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

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***Abstract*—Nemo Carrot is the fourth generation of the Nemo series of Autonomous Underwater Vehicles (AUVs) developed by IMVT for the 21th Robosub Competition. Successful elements from the 2017 competition vehicle, Nemo III, like dual-hull design, isolated pneumatic and navigation chambers, motherboard with PCI slots, are further polished while new elements, like vision processing with neural networks, brand new mechanical claws, are first introduced for the good of utility and simplicity.**

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.

I. Introduction

THE primary objective of IMVT is to design and build an autonomous underwater vehicle (AUV) to deal with the challenges that mirror real world tasks. The formost goal of IMVT is to help its members develop engineering, communication, and collaboration skills in a hands-on environment. Additionally, the team takes part in the AUVSI International RoboSub competition which provides both the engineering constraints and extra motivation to the team annually.

IMVT is a group of over 30 multidisciplinary students 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 Mechanical, Electrical, Control, Vision and Acoustics sub-teams. All of the sub-teams are committed to close cooperation to maximize the chances for success in the RoboSub competition.

II. Design Strategy

Nemo Carrot has been designed, developed, manufactured and tested over six months. And Nemo Carrot draw heavily on the past experience building Nemo Seiries, especially Nemo III, the previous vehicle competed in the 20th Robosub, bringing together the advanced and sophisticated technology to build our best AUV ever.

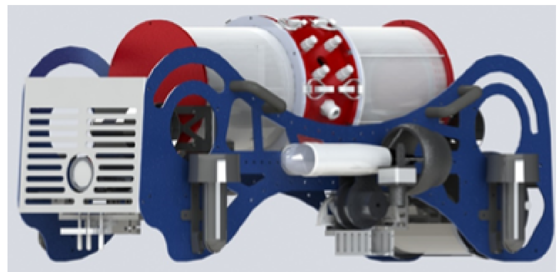

Fig. 1: Nemo Carrot

Compared with Nemo III, Nemo Carrot 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 Carrot measures 40.75 inches in length, 22.44 inches in width, 17.13 inches in height. Its dry weight is 103 pounds. 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. Battery pod holding five lithium polymer batteries can sustain the vehicle for almost six hours.

Electronic components are distributed in the fore and aft hulls. Sensors in terms of vision, acoustics, inertia, depth acquire related information transmitted to controller. The software system, running 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 Carrot consists of the frame, main hull, actuators, and separate enclosures. The hull and enclosures are responsible for sealing circuit boards, battery pods, and sensors components, while the actuators including thrusters, active grabbers for providing functionality. Inspired by the experience last year, the new design of the mechanical system adopts innovative technologies and crafts bravely. 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. we optimized the overall layout, especailly compacting the structure and reducing the material. 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, The color of the side cutting pieces is blue, while the sheet metal parts is black.

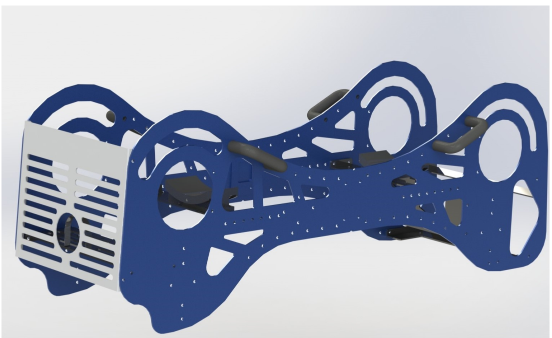

Fig. 2: A SolidWorks Rendering of Nemo Carrot's Frame

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:
Nemo Carrot followes the design concept of NEMO III's main equipment cabin, with the the idea of piecewise design, we divide the circuit into two parts, which are located on both sides. Middle cabin is used to fixed connector, the downward camera is also placed in the middle cabin. Spring card buckle is designed to fix the two cabins. It's easy to disassemble and conducive to the maintenance of the internal circuit of the vehicle. The body material of main equipment cabin is organic glass, the others are made up of aluminum alloy.

In terms of the overall size, the axial length of the vehicle was reduced by 30mm, the diameter by 20mm, The smaller overall volume makes the mass decrement.

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.

3) Actuators:
Eight thrusters are used to provide station keeping and attitude control for Nemo Carrot, 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.

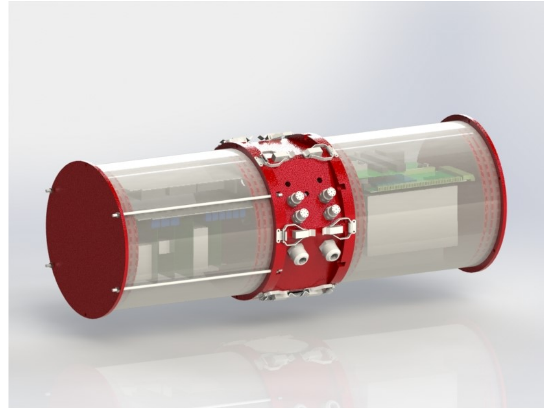

Fig. 3: A SolidWorks Rendering of Nemo Carrot's Main Hull

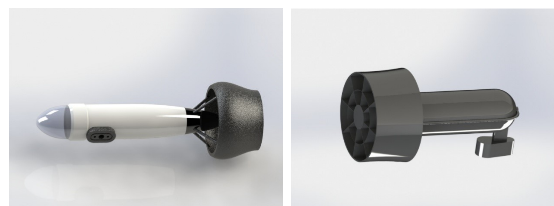

Fig. 4: VideoRay(left) and SeaBotix(right) thrusters

4) Enclosures:
a) battery pod: The hull of battery pod is still made of acrylic while the end caps of nylon plastics. Accordingly, the status of batteries shown on a LED display can be easily observed. Compared with the previous generation of vehicles, the number of battery pods changes from two to one, reducing the mass and the volume. The battery pods have been designed to be convenient to install or remove because they are the most frequently disassembled parts during the testing.

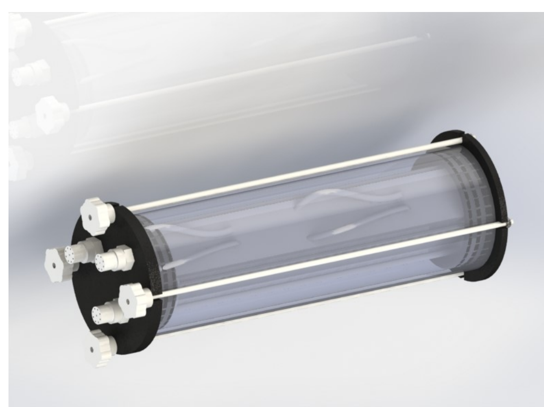

Fig. 5: A SolidWorks Rendering of Nemo Carrot's Battery Pod

b) steering chamber and mechanical claws: The mechanical claws that perform the task are controlled by the helmsman. Mechanical claws are used to drop the ball, the right and left two mechanical claws achieve the ball placement with the help of slider crank mechanismwhile the material of the connecting mechanism is aluminum alloy, the guide rails and sliders are engineering plastics and the mechanical claws are PLA 3D printings.

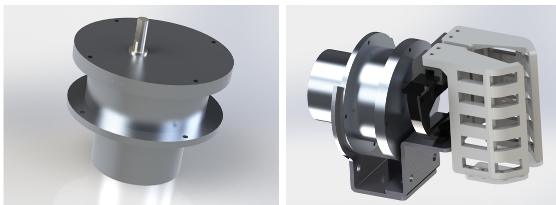

Fig. 6: Steering Engine Chamber(left) Mechanical Claw(right)

Griping mechanical claw is similar to the dropping one, but the griping claw is more sophisticated cause the ball griping is realized through the modified PLA mechanical claw and the special camera.

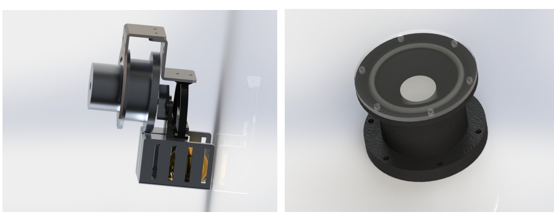

Fig. 7: The mechanical claw(left) and The Matching Camera(right)

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.

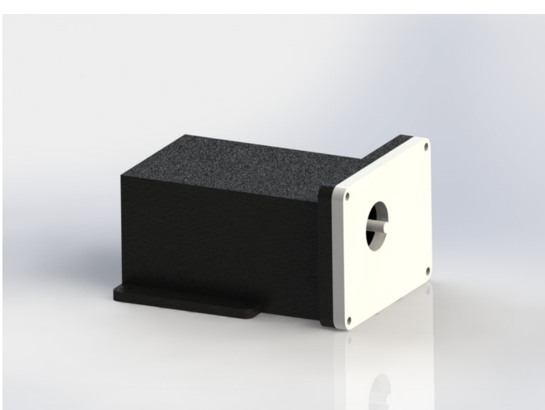

Fig. 8: A SolidWorks Rendering of Nemo Carrot's Navigation Chamber

B. Electrical

The primary goal of the electrical system is to ensure a robust and efficient hardware platform for the software system, therefore, improvements have been made in several aspects.

This control system consists of single-board computer and single-board microcontroller two levels system. The single-board computer with an Intel i7-6700 quadcore processor is used to handle image data and control the systems with its powerful performance.

Nemo Carrot makes full use of STM32 as the main controller for its high performance and robustness. STM32 can be used to communicate with single-board computer, process data and control the motors. Combined with power circuits, acoustics unit and other sensors, Nemo Carrot can achieve lots of the functions and complete a series of prescribed tasks.

In addition, we also designed the PCB boards to be circular to improve utilization of the space.

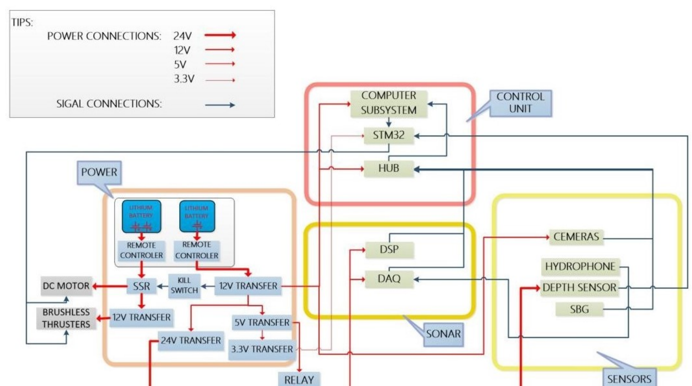

Fig. 9: Block Diagram of Nemo Carrot's Electrical System

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) PCB Board:

To fit and operate vehicle perfectly, IMVT designs four custome electrical PCB boards, namely Digital Power Board, Motor Power Board, Control Board and Drive Board. Digital board is responsible for the power supply of the entire AUV digital system, and Motor Power board for the eight propellers. Control board is the core of lower position machine system, meantime Drive board is used to drive motors.

3) Power Management:

Two 6S Li-Po Batteries will provide power for digital

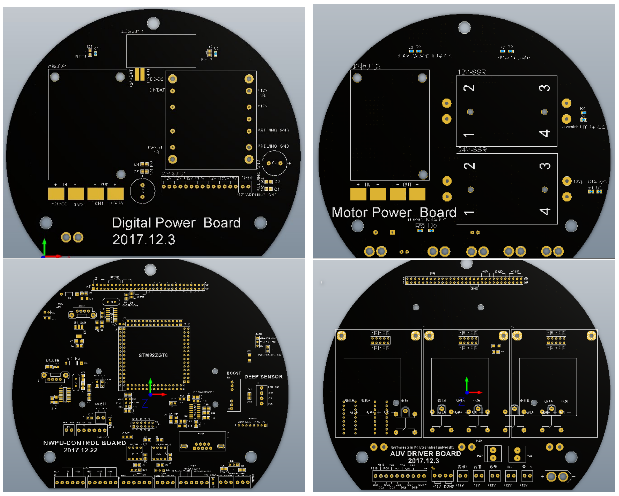

Fig. 10:
Digital Power Board(up left), Motor Power Board(up right), Control Board(down left), Overall Layout(down right)

system and brush DC motor, while the power supply of the two main brushless thrusters is independent from other electrical parts. Nemo Carrot uses another three 3S Li-Po batteries separately for brushless thrusters. Each battery is endclosed inside a battery hull, which allows for both charging and discharging.

The battery capacity of the 6s Battery is 8000mAH, so as the 3S Batteries. These batteries extend Nemo Carrot's testing time up to 240 minutes before a recharge is required.

Because the whole power mainly consumed by the motor which enables the AUV to move forward, turn back, dive up and down. Besides, It takes around two hours to fully charge a battery, so in order to work for the whole day without a break, Nemo Carrot has ten batteries in total.

In digital power system, we cannot power the sensor and the processor directly by the batteries and each module has different power voltage. So we used several isolation module, including 24V-12V module, 12V-5V module and 5V-3.3V module. Which is so beneficial for the digital system too, the supply voltage can be maintained unchangeable and the ground is isolated from the thrusters.

In order to cut off the power supply of the thrusters quickly, Nemo Carrot has a kill switch. The kill switch is designed to generate a pulse signal applied for the solid-state relay(SSR), which can control the power supply of all the thrusters. The kill switch on Nemo Carrot this year has been designed like a large screw outside the main hull. Considering that the kill switch is the only phyical control interface with the vehicle underwater, Nemo Carrot's kill switch is bright yellow, which means easy to spot. When the kill switch is screwed a little bit looser, the power supply to the solid-state relay is cut off, then the thrusters will stop immediately. It has been tested many times underwater to guarantee that it will work properly during the competition. switch is bright yellow, which means easy to spot

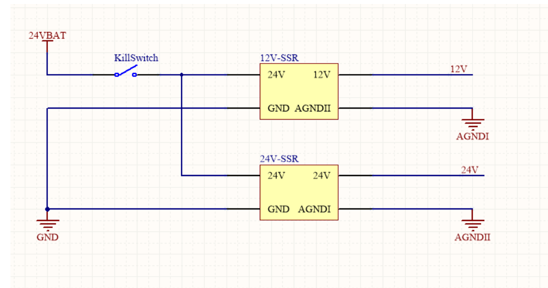

Fig. 11: Operating Principle of Killswitch

4) *Serial Communication:*

The serial communication is the main interface among the computer, various on board sensors and custom designed PCB 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.

It is generally accepted that RS-485 can be used with data rates up to 10 Mbit/s or, at lower speeds, distances up to 1200 m. With RS-485, Nemo Carrot can easily read depth data from the depth sensor instantly. Apart from all the serial communications and considering the mass data and frequent data exchange among the camera, CPU and DSP, an ethernet switch is equiped so massive data can be quickly transferred among the industrious motherboard.

5) *Control system:*

The STM32F103ZG core board and customized peripheral PCI boards are the core of control system. Both of them communicate with embedded computer through the UART-USB port. STM32 can share responsibility for the computer and provide stable performance with high work frequency, large data capability, so the STM32 takes on an additional task to process data, which was once directly transmitted to the computer, from deep sensor. Also, STM32 provides enough PWM channels and IOs to control the thrusters' driver board and relays, which in turn full 6-degrees of freedom control

Additionally, compared to past Nemo series, we develop more advance control technology to get a better control of vehicle. PID (Proportional Integral Derivative) control loops are totally redesigned. Both adaptive PID control based on back propagation neural network and incremental PID control based on anti-windup technology are first developed on Nemo's control system, as result, these strategies allows for significantly decreased time spent in testing and debugging.

6) *Acoustics unit:*

The acoustics unit is divided into three stages mentioned blow.

- Signal Conditioning
  The hydrophones vary in acoustic output for a given input power. The gain of preamplifiers, power amplifiers, and filters differs from brand to brand and circuit to circuit. The underwater acoustic system uses a custom signal conditioning board, which has the following characteristics:
  1) Four-channel data processing
  2) Passband frequency: 15kHz $\sim$ 47kHz
  3) Stopband frequency: 100kHz $\pm$ 3dB
  4) Stopband attenuation: $\geq$ 40dB
  5) Gain: 1000 times(60dB)
  6) In-band ripple: $\leq$ 0.5dB
  7) Amplitude consistency: $\leq$ 0.5dB
  8) Phase consistency: ≤ 1
  9) Power supply: 12V DC

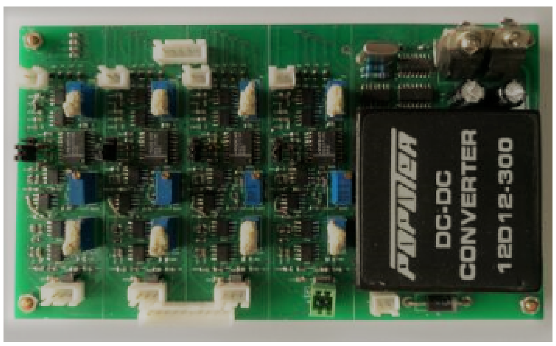

Fig. 12: Signal Conditioning Board

- 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
  Texas Instruments TMS320C6678 Multicore Fixed and Floating Point Digital Signal Processor which based on TI's KeyStone multicore architecture, integrated with eight C66x CorePac DSPs, while each core runs at 1.0 to 1.25 GHz enabling up to 10 GHz is used for acquiring data at high speed and for final processing of the signals for calculation of bearing angle to the specific pinger with respect to the vehicle.

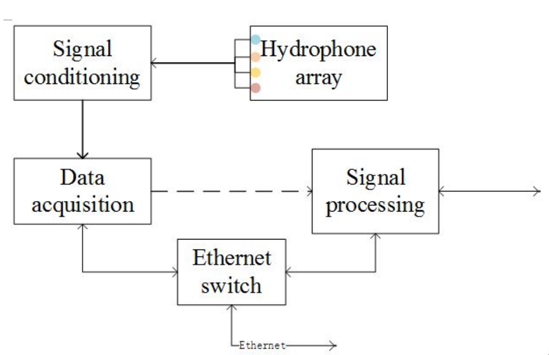

Fig. 13: Three Stages of Acoustics Unit

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: The hydrophone system uses four Reson TC-4013 piezoelectric elements to detect incoming acoustic signal and is kept separate from other electrical compontents due to noise jamming. The TC4013 offers a usable frequency range of 1 Hz to 170 kHz. It furthermore provides uniform omnidirectional sensitivities in both horizontal and vertical planes up to high frequencies, which can receive signals from any directions.

Fig. 15: Hydrophone TC4013

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 in both static and dynamic conditions

C. Software

Nemo Carrot's core software runs on Ubuntu 16.04 LTS operating system, built upon Qt 5.3. All the programs are developed in C/C++, supplemented by templates and built-in functions of Standard Template Library (STL) and Boost library. 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.

Fig. 16: Ellipse-A AHRS Motion Sensor

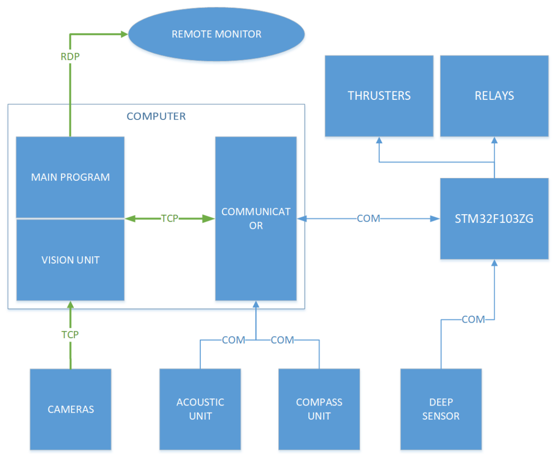

Fig. 17: Nemo Carrot's Software Block Diagram

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.
- 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 communicate module takes charge of communicating between the upper level and the lower level, transmitting data and commands via the transceiver class.

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

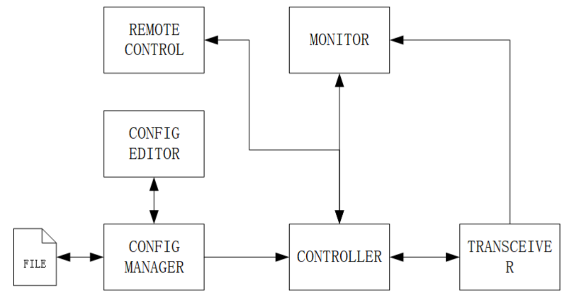

Fig. 18: Nemo Carrot's Core Control Flow

stored in public variables for main program to poll. Also, in order to prevent the naming conflicts of variables, we use the namespace in C++, and use a lot of C++'s class to make the software more modular.

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.

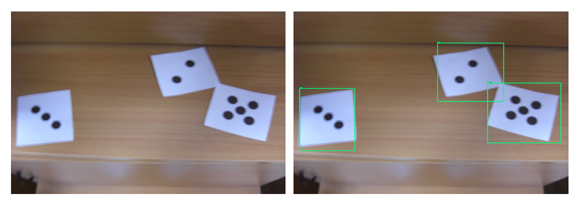

Fig. 19: Source Image(left) and Image after detect(right)

For the task of finding dice, we used the SSD-MobileNet convolution neural network, using TensorFlow open source deep learning framework, we collected 500 pictures of different time and different locations, using LabelImg software manual annotation, make them into a training set. Then, after 20,000 steps of training on Nvidia-Titan-V, our results reached 20 frames per second and the recognition rate reached 80 persents. Therefore, we can realize real-time high-speed identification. At the same time, we will use Nvidia-Jetson-Tx2 to run the classify code to ensure the real-time performance of the code.

The picture above shows the results of our training and the actual results.

For the task of passing through the gate, we have fully combined the template matching method with the color recognition technology of adaptive threshold value and edge detection, color threshold, morphology operation, and achieved the task of passing through the door stably and efficiently.

Fig. 20: Source Image(left) and Preprocessed Image(right)

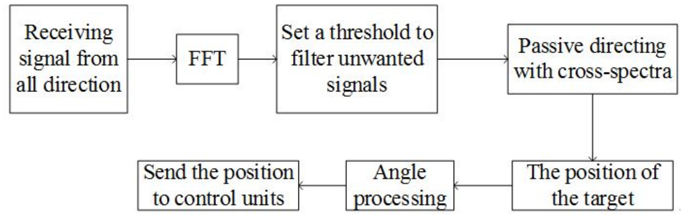

Fig. 22: Algorithm Flow

As far as possible in order to reduce the recognition error rate, make the submarine to make the right judgment, we use the method of template matching, and combined with edge detection, realized the high precision calibration, effectively reduce the submarine of miscalculation.

We cooperate with mechanical, skillfully using small cameras installed in the mechanical paw, and, in conjunction with the control code implemented more flexible mechanical arm craft operation, so as to fully improve the fetching of mission success rate.

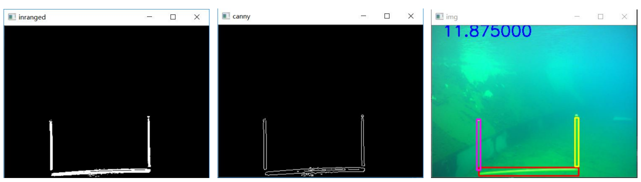

Fig. 21: Navigation Pass Detection

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 calculating 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, meanwhile, with the combination of data from IMUs and the depth sensor, the main computer can realize navigation control.

Four hydrophones are laid in four vertexes of the trapezoid, three of the sides of which are in length of $\lambda/2$, and λ is the wave length of signal. 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.

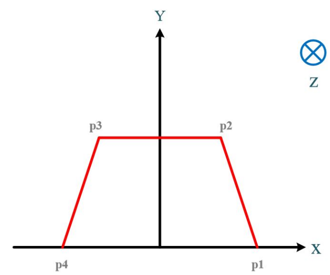

Fig. 23: Hydrophone Array

2) Mission Planner:

a) task list:

The task list is an innovative and user-friendly UI design which enables to scheduling tasks simply by some clicks 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 user's scheduling, 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.

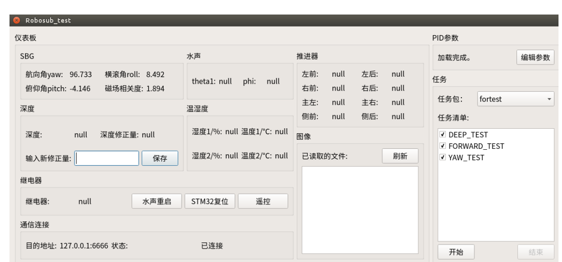

Fig. 24: Task List

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 and configuration function, which initializes counters, task status, vision unit, parameters of PID and so on. The control frame function inspects current data of running state, makes decision and executes next action. The termination function destroys related private variables and keeps the vehicle idle to wait until the next process excutes.

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 scheduled 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.

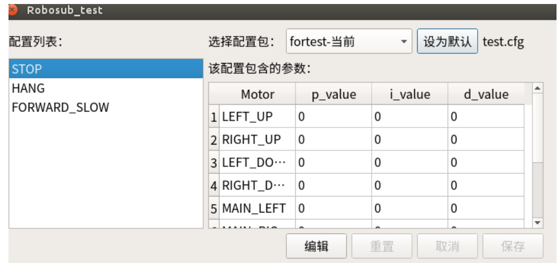

Fig. 25: Configuration List

IV. Experimental Results

Nemo Carrot 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.

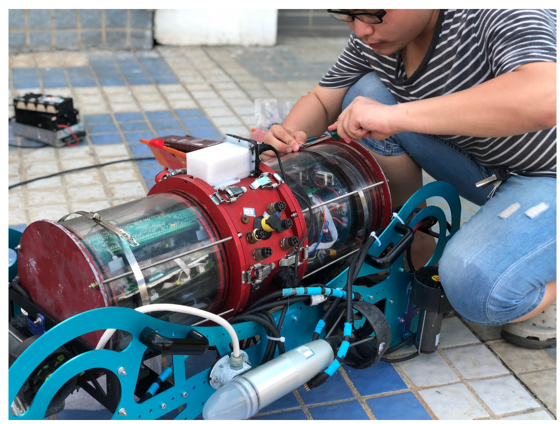

Fig. 26: Assembly Process

Fig. 27: Pool Testing

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