optimized the design by thickening the part and adopting transition fillets on the edges of planes. Figure 7 (b) showed that the phenomenon of stress concentration still existed in the optimized design, but the area size of stress concentration decreased significantly. And the maximum displacement and von mises stress were reduced to 1.162×10⁻¹ mm and 3.461×10⁶ N/m².
IV. ELECTRONIC CONTROL MODULE DESIGN WITH ZYNQ-7000

A. Technical Characteristics of Zynq-7000

As we have introduced in Section II, the first version of the spherical robot was controlled by an AVR MCU, the processing speed of which is up to 16 MIPS. The performance of the processor is extremely limited and cannot satisfy the requirements of an intelligent robot design. Besides, the embedded software and the peripheral interface of the electronic control module were highly customized. That enhanced the difficulties to validate novel algorithms and upgrade the system.

SoC is an upgrade technology of field programmable gate array (FPGA). It supports the rapid deployment of algorithms or functional modules through designs based on hardware description languages (HDLs) or instantiations of intellectual property (IP) cores. Unfortunately, numerous properties or registers have to be configured when developing a SoC system based on FPGA, which is highly difficult to designers. The latest All Programmable SoC named Zynq-7000 proposed by Xilinx changes this situation [21]. Unlike existing SoC products, Zynq-7000 is centered with an ARM Cortex A-9 processor (Processing System in Fig. 8), one of whose peripherals is a Xilinx 7-Series FPGA (Programmable Logic in Fig. 8) which support customizing functional modules running in parallel. Meanwhile, basic devices (e.g. UARTs and memory controllers) for embedded system development are deployed in the form of hardcore, which decreases workload of hardware design significantly. The high performance advanced extendable interface (AXI) bus set and memory sharing mechanism are used for data interchange between the ARM processor and the IP cores.

B. General Design of Electronic Control Module

Figure 9 provides an overview on the modified electronic control module based on Zynq-7000. Servo motors, water jet motors and various sensors were still used to implement functions of the spherical robot. But the control mode and circuit structure were redesigned by substituting IP cores in Zynq-7000 for most ASICs.

The processing center of the improved electronic control module was a core-board which contained a Zynq-7000 and some necessary devices to run embedded Linux operating system including a crystal, a 512MB DDR2 SDRAM and a 1GB NAND Flash. The core-board installed on a larger mother board which provided power supply and connected with functional peripherals including motors and sensors. To ease robot upgrade and technology validation, four PMod sockets and a FMC slot were also available on the mother board to expand functions, upgrade hardware or install third part scientific instruments for special mission. PMod (usually for low-speed applications) and FMC (usually for high-speed applications) are standard connectors which support various buses or interfaces including low voltage differential signaling (LVDS), serial peripheral interface (SPI) and peripheral component interconnect (PCI). Controllers or interface modules for motors, sensors and expand modules were designed and instantiated with Verilog HDL in the programmable logic of Zynq-7000. And the final controllers were the Linux application programs running in the processing system of Zynq-7000. Those programs controlled the HDL modules though Linux system calls and AXI buses which connected the processor and the IP core.

C. Customized IP Core Design

As we have mentioned before, the greatest technological advantage of adopting Zynq-7000 is the improved expansibility and the convenience in system upgrade and technology validation. When testing a novel function or algorithm, there is no necessary to redesign the whole electronic sub-system. The only thing need to do is designing a daughter board with a PMod or FMC connector and then writing related HDL control modules and Linux programs.

To simplify the design of IP core in Zynq-7000, various buses or interfaces are provided to implement the interconnection between the processing system and the programmable logic. According to the requirement of data transmission speed, the designer can select AXI-Lite (for low-speed applications), AXI (for general applications) or AXI-Stream (for high-speed applications) to connect the IP core and the embedded system.

For instance, Fig. 10 shows the self-designed IP core for robot motion control. A sub-module (written in VHDL) generated by the Xilinx Design Tools automatically contained the definition of AXI Lite signals and control/state registers for motor control. And a self-designed module (written in Verilog HDL) was instantiated in this VHDL file to implement detail functions for sensor data analysis and PWM signal generation. The function of the module can be easily configured through...
register access, which was under the control of the software of the embedded system. The functional modification or upgrade can be completed by just redesigning the Verilog HDL module with software.

V. CONCLUSION AND FUTURE WORK

This paper proposed an improved technical solution for the design, development and evaluation of underwater robots. 3-D printing, which is a direct and efficient process from mechanical drawings on the computer to prototypes on the hand, was used for construct the body of our spherical underwater robots. And Xilinx Zynq-7000 All Programmable SoC, which integrates the advantages of FPGA and ARM-Linux embedded system, was adopted to integrate functions and modules of the electronic control module of the robot. Those two technologies effectively optimized the reliability and performance of the mechanical structure and electronic control modules. By applying the thought of modular and “all programmable” design in mechanical and electronic systems, the follow-up research on underwater robots will be much more efficient. To validate new algorithms, strategies or functions, we only need to design interchangeable modules with FMC or PMod connectors and then modify electronic and mechanical functions with software (Xilinx Design Tools, SolidWorks or CATIA). That liberates designers from toilsome productive works and broadens the design room for intelligent robots.

As we have talked about in Section II, the basic object to design an intelligent robot is to implement intelligent functions including system identification, adaptive control, automatic navigation, path planning, etc. We only implemented an embryo of the robot which contained elementary functions. In the follow-up work, we will design and then validate adaptive control algorithms on the platform of Zynq-7000.

ACKNOWLEDGMENT

This work was supported by the Fund for Basic Research (No. 3160012211405) of the Beijing Institute of Technology. This research project was also partly supported by National Natural Science Foundation of China (61375094), and Key Research Program of the Natural Science Foundation of Tianjin (13JCZDJC26200).

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