Northwestern Polytechnical University Design and Implementation of Autonomous Underwater Vehicle "Nemo III"

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***Abstract*—Nemo III is the third generation of the Nemo series of Autonomous Underwater Vehicles (AUVs) developed by NWPU-AUV Team for the 20^{th} Robosub competition. Successful elements from the 2016 competition vehicle, Nemo II, like open-shelf frame, modular design, are further polished while new elements, like dual-hull design, isolated pneumatic and navigation chambers, motherboard with PCI slots are first introduced for the good of utility and simplicity. The operating system has been translated from Windows into Linux, which brings stable performance at the cost of huge amount of workload. The trapezoid hydrophone array has replaced the previous cross array to avoid problems existed in endfire array.**

The depth and inertial sensors provide attitude information of the vehicle, while the cameras and hydrophones provide information of external objects. Novel algorithms are applied to calculate precise position relationships from acquired data and issue proper commands for navigation and actuation. After six-month development, the vehicle will be fully capable of autonomously completing the predefined missions set forth by the competition.

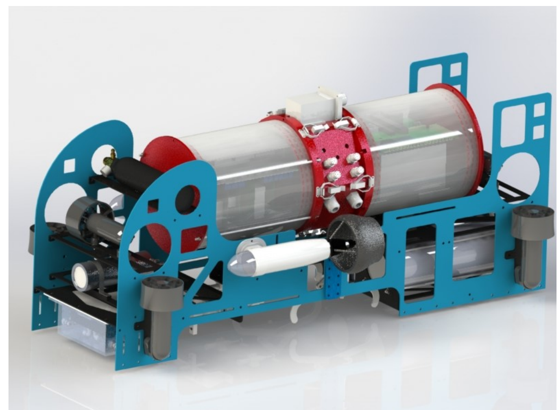

Fig. 1: Nemo III

I. Introduction

ONE of the main objectives of NWPU-AUV Team is to compete in the annual Robosub competition hosted by the Association for Unmanned Vehicle Systems International (AUVSI) Foundation and the U.S. Office of Naval Research (ONR). The team will compete in a challenging underwater course using an AUV designed and built by students to complete tasks like finding specific pingers, firing torpedoes and following the path. The tasks are tightly connected to the civil and military requirements and the competition environment is as challenging as the real ones.

NWPU-AUV Team is a group of over 30 multidisciplinary students studying at Northwestern Polytechnical University, ranging from freshmen to graduate students. Most team members come from School of Marine Science and Technology and all of the members have strong interests in underwater vehicles. The team is divided into five subteams, namely mechanical, electrical, control, vision and acoustics. All the subteams are dedicated to their respective work and cooperate well with each other all for the AUV Nemo III.

II. Design Strategy

Nemo III has been designed and developed in a six-month long process. Compared with Nemo II, the previous vehicle competed in the 19^{th} Robosub, it has been improved and perfected in modularity, flexibility, stability and general function. The mechanical system has been redesigned and substantial changes have taken place in electrical and software system.

Nemo III measures 44 inches in length, 22 inches in width, 19 inches in height. Its dry weight is 99 pounds. Those eight thrusters provide six degrees of freedom, namely surge, sway, heave, roll, pitch, and yaw. The new dual-hull design adopts acrylic over aluminum alloys as the main material, considering of both aesthetics and utility. Isolated pneumatic and navigation chambers are employed for the good of modularity. Two battery pods holding four lithium polymer batteries can sustain the vehicle for almost 6 hours.

Electronic components are distributed in the fore and aft hulls. Motherboard is used to place peripheral boards through PCI slots to decrease the complexity of wire routing and boards locating. Sensors in terms of vision, acoustics, inertia, depth acquire related information transmitted to controller. The software system, run on a single board computer with a quad core Intel i7 CPU, collects and processes information to issue proper commands of navigation and actuation.

III. Vehicle Design

A. Mechanical

The mechanical system of Nemo III consists of the frame, main hull, actuators, and separate enclosures. The hull and enclosures are responsible for sealing circuit boards, battery pods, sensors, and pneumatic components, while the actuators including thrusters, active grabbers and torpedo launchers for providing functionality. Inspired by the experience last year, the new design of the mechanical system adopts innovative technologies and crafts bravely. Acrylic is first used as the major material instead of the nontransparent aluminum alloys, considering of both aesthetics and utility. The layout of the vehicle is well designed to ensure a minor positive offset from neutral buoyancy, which saves from troubles of configuring buoyancy blocks.

1) Frame:

The frame is responsible for mounting many peripherals and providing robust structure for the vehicle. Thus, open-shelf frame is adopted to the benefit of modularity, flexibility, and portability. Lightness and rigidity of the frame is a trade-off issue, which has been balanced by using aluminum alloy with holes carefully cut out on it.

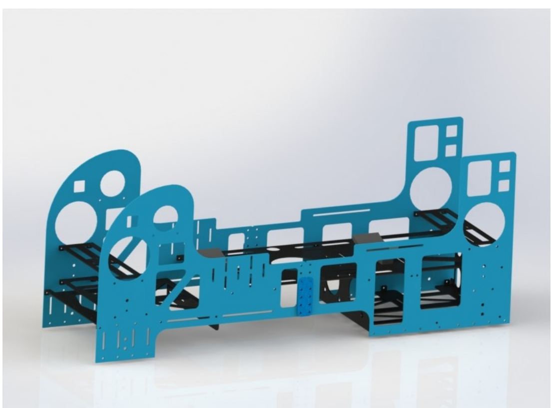

Fig. 2: A SolidWorks Rendering of Nemo III's Frame

An important issue to be considered is the complexity of assembly. Reduced number of total parts, combining with different colors, blue for lateral frames and black for the base, are employed to facilitate the assembly.

2) Main Hull:

Dual-hull design is the biggest change of the mechanical system. The fore and aft hulls host electronic components and the middle chamber posits the bottom camera and connectors. O-rings are sandwiched between the end parts of hulls and grooves of end caps for sealing. The placement of middle chamber connected to sealed end parts by snap rings is fixed, which avoids wrong installation.

The casings of tubular hulls are made of acrylic, the transparent feature of which makes it easy to supervise the states of internal components and more importantly, water seepage. The fore and rear end caps, along with the middle chamber still use aluminum alloy because of its good thermal conductivity.

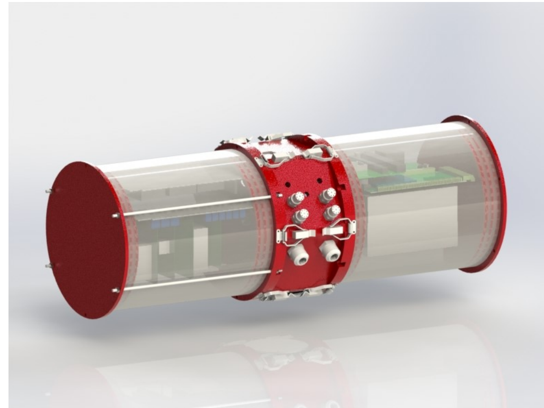

Fig. 3: A SolidWorks rendering of Nemo III's main hull

3) Actuators:

Eight thrusters are used to provide station keeping and attitude control for Nemo III, 4 for heave, 2 for surge, and 2 for sway. Surge thrusters have been changed to VideoRay thrusters due to their powerful propulsion, while SeaBotix thrusters with smaller size are kept as heave and sway thrusters for high-accuracy control.

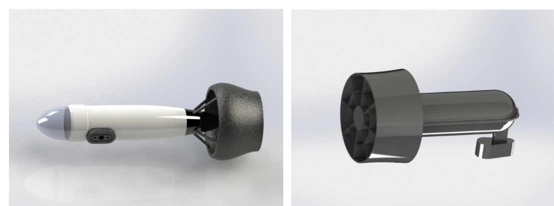

Fig. 4: VideoRay(left) and SeaBotix(right) Thruster

4) Enclosures:

a) battery pod: The hull of battery pod is made of acrylic while the end caps of nylon plastics. Accordingly, the status of batteries shown on a LED display can be easily observed. The battery pods have been designed to be convenient to install or remove because they are the most frequently disassembled parts during the testing.

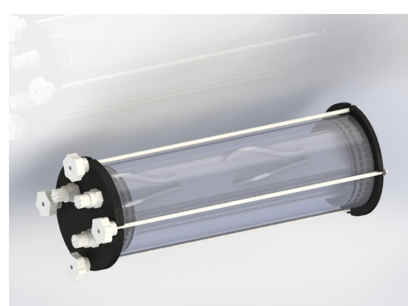

Fig. 5: A SolidWorks rendering of Nemo III's battery pod

b) pneumatic component: The enclosure of pneumatic component is cuboidal in shape, with aluminum alloy hull and acrylic upper end cap. There are 2 two-position five-way valves and 2 three-position five-way valves inside, with conflux boards adopted to save space. Compared with Nemo II, the pneumatic component has been upgraded in many ways, like adopting more regular gas system and more rigid hull.

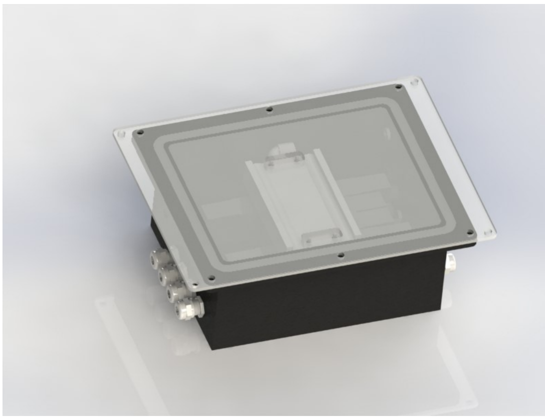

Fig. 6: A SolidWorks Rendering of Nemo III's Pneumatic Component

c) navigation chamber: The navigation chamber is a newly designed cubic nylon plastics enclosure, holding a device acts as the Attitude and Heading Reference System (AHRS). The goal of this chamber is to isolate the sensors from the electromagnetic noise caused by the thrusters and electronic components.

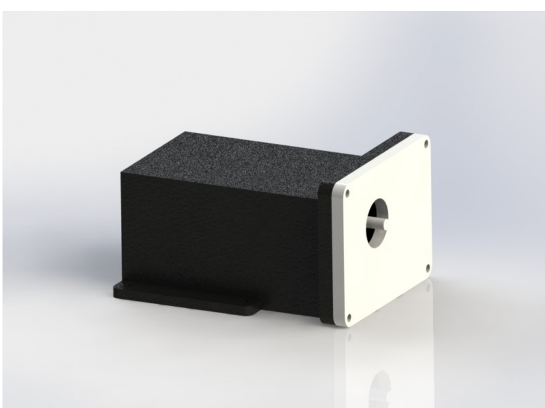

Fig. 7: A SolidWorks rendering of Nemo III's navigation chamber

B. Electrical

The primary goal of the electrical system is to ensure a robust and efficient hardware platform for the software system, and improvements, therefore, have been made in several aspects. STM32 has been chosen as the main controller for its high performance and robustness, substituting for the Arduino mega2560. In terms of layout, motherboard has been used to decrease the complexity of wire routing and boards locating. Its also worth mentioning that most boards are designed and developed in-house.

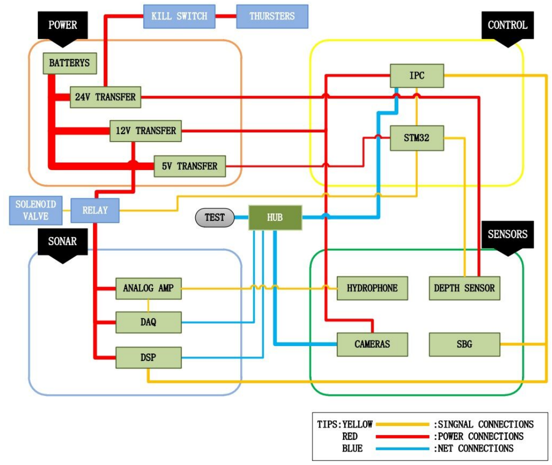

Fig. 8: Block Diagram of Nemo III's Electrical System

1) Single Board Computer:

The software on the vehicle is powered by an Intel i7-6700 quad core processor clocked at 3.4GHz. It communicates and commands the power management, motion controller, and acoustics unit according to the demands of specific tasks.

2) Motherboard:

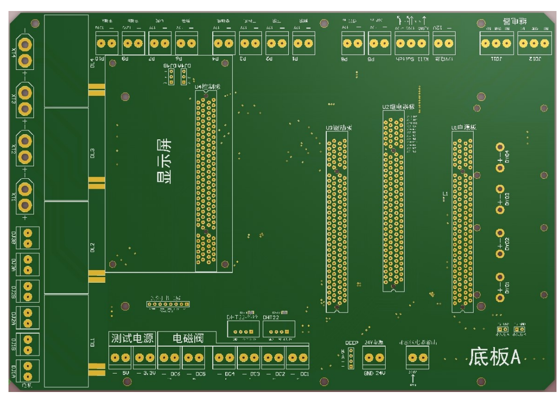

Fig. 9: Motherboard A

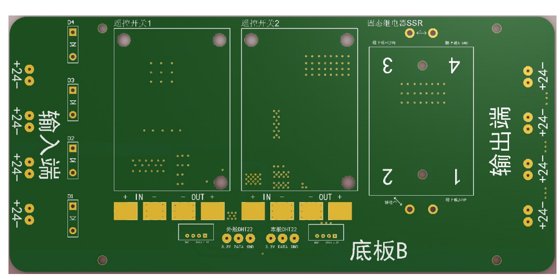

Fig. 10: Motherboard B

Motherboard is divided into two boards, with large components, like remote switches and solid-state relays, on the board B, and PCB boards on the board A. Board B is piled above board A with a gap of 3cm. The power unit, relay unit, drive unit, and control unit are separated on four PCB boards that are all connected to the motherboard through PCI slots to reduce the number of wires and make full use of space.

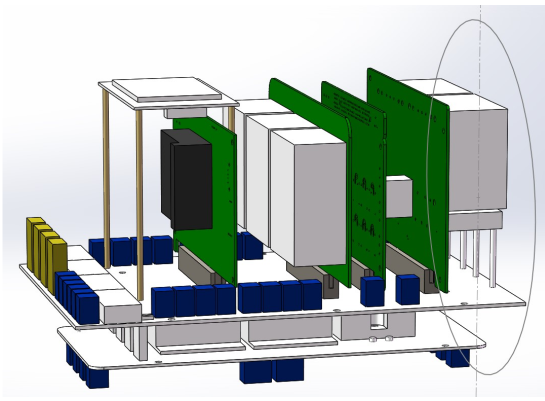

Fig. 11: Overall Layout

3) Power Management:

Four hot swappable, 24v lithium polymer batteries, providing a run time of 6 hours, power the whole system. It takes around two hours to fully charge a battery, so in order to work for the whole day without a break, we have eight batteries in total, four in a group, which work in turn. Standard +5, +12, +24-Volts supplies are also accessible through different kinds of DC/DC converters to drive all sorts of sensors.

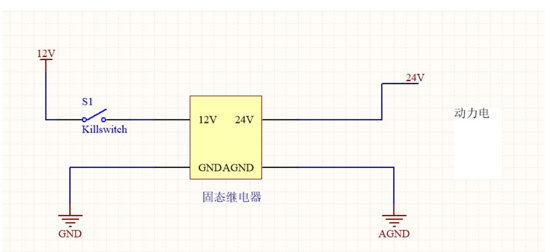

Fig. 12: Operating Principle of Killswitch

The kill switch is used to cut off the power supply to thrusters quickly in case any dangers might occur. A solid-state relay has been used to control the 24V power supply via the 12V power supply. The kill switch this year has been designed like a large screw outside the main hull, which is bright yellow and very easy to spot. When the kill switch is screwed a little bit looser, the power supply to the solid-state relay is cut off, so the thrusters will stop immediately. It has been tested many times underwater to guarantee that it will work during the competition.

4) Serial Communication:

The serial communication is the interface between the computer and various sensors and custom designed boards. Sorts of communication ports such as the UART/USART, SPI, CAN, and I2C bus, are provided by STM32. The RS-485 protocol has been chosen because it is noise tolerant and widely used, and the RJ-45 protocol has been chosen because of its scalability.

5) Control system:

The STM32F103ZG core board and customized peripheral PCI boards are the core of control system. They communicate with embedded computer through the UART-USB port. Compared to previous controller mega2560, it takes on an additional task to process data, which was once directly transmitted to the computer, from deep sensor. STM32 can share responsibility for the computer and provide stable performance with high work frequency, large data capability. It also provides enough PWM channels and IOs to control the thruster drive board and relays.

6) Acoustics unit:

The acoustics unit is divided into three stages mentioned blow.

- signal conditioning
  Every channel is signal conditioned before being converted to digital signals. After preamplification and band-pass filtering, the center frequency and passband width of which are adapted to the desired signals.
- data acquisition
  The DAQ EM-9118B with 16bit sampling-resolution is applied for real-time and synchronous sampling of conditioned four-channel signals.
- signal processing
  The digital signal is transmitted to a digital signal processor at high speed. Therefore, quad-core Texas Instruments TMDSEVM6678L clocked at 1.0GHz is used to process element data and finally measure the bearing angle of the specific pinger with respect to the vehicle.

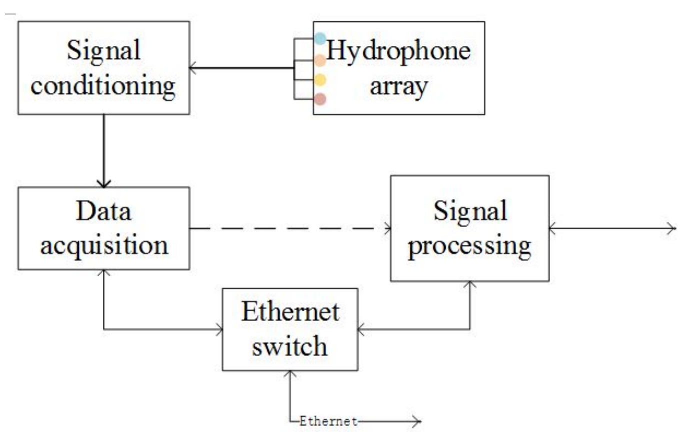

Fig. 13: Three Stages of Acoustics Unit

7) Sensors:

a) camera: The Manta G-046C industrial color camera, provided by Allied Vision Technologies, has been chosen for front and bottom cameras, with fixed-focal length, 5 mm wide-angle lenses from a Japanese company Computar.

This camera-lens combination allows capturing very high quality images because they provide precise flexibility in focus, aperture, and white balance. To ensure a relatively high transfer rate, cameras communicate with the on-board computer through Gigabit-Ethernet switches.

Fig. 14: Manta G-046C(left) and Computar 5 mm Wide-angle Lens(right)

b) hydrophone: Four Reson TC4013 piezoelectric elements are used to detect incoming acoustic waves and are kept separated to avoid noise. TC4013 offers a wide range of frequency from 1 Hz to 170 kHz and uniform omnidirectional sensitivities in both horizontal and vertical planes.

c) orientation: The SBG Ellipse-A, which is a small-sized Attitude and Heading Reference System (AHRS) with high performance, has been chosen as a navigation device for some sophisticated tasks. It provides attitude information including roll, pitch, heading, and heave.

Fig. 15: Hydrophone TC4013

C. Software

Nemo IIIs core software runs on Ubuntu 16.04 LTS operating system, built upon Qt5.3. All the programs are written in C/C++, supplemented by templates and built-in functions of Standard Template Library (STL) and Boost library. For efficient maintenance and development in the future, the environment has been chosen over windows 7 with Visual Studio 2010 because it enables programmers to develop simple and stable code with high compatibility, inherited attributes and portability. The software system is comprised of blocks on different hierarchical levels, main program and vision unit on upper level, slave programs, communication programs and the acoustics unit on lower level.

1) Architecture:

a) main program:

- The status monitor module supervises the heading, the speed of thrusters, the status of relays and so forth and displays these states on a window synchronously.

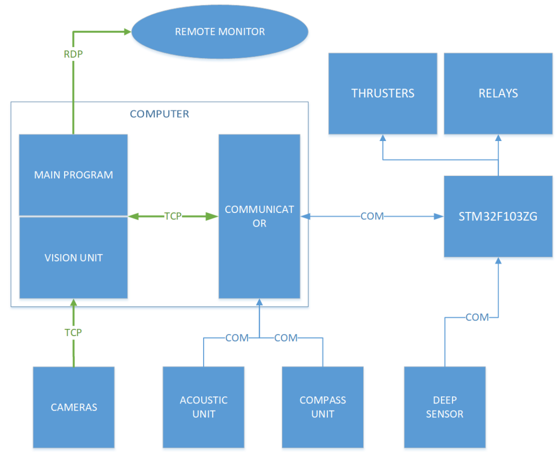

Fig. 16: Nemo III's Software Block Diagram

- The Remote control module has its own independent flow of control, enabling single-action controls, like the rotation of motors and the switch of relays, done by clicking button on interface widgets.
- The newly designed parameter edit module facilitates debugging according to previous experience. Parameters changed in files and Config Editor widget both can be entered into configManager class and be processed in real time.
- The control module is responsible for autonomous tasks operating, which is the kernel module tightly connected to any other module in the software system.
- The communication module takes charge of communicating between the upper level and the lower level, transmitting data and commands via the transceiver class.

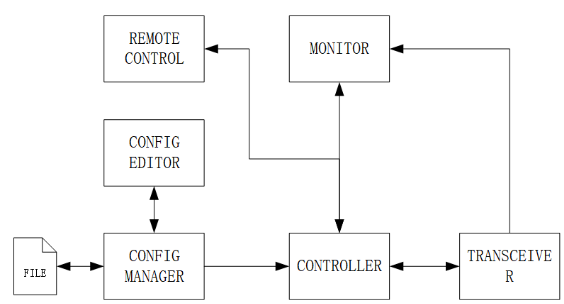

Fig. 17: Nemo III's Core Control Flow

b) vision unit:

Source images, captured by front/bottom camera, can be dynamically loaded into the image processing program to save computer resources. Open source OpenCV library is used during the process. The results of image processing are stored in public variables for main program to poll.

In consideration of the complex underwater imaging environment, the quality of image is poor. Suspended mineralogical materials and intense illumination both degrade image quality seriously. Accordingly, applicable image preprocessing operations are inevitable. Adaptive exposure and white balance control is added to enhance camera performance. Besides, image enhancement algorithms based on histogram are used to enhance image quality.

Fig. 18: Source Image(left) and Preprocessed Image(right)

A combination of edge detection, color threshold, morphology operation is performed on each frame to detect the position of assigned objects. The input image is converted from RGB space into HSV space. All six channels: red, green, blue, hue, saturation, and value, are extracted and part of them are segmented through predetermined threshold for subsequent processing.

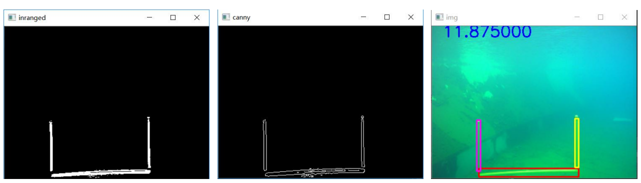

Fig. 19: Navigation Pass Detection

c) slave program:
The slave program runs on STM32F103ZG, which combines commands received from upper computer and data acquired from depth sensor to calculate correction of heave thrusters. Actions can be realized by controlling relays and motor drivers via pins.

d) communication program:
The communication program takes charge of communicating in the lower level. It acquires data from IMU and acoustics unit and transmits them to STM32 and main program accordingly. It connects to the communication module in the main program to receive commands and send data.

e) acoustics unit:
Four hydrophones are laying into trapezoid array and cross-spectra algorithm is used for angle position. It can accurately calculate the heading and elevation of a pinger relative to the vehicle. Stream data following a customized exchange protocol are extended over Ethernet to the vehicles main computer, so that, with the combination of data from IMUs and the depth sensor, the main computer can realize navigation control.

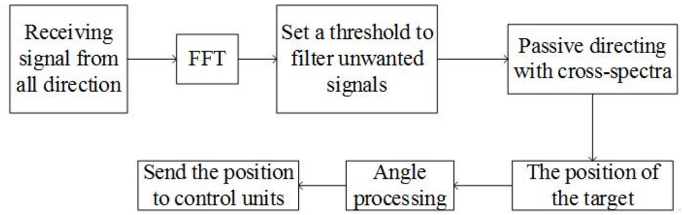

Fig. 20: Algorithm Flow

Four hydrophones are laid in four vertexes of the trapezoid, three of the sides of which are in length of $\lambda/2$. Every two elements can calculate an angle. Two of three angles representing two vectors can compound a three-dimensional coordinate vector. Compared to the cross array, the new array avoids the end-fire situation which will bring pendulum and amends error of previous approximate coordinate, greatly improving the reliability and stability of orientation.

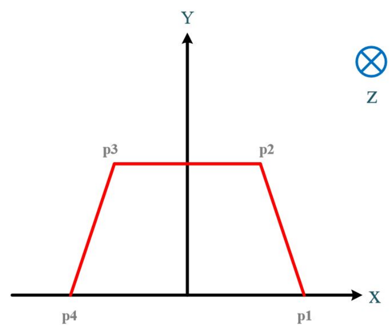

Fig. 21: Hydrophone Array

2) Mission Planner:

a) task list:
The task list is an innovative and user-friendly design which enables to sort each task simply by a click on the interface widgets. Each task is kept in a specified file which will be loaded in the beginning of the main program. According to users ordering, the corresponding task list with task identifiers will be sent to the control module. The control module then adds task description structs in order into a linked list of task queue and puts pointer to the head to start task scheduling.

Fig. 22: Task List

b) task scheduling:
The task description struct includes a task initialization

function pointer, a control frame function pointer, and a task termination function pointer. The initialization function pointer points to the initialization configuration function, which initializes counters, task status, vision unit, parameters of PID, etc. The control frame function inspects current data of running state, decides and executes next action. The termination function destroys related private variables and keeps the vehicle idle.

During the task scheduling, the control module first takes out the initialization function pointer, and then associates the control frame timer with the control frame function pointer. The following operations are autonomously and regularly controlled by the timer until the termination function invokes the endTask() function.

c) dynamic task assignment:

The tasks can be sorted not only by predetermination, but can also be changed by the specific circumstances. Especially for missions like random pinger, the task order should be changed due to location of the pinger. The usage of linked list seems quite suitable for the dynamic assignment because task queue can be easily modified. For example, once the random pinger is located, tasks nearby will be added into the linked list before another pinger mission.

3) dynamic subtask:

Subtasks like rotating by specific angle, going backwards for 10 seconds needed in other tasks are tricky problems. Coding repeatedly in different tasks means less flexibility and expensive costs. Thus, framework API is introduced to handle the problem. The development of a framework API is obviously not trivial, but it is really effective to simplify and adds robustness to the program.

State stack is indispensable for preserving the previous status to resume the suspended task. State is kept in a struct containing current task pointer, current subtask identifier, a private counter, current inter-frame space, and current parameter. The state is pushed when switching to the subtask and popped when back to the previous task.

4) Parameter Loading:

Parameters used to exist in forms of constant objects which brings troubles that the program needs to be compiled once modified. Two methods have been applied to edit parameters without trouble of compiling. One is saving parameters in agreed format in text file and the other is editing parameters in table or list presented on the interface. Parameters edited in the text file can be parsed into data by regular expression and those edited in the interface can be loaded in real-time even when the tasks are running. This increases the debugging efficiency enormously.

One set of parameters is identified by a unique CONFIG_ID, which will be read and stored in a map in the beginning of the program and is managed by the configManager class. The required parameters can be achieved through the interface function and loaded to the task status struct. One set contains PID parameters of surge and sway thrusters controlled by upper computer.

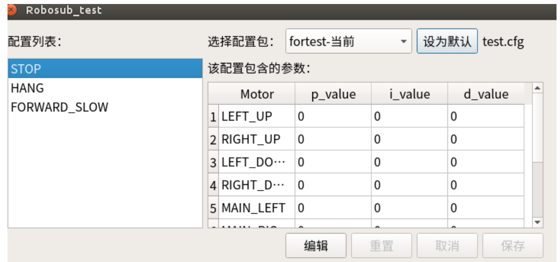

Fig. 23: Configuration List

IV. Experimental Results

Nemo III is now in the pool testing phase. Since the mechanical system of the vehicle is a brand-new design, the testing is facing lots of new challenges. Testings of electrical system and software system are carried out at the same time. The first underwater testing took place in early June. Testing is proceeding smoothly in an orderly way.

Fig. 24: Assembly Process

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