Design of an AUV System Based on Wireless Mesh Network for Data Collection in the Water Column

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***Abstract*—The efficiency of data collection in the water column is a major challenge in oceanographic field studies. We propose an AUV system based on wireless mesh network to cope with it. The investigated field for water column sampling mission is structured in several areas. Multiple AUVs collect data in the water simultaneously. After the data collection, AUVs can access to the wireless mesh network for data consolidation and mission allocation. The design of the AUV System also pays attention to the endurance and the cost of AUVs. The introduction of the wireless mesh network and the proposed scenario give a new way for data collection in the water column.**

***Index Terms*—AUV, wireless mesh network, data collection**

I. Concept

A. Background

In numerous active areas of ocean engineering, there are considerable interests in unmanned underwater vehicles (UUVs) which benefit with low-cost and increased safety and reliability of oceanic missions. UUVs can be classified under two main categories: remotely operated vehicles (ROVs), which are tethered underwater vehicles with human operators, and autonomous underwater vehicles (AUVs) which are completely autonomous vehicles without human interventions. The field application of these vehicles is rapidly increased as they can operate in deep and risky areas where divers can not reach [1], [2].

The reliance on the operator and on the communications channel(tether) is the principal limitation of ROVs. AUVs are the perfect answer to the limitation of ROVs in environmental field [3]. AUVs are capable of executing mission plans without the intervention of human operators [4].

Future generations of AUV systems will reflect several current trends: increased levels of autonomy and self-awareness, lower cost, longer endurance and networking capabilities [5], [6].

B. Approach

A capable and affordable AUV is designed by our team, named as ARMs-I, which is illustrated in Fig.1.

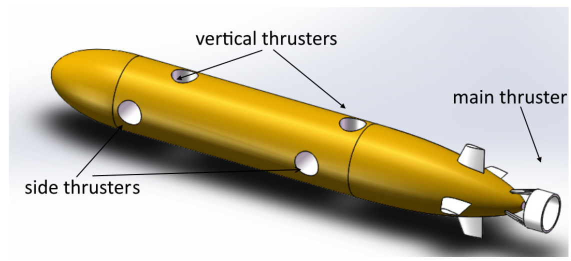

Fig. 1. Designed autonomous underwater vehicle: ARMs-I

ARMs-I has five thrusters, one main thruster generates force to push ARMs-I move forward, two vertical thrusters give the ARMs-I ability to maintain the desire depth, two side thrusters aid steering action of ARMs-I.

ARMs-I has the ability to establish a wireless mesh network on the surface of the sea. Each ARMs-I is an access point, and can communicate with each other ARMs-I in the networked mission area in order to collect and consolidate all the sampling data of the water column.

Scenario

The investigated field for water column sampling mission is structured in several equal square areas called data collection area. Each square area has a circular area called networked mission area. On the surface of networked mission area, ARMs-I can establish wireless Mesh network with neighboring ARMs-I automatically [7].

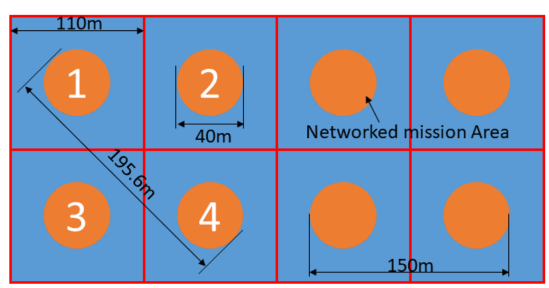

Fig. 2. Networked mission area

The chosen network device's communication distance is 200m. As showed in Fig.2 , wireless Mesh network can be established between area 1 and 2, between area 1 and 3, between area 1 and 4. The networked mission area guarantees network connectivity of the network between the neighboring ARMs-I, while making the data collection area as large as possible.

1) Launch: ARMs-I can be launched easily from ship.

2) Move to Networked Mission Area: After launch, ARMs-I vehicles move to predefined networked mission area.

3) Perform Data Collection: As soon as all ARMs-I vehicles arrive, data collection mission starts.

4) Data consolidation via wireless mesh network: Once the data collection is completed, all ARMs-I vehicles will move back to the surface of networked mission area and consolidate all data via wireless mesh network. ARMs-I vehicles will wait for further instructions on networked mission area via mesh network as well.

5) Move to Next Network Area: All ARMs-I vehicles move to next network area, after all ARMs-I vehicles arrived, start data collection. Repeat this step until the data collection mission complete.

6) Recover: All ARMs-I vehicles move toward ship. ARMs-I vehicles can be recovered by tuck net or work level ROV.

A typical scenario is illustrated in Fig.3.

The designed AUV system can work at semi-autonomous mode or fully-autonomous mode. In semi-autonomous mode, a mother ship is needed as a companion ship. After data collection and consolidation, the operator on companion ship gather the consolidated data and then allocate the mission area for each ARMs-I vehicle manually. In fully-autonomous mode, the mother ship is involved only while launch and recover. This means ARMs-I vehicles are self-organized after launch. ARMs-I vehicles communicate with each other and determine the allocation of mission areas dynamically depend on the status (such as battery status, fault and etc.) of ARMs-I vehicles.

Features

- **The wireless Mesh network is adopted to provide a capable and affordable network, which enables the networked communication capability of ARMs-I.**
- **The proposed scenario is able to improve the efficiency of data collection mission greatly.**
- **Low-cost. ARMs-I is low-cost and can be utilized in data collection field widely.**

II. Design solution

A. Hull Structures

Several AUVs have been reviewed to lead the concept of our AUVs [8]. Sea Squirt AUV, which has 1m in length and 35kg in weight, was built in 1988 in MIT Sea Grant to gather oceanographic data in the Charles River and serve as a test-bed for software and instrumentation with component cost of $40,000. Then, MIT Sea Grant built Odyssey I and II for oceanographic research with component cost of $50,000 and $75,000 respectively [9].

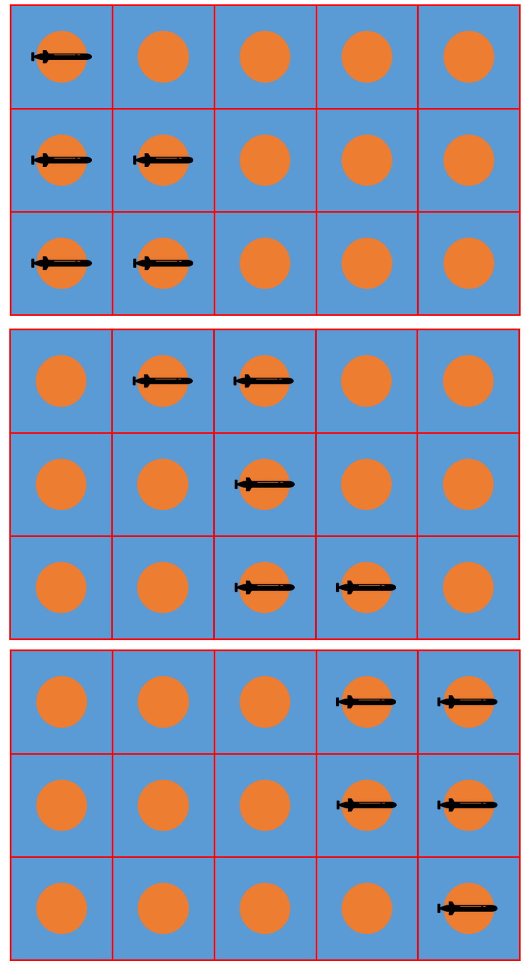

Fig. 3. A typical scenario

The purpose of ARMs-I is to collect data in the water column, the size of sensors must be considered. LeveLine™ Mini-CTD and Cyclops Integrator™ Submersible Fluorometer are chosen as relevant sensor [10]. The size of sensors is shown in TABLE I.

TABLE I
SIZE OF SENSORS

Sensor	Function	Size(diam/length)
Mini-CTD	Conductivity,Temperature,Depth	22mm/146mm
Fluorometer	Chlorophyll,Fluorescein,Turbidity	77mm/41mm

For the special efficiency, streamlined shape is chosen rather than open frame structure. The design of hull shape refers to ISiMI [11]. Dimensions of ARMs-I is illustrated in Fig.4 and TABLE II.

B. Power Consumption

The capacity of the thruster motor was estimated based on the drag equation, described as (1),

$$F_d = \frac{1}{2}\rho v^2 C_d A \quad (1)$$

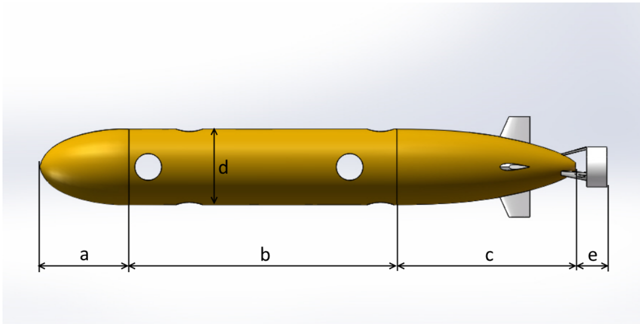

Fig. 4. Dimensions of ARMs-I

TABLE II
DIMENSIONS OF ARMS-I

Parameters	Value	Unit	Description
a	200	mm	Nose section
b	600	mm	Mid-section
c	400	mm	Tail section
d	170	mm	Diameter
e	60	mm	Main thruster

wherein F_d is the form drag acting on the hull, ρ is the water density, v is the advanced speed, C_d is the drag coefficient, A is the maximum cross-sectional area of the hull. Drag force for ARMs-I at $Re = 1.6E{+}6$, $d = 0.17$, $C_d = 0.2$, $\sigma = 1.00E{+}3$ is given in TABLE III. [12]

TABLE III
DRAG FORCE

Speed	1m/s	1.5m/s	1.8m/s	2m/s	2.5m/s
$F_d(N)$	2.2698	5.1071	7.3541	9.0792	14.1867
$F_d(lbf)$	0.5101	1.1481	1.6533	2.0411	3.1893

Performance charts of T200 thruster is given as Fig.5 and Fig.6 (the data of performance experiment is provided by Blue Robotics Inc [13]). It should be noted that the normal operating voltage of the chosen lithium battery can vary from 12 volts to 16.8 volts [14], so there are two curves describe the performance of T200 thruster at 12 volts and at 16 volts. As we can see from the Fig.5, the efficiency is increase rapidly to reach maximum and then gradually decrease as the thrust increases. The correlation of power and thrust is shown in Fig.6.

The efficiency and power of T200 thruster in different speed is given in TABLE IV, wherein E_1 is the efficiency of T200 at 12 volts, E_2 is the efficiency of T200 at 16 volts, P_1 is the power of T200 thruster at 12 volts, P_2 is the power of T200 thruster at 16 . It should be noted that the efficiency is described as thrust generated per watt of power.

The chosen batteries' capacity is 18Ah(266Wh) [14]. The required endurance is 9 hours. Which means, to match the requirement, the total power of ARMs-I must be controlled under 29.5 watts.

To simplify the calculation we directly assume that the power of the devices except main thruster is 8 watts.

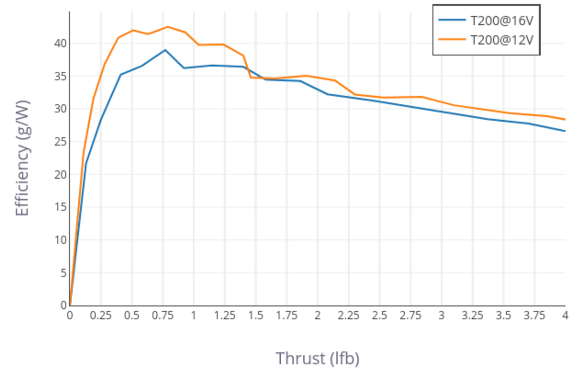

Fig. 5. T200 Thruster: Efficiency vs. Thrust

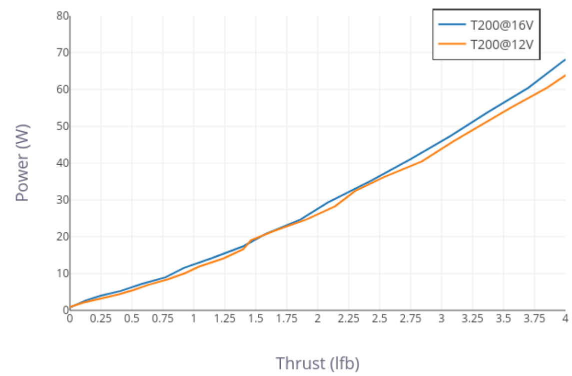

Fig. 6. T200 Thruster: Power vs. Thrust

In order to strike a balance between speed and efficiency, the maximum speed of ARMs-I is designed as 2m/s while the continuously operated speed is 1.5m/s. The average power of main thruster is 19.23 watts, which is calculated by (2).

$$P = (13.02+14.16)\times 0.3+(26.77+28.61)\times 0.2 = 19.23 \quad (2)$$

The endurance can be calculated through (3),

$$C = (P_T + P_E)T \quad (3)$$

TABLE IV
EFFICIENCY AND POWER IN DIFFERENT SPEED

Speed	1m/s	1.5m/s	1.8m/s	2m/s	2.5m/s
$F_d(lbf)$	0.5101	1.1481	1.6533	2.0411	3.1893
$E_1(g/W)$	41.98	39.77	34.64	34.61	30.31
$E_2(g/W)$	36.01	36.57	34.41	32.58	29.04
$P_1(W)$	5.516	13.02	21.61	26.77	47.68
$P_2(W)$	6.463	14.16	21.71	28.61	49.93

wherein C is the capacity of batteries, P_T is the power of main thruster, P_E is the power of other devices except main thruster, T is the endurance. The calculated endurance is 9.77 hours.

C. Communication

Wireless Mesh networks are used in our proposal as communication method. Wireless Mesh networks (WMNs) are dynamically self-organized and self-configured, with the nodes in the network automatically establishing an ad hoc network and maintaining the Mesh connectivity [15], [16].

ESP Mesh is an implementation of Wireless Mesh networks, which has higher data rate and larger payload than ZigBee and BLE Mesh. The comparison of different wireless Mesh networks is shown in TABLE V. ESP Mesh is developed by Espressif™ based on ESP32 IoT platform. As a highly reliable, widely-covered Wireless Local-Area Network (WLAN) network, the ESP Mesh is ideal for wireless solutions covering a large open area (both outdoors and indoors) [17].

TABLE V
COMPARISON OF DIFFERENT WIRELESS MESH NETWORKS

Mesh	ESP Mesh	ZigBee	BLE Mesh
Data rate	150Mbps	250Kbps	1Mbps
Payload(Byte)	1500	85	251
Range(m)	200	75	100
Nodes	1000	400	870

III. SYNTHESIS

The length of the ARMs-I is 1.26m while the diam is 170mm. The details are shown in Fig.4 and TABLE II. Specifications of ARMs-I are shown in TABLE VI. The separate battery watertight enclosure is used. The battery replacement operation can be performed in 30 minutes.

TABLE VI
SPECIFICATIONS OF ARMS-I

Parameters	Value	Unit
Length	1.26	m
Diameter	170	mm
Weight	20	kg
Depth Rating	100	m
Battery Capacity	18	Ah
Power	29	W
Endurance	9.77	hour
Time between deployments	0.5-6	hour

IV. SCHEMATICS

Fig.7 describes the hardware architecture of ARMs-I [18], [19]. The main board is Raspberry Pi 3 Model B, which is small and affordable and widely used by the open source community. The main board is under the responsibility of communication establishment, data storage and motion control. The MCU is implemented by STM32F103 series MCU. The MCU is mainly to gather and process sensor information, then send the data to main board. Pixhawk is an open-hardware project that aims to provide the high-quality and low-cost autopilot hardware designs for the academic, hobby and developer communities. In our proposal Pixhawk is in charge of motor control through electronic speed controller (ESC), provide position and attitude information. ESP32 is a highly-integrated Internet on things(IoT) chip. ESP Mesh Network is established by ESP32. The power management unit (PMU) is responsible for Charge and discharge protection and provide reliable power supply to every part in different voltage [20].

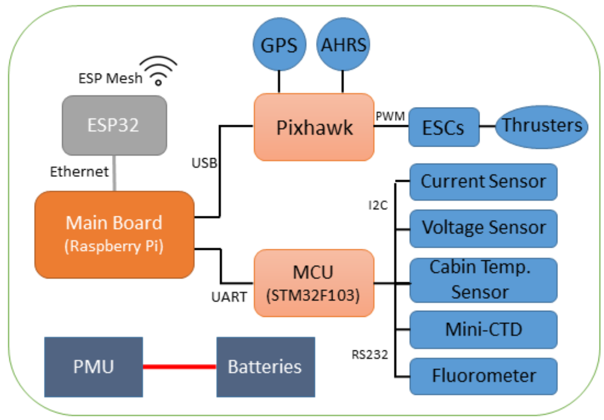

Fig. 7. Hardware architecture

ESP Mesh network topology is shown as Fig.8. In sea area, thanks to ESP Mesh network, the mesh network is self-organized, ARMs-I can join or leave the network at any time. Cell-phone connect to network In shore or boat, then the commands can be sent to ARMs-I and sensors data can be accessed and consolidated.

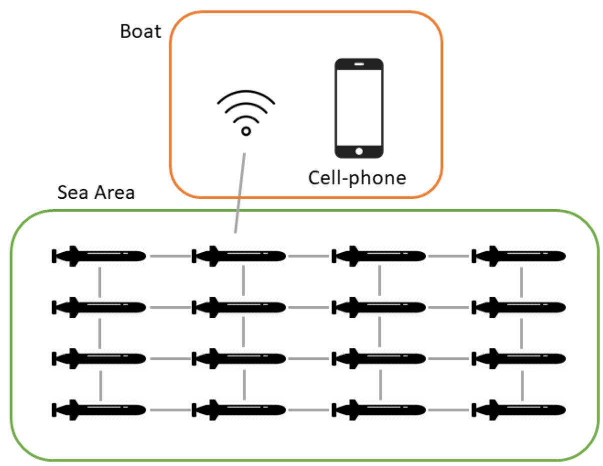

Fig. 8. ESP Mesh network for data consolidation

V. COST

Blue Robotics™ T200 thruster is used as main thruster, which is affordable and capable. Watertight enclosure and Batteries are also provided by Blue Robotics Inc. Vertical thrusters and Side thrusters are provided by ROVMAKER. Raspberry Pi, ESP32 and MCU can be bought from seeed studio while mRo Pixhawk can be bought from mRobotics.

Budget list is shown in TABLE VII.

TABLE VII
BUDGET LIST

Part	Cost	Description
Hull	$200	
Watertight enclosure	$148	100m depth rate, for electronics
Watertight enclosure	$113	150m depth rate, for battery
Raspberry Pi	$35	
MCU	$2	
mRo Pixhawk	$119.9	
ESP32	$10	Widora-AIR
PMU	$10	
Main thruster	$169	T200
Vertical thrusters	$90 x 2	
Side thrusters	$90 x 2	
Batteries	$249	18Ah, 4S
Consumables	$100	
Sum	$1515.9	

VI. SCHEDULE

Milestones for development include hull and hardware design, hull manufacture, hardware implementation and debug, software implementation and debug, pool tests, field tests. Milestones and time-line for development are described as follow:

- Hull and hardware design: 1 month.

The hull shape of ARMs-I vehicles refers to ISiMI [11]. The separate watertight enclosures are used for batteries and electronic components. The design of component placement and schematic of electronic components is the main work of this period.

- Hull manufacture: 1 week.

Separate watertight enclosures are used in ARMs-I, the hull does not need to be watertight. In order to speed up the manufacture of hull, 3D printing technology is used. Operations such as sanding and painting are required to reduce water resistance.

- Hardware implementation and debug: 2 weeks.

PCB layout, implementation and test are the main work of this period. Tests of thrusters, Raspberry Pi, Pixhawk, MCU, ESP32 and batteries are required too.

- Software implementation and debug: 2 weeks.

The software include Cell-phone APP, ARMs-I on board Pixhawk software, ARMs-I on board Raspberry Pi software, ARMs-I on board MCU software. Single tests such as network test and emergency function test need to applied while software implementation.

- Pool tests: 2 weeks.

Performance tests of watertight enclosure are required before the pool test. Maneuverability tests should be applied first. Afterwards, control parameters adjustment can be performed based on maneuverability tests result. Endurance tests also need to be done in pool test period.

- Field tests: 2 weeks.

Field tests of ARMs-I must be carried out at surface mode at first. After several surface trials, the formal field tests can be applied.

ACKNOWLEDGMENT

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