A Modular Approach to the Development of a Fault Tolerant Free-Vehicle

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***Abstract*– Free-vehicles are autonomous instruments that perform oceanographic observations. They have been used for decades to study not only the seafloor through sediment samples or fish traps, but also ocean properties through water samples and different types of sensors. This paper presents the Control Computer redesign process of a free-vehicle using modular design techniques. The modular approach allows for grouping the system components into different subsets that are implemented as modules in the new free-vehicle design. A data sample is presented to demonstrate the functionality of the new design.**

***Keywords*—Modular Design, Embedded Systems Design, Free Vehicle, Unnamed Vehicle, Fault Tolerant.**

I. INTRODUCTION

During the design process of systems or devices, there are several methods that define the structure, construction, and functionality. One such method is Modular Design (MD). MD allows for developing a system from a set of different smaller components, each of which represents a functional subset of the entire system. This approach also provides the advantage of easily replacing one module with another of similar characteristics without affecting the overall system functionality [1] [2].

In MD, modularity corresponds to the action of separating or organizing the parts of a product or process into specific functions or tasks. Once the tasks or parts are established, then, the modules are created. It should be noted that a module is a component formed by one or more elements, which has one or several functions and can work independently or collectively with other elements or modules [3] [4] [5].

MD can be applied in different areas. Kamal [2] and Zurawski [6] pointed that MD is currently used in the design and construction of embedded systems. This process allows for separating the hardware components of an embedded application into a set of modules. Kamal and Zurawski also argued that embedded systems implemented as MD allow for intellectual property (IP) reuse of hardware or software components from other projects, risk reduction, uncertainty mitigation, and cost reduction. Kamal remarked that the advantages of MD also apply to robotics applications, permitting rapid deployment of field robots constructed from an inventory previously developed actuated joints, links, power supplies, and software modules. The authors explained that this inventory allows for the construction of robots for different tasks by interchanging the pieces attached to the robot's main body.

Another area in which MD has been used is in underwater oceanographic instrument platforms. Successful examples of this approach include the development of ROUGHIE 2.0, an autonomous underwater vehicle (AUV) developed by The Nonlinear and Autonomous Systems Laboratory at Michigan Technological University [7]. This AUV used MD for the arrangement of internal sensors and moving masses in a common mounting rail. This configuration brought flexibility to the sensors placement at various vehicle locations, improving performance for different missions. Authors in [8] presented another application of MD. In this project, the authors used MD for developing a control scheme for an underwater-vehicle manipulator system. As this kind of vehicle incorporates a manipulator composed of several bodies and links, the authors proposed decomposing the manipulator motion into a set of elementary control problems, allowing for the definition of individual control actions for each body.

In this paper we propose a computer control and mechanical frame redesign for an untethered, underwater free-vehicle (FV), jointly developed by the Departments of Marine Sciences (DMS), and Electrical and Computer Engineering (ECE) of the University of Puerto Rico at Mayagüez (UPRM). This redesign uses a modular design approach to improve several aspects of the vehicle structure. The rest of this document is organized as follow. Section II provides a brief background of autonomous vehicles, their evolution, and usage to give context to our approach. This section also introduces the DMS-ECE FV design. Section III describes the necessities of MD in this vehicle, while Section IV presents the techniques used to redesign the free-vehicle computer control and frame. Section V presents results from the redesigned vehicle through a data sample acquired in a field test. Section VI offers concluding remarks.

II. BACKGROUND

Priede and Bagley defined free-vehicles as untethered underwater autonomous apparatus that permit performing observations during extended periods of time [9]. FVs are commonly composed of a buoyancy element, a timer module, an oceanographic instrument, a ballast, and a ballast release mechanism. FVs are deployed from a vessel with ballast attached. Before deployment, a ballast release time or depth is configured. The ballast weight is calculated to adequately overcome FV buoyancy, pulling it underwater at a modest velocity (e.g., 1 m/s) and providing a soft landing. Once the pre-configured release parameter is met, the ballast release

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mechanism frees the ballast and the resulting positive buoyancy pulls the FV back to the surface for retrieval.

Since the early 1930's, several approaches have been reported to reach ocean depths with untethered instrument platforms capable of performing descend-ascend operations and collecting varied types of data (i.e., FV). One of the earliest approaches documented in literature refers to the work of Ewing and Vine (1938) using kerosene-filled containers to produce buoyancy [10]. Subsequently, numerous approaches have been documented through the years showing incremental technology improvements [11] [12] [13] [14]. The usage of lighter-than-water hydrocarbons liquids has been replaced by high-density foam or buoyant spheres made of advanced ceramic or tempered glass [15] [16]. In recent times, high budget missions have produced FV capable of trapping water samples, sediment, life forms, capturing stunning images from the deepest points on the planet, and working as measurement labs [17] [18] [19].

A. DMS/ECE FV Design

UPRM DMS and ECE have developed a low-cost FV to explore the hadal (> 6000 m) water column of the Puerto Rico Trench (PRT). This FV is capable of reaching ocean depths of 9000 m as designed, and greater depths with optional stronger buoyancy spheres, making it use suitable for any oceanic location. The FV utilizes two glass spheres enclosed in plastic protectors ("hard hats") for buoyancy and as electronics pressure cases. Each sphere contains a control computer (CC), a set of sensors, a communication system, a signaling sub-system, and a ballast release system. An early version of the UPRM FV was tested in the PRT during 2008 in collaboration with researchers from the Scripps Institution of Oceanography (SIO). This test had the objective of collecting data related to the FV design, ascent/descent rates, tilt parameters, and the first ever PRT near-bottom currents using a 2MHz Aquadopp DW ADCM oceanographic instrument [16].

III. Modularity Need

The CC is in charge of monitoring and controlling the FV deployments states, recording all data coming from internal temperature, humidity, pressure, accelerometers, gyroscope, and magnetometer sensors, and establishing communications with a host computer for pre-launch FV configuration and post-recovery data retrieval. For its operation, the CC is composed of the following electronics components: three microcontrollers, two communications protocol interfaces, seven internal sensors, a power management system that includes two batteries, an electronic ballast release system, an RF beacon, and a strobe light.

Initial versions of UPRM FV had all electronics components housed in a plastic enclosure ("hobby box"). Although they were strategically placed, the number of connections required multiple cables crossing from one side of the enclosure to another, making it difficult for the controller setup and maintenance (Fig. 1). Moreover, as all components were designed on a monolithic board, cumbersome spacers, connectors and wires were required to accommodate the entire system. This arrangement made it difficult for the control computer assembly process, for testing and replacing faulty components, and made the system more susceptible to failure. It should be noted that failures can be introduced either by human errors during the assembly process, by electromagnetic interferences generated by component proximity, subsequent detachment of wires or connectors due to shock loads during deployment, and/or any combination of the above. These risks combined with experiences in FV operation [20] pointed to the need of a more robust design. Specific areas to be addressed in the FV re-design included easing the access to electronic components in the control computer, reducing number of wires running across the sphere, and minimizing the chances of wrong connections.

IV. Modular Design

Due to the number of connections and electronic components that are part of the FV CC, a basic version of a Design Structure Matrix (DSM) approach was followed to establish the system modules. This approach was used because it permits managing and determining the relations that could exist between components [21]. In addition, this approach enabled modularization as the relations determined using the DSM produced groups of components with reduced interconnectivity, yielding system partitioning with reduced inter-module wiring.

The DSM approach consists of creating a relational matrix between the devised system components. Each element of the matrix indicates a weight that refers to the degree of relation that one component has with another. The weight is assigned based on design criteria. Once the weights are assigned, a visual inspection can be used to determine which elements have strong relations and therefore are more suitable to group into modules.

A. Module Design

The main criterion in the design of the current FV version was reducing the number of shared connections between board elements while maintaining the desired system functionality.

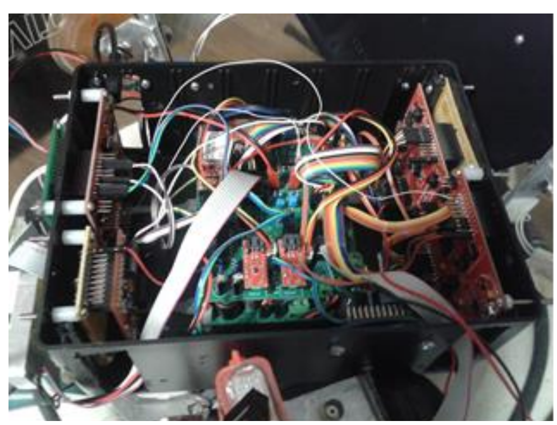

Fig. 1. Electronic component distribution of the early FV version

Applying the DSM method allowed for minimizing the main criterion while also providing information for the relative position of system boards.

From the DSM matrix in TABLE 1, we could identify the elements having the most signals in common for developing the system modules. The initial modules created from this table were:

- Module 1 composed by the Main and backup MCUs.
- Module 2 composed by the Translator MCU, Sensor Hub, and SD card.
- Module 3 composed by the 3.3V main and backup regulators and 12V main and backup regulators.

In the case of Module 1, this arrangement allowed for grouping all elements controlling the FV state in one module. Although the 7-segment display shared a considerable number of signals with the two Microcontroller Units (MCU), the necessity of having this display in a visual part of the vehicle did not permit placing it in the same module. For Module 2, the arrangement made possible having the Translator MCU (T-MCU) near the SD card and the sensor hub. It should be noted that the T-MCU is in charge of reading all parameters from the sensor hub and passing them into the main and backup MCUs. In addition, the T-MCU is in charge of storing all sensor readings and vehicle logs into the SD card. In the case of Module 3, the voltage regulators shared a low number of signals (4) between them; locating the regulators in the same module allowed for power to be distributed from a single point.

TABLE 1
DSM MATRIX BASED ON NUMBER OF SHARED SIGNALS

	Elements	1 Main MCU	2 Backup MCU	3 Sensor HUB and SD	4 Translator MCU	5 3.3V Main Regulator	6 3.3V Backup Regulator	7 12V Main Regulator	8 12V Backup Regulator	9 7-Segments Display	10 RF antenna circuit	11 Strobe light circuit	12 Bluetooth interface	13 USB interfacing circuit	14 BurnWire control circuit
1	Main MCU	X	14	4	4	2	2	0	0	9	1	1	0	0	3
2	Backup MCU	14	X	4	4	2	2	0	0	9	1	1	0	0	3
3	Translator MCU	4	4	X	9	2	2	0	0	0	0	0	4	4	0
4	Sensor HUB and SD	4	4	9	X	2	2	0	0	0	0	0	0	0	0
5	3.3V Main Regulator	2	2	2	2	X	5	4	4	2	2	2	2	2	2
6	3.3V Backup Regulator	2	2	2	2	5	X	4	4	2	2	2	2	2	2
7	12V Main Regulator	0	0	0	0	4	4	X	5	0	0	0	0	0	2
8	12V Backup Regulator	0	0	0	0	4	4	5	X	0	0	0	0	0	2
9	7-Segments Display	9	9	0	0	2	2	0	0	X	0	0	0	0	0
10	RF antenna circuit	1	1	0	0	2	2	0	0	0	X	0	0	0	0
11	Strobe light circuit	1	1	0	0	2	2	0	0	0	0	X	0	0	0
12	Bluetooth interface	0	0	4	0	2	2	0	0	0	0	0	X	0	0
13	USB interfacing circuit	0	0	4	0	2	2	0	0	0	0	0	0	X	0
14	BurnWire control circuit	3	3	0	0	4	2	2	2	0	0	0	0	0	X

The rest of components that were not grouped in the modules previously established, were arranged in additional PCBs. The RF antenna circuit, the strobe light circuit, and the Bluetooth interface were placed in one small PCB (communications board) due to the small size of the circuits. In the case of the burn wire control, it was placed in a separate PCB because it incorporates two heat dissipating elements. Finally, an additional PCB for the distribution board was designed to carry all the signals between the boards that composed the control system. Fig. 2 illustrates how the modules and the PCBs were arranged.

B. PCBs Fabrication

The set of PCBs for all modules were fabricated with the following considerations: 1) all connections between modules were carried out through the distribution board. 2) All modules and boards were connected to the distribution board through pin headers, data bus cables, and twisted pair cables. 3) Additional small circuits were placed onto the distribution board. 4) Module 1, Module 2, and Module 3 had the same PCB dimensions with different pin headers locations for each PCB, allowing for uniformity in the design and preventing placing either of them in the wrong slot. 5) Module 3 (power supply) incorporates inline fuses for each voltage regulator. 6) Module 3 incorporated a set of jumpers to manually disable each voltage regulator for testing purpose. Fig. 3 shows the translator board as an example of how the modules were fabricated, while Fig. 4 shows the complete set of fabricated PCBs assembled.

All these considerations allowed for the control system to have a quick and easy assembly process while providing an easy way to replace faulty components. This last objective was achieved by using detachable boards and components. Additionally, the modular characteristics facilitated the system testing process as it offered the opportunity of individually accessing the signal ports in each module.

C. Frame Design and Fabrication

In order to provide a platform for the PCB that facilitates mounting the control system into the sphere, a detachable

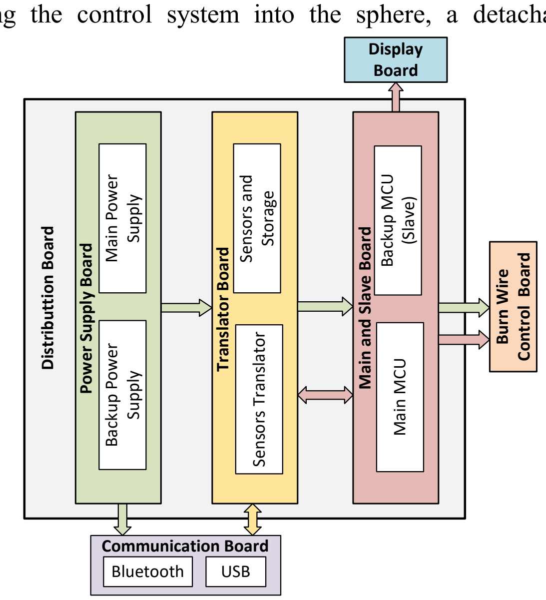

Fig. 2. Module distribution scheme

frame was designed and constructed. For the design of this frame, several considerations were made. An important consideration was the weight, in order to limit the reductions to the floating force of the sphere. Acrylic was selected as a fabrication material based on its low density. Another consideration was the possibility of having a structure that permitted disassembling the control system or replacing a module with ease. The final consideration was for the LiPo (lithium-polymer) batteries. The frame had to provide housing for two such batteries and be adjustable for to accommodate future different battery numbers/sizes.

The final design for the frame is presented in Fig. 5 and Fig. 6. The frame was designed to be completely detachable, easing the assembly process. Additionally, the frame provided enough room to manipulate the attached PCBs. All PCBs were attached to the frame through screws with lock nuts and supports. This made possible maintaining the PCB in position, even when the vehicle is upside down. The batteries were located at the bottom of the frame and held in position through sliding supports that can be adapted to multiple or different sized batteries.

D. Exploded Diagram

Fig. 7 presents an exploded view of the entire FV CC. This figure shows both, the actual position of each component and provides a guide for the CC assembly process. The distribution board and the module PCBs were located inside of the frame while the burn wire control, the 7-segment board, and the communication board were placed on the sides of the frame. As described in Subsection C, the batteries were placed at the bottom of the frame and held in position with support elements. Finally, Fig. 8 shows the Computer Control inside of the Acrylic frame with the batteries and all necessary cables for its operation. To this date, the MD approach as described, has enable our team to fabricate a fleet of ten free-vehicles.

E. FV Testing

To verify the intended FV functionality, each module and PCB of the CC were systematically tested. These tests were designed to verify the functionality of each module, starting with the power supply module and finalizing with the signaling (strobe light and RF) circuits. First, a careful visual inspection of the soldered components was performed to ensure that no

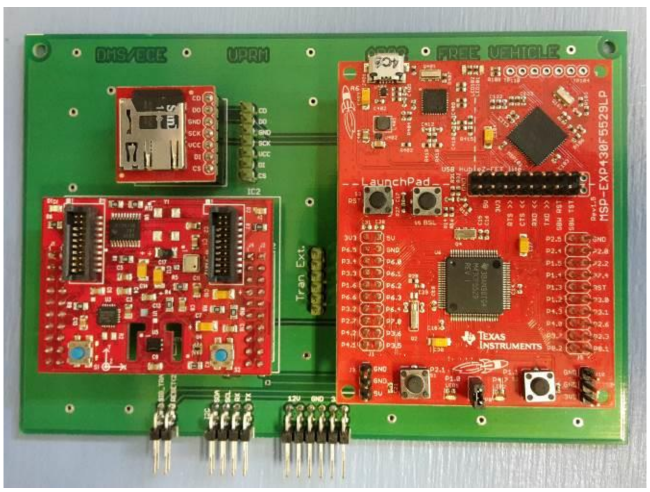

Fig. 3. Module 2 (translator board).

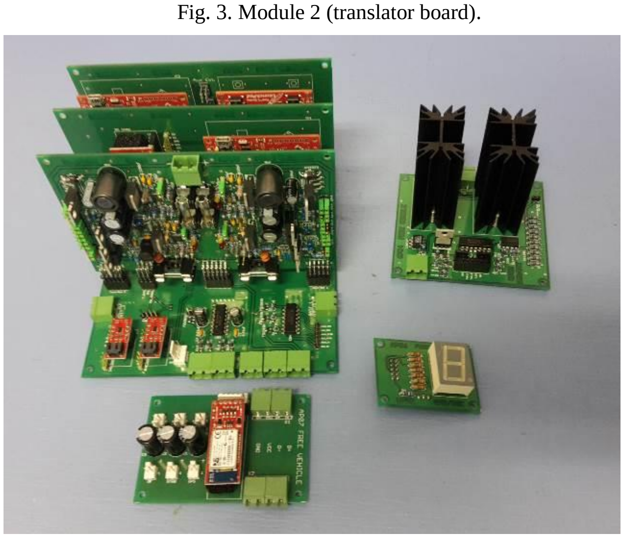

Fig. 4. Assembled computer control boards.

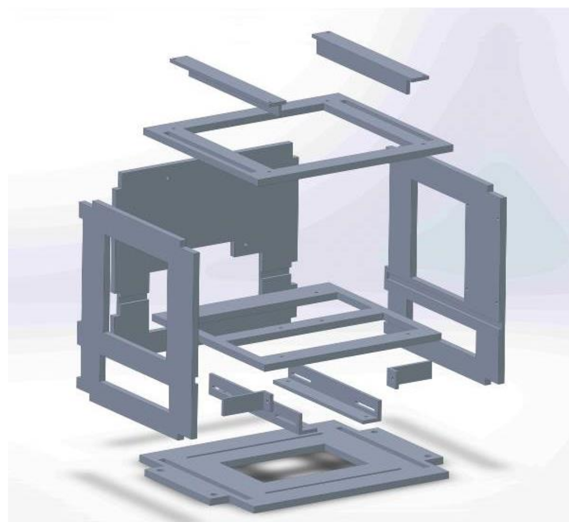

Fig. 5. Exploded view of the frame.

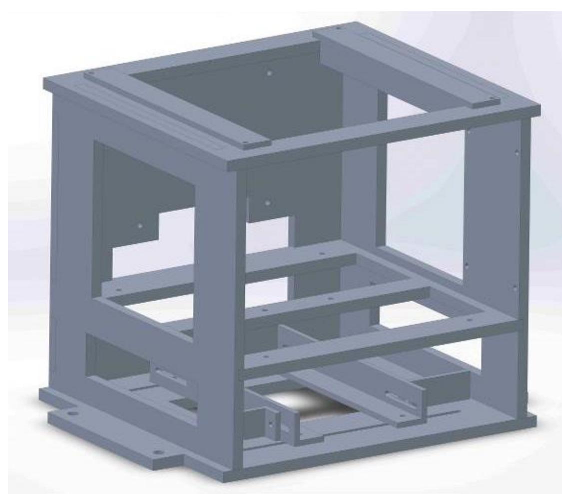

Fig. 6. Assembled view of the frame.

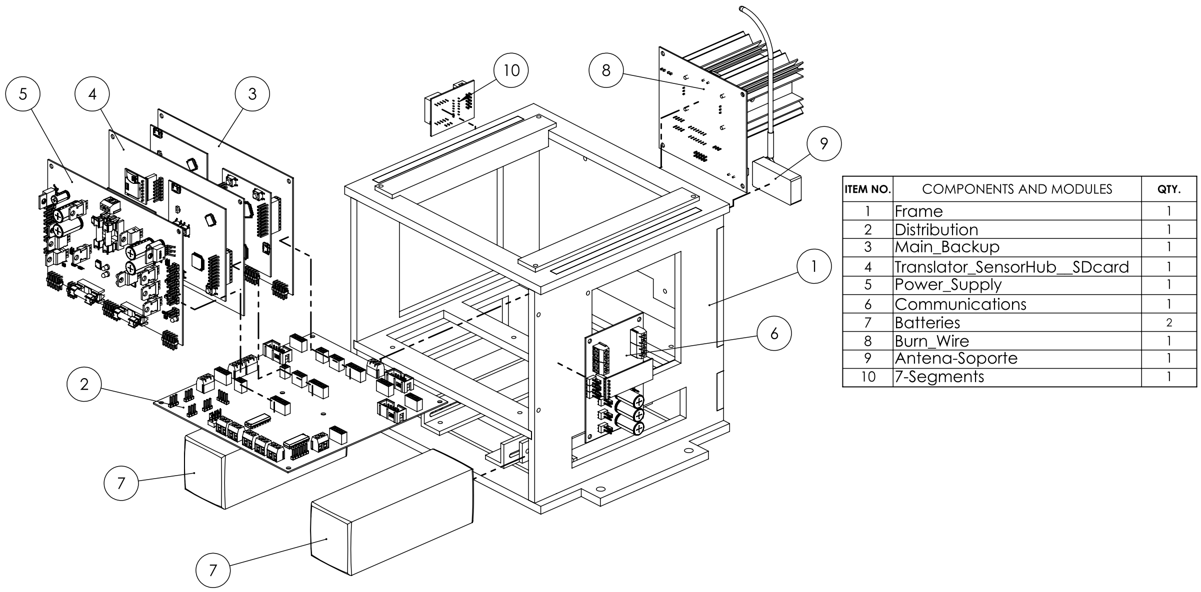

Fig. 7. Exploder view of the control system with frame

Fig. 8. One of the Control System Assembled

mistakes were made during board assembly. Second, each module was subjected to functional tests that required in some cases the activation or deactivation of modules components and signals. Below we provide a list of the tests performed in each control system:

- Redundant battery test
  - Simulating a Main battery failure
  - Simulating a Backup battery failure
- Redundant main 3.3V Rail test
  - Simulating Main 3.3V rail failure
  - Simulating Backup 3.3V rail failure
- Redundant main 12V Rail test
  - Simulating Main 12V rail failure
  - Simulating Backup 12V rail failure
- Strobe light recovery control test
  - Main strobe controller functionality
  - Backup strobe controller functionality
- RF recovery control test
  - Main RF controller functionality
  - Backup RF controller functionality
- Burn wire recovery control test
  - Main MCU control functionality
  - Backup MCU control functionality
- UART Communication failure
- MCU Functionality tests
  - MCU power loss
  - MCU incorrect state
  - MCU unresponsive state

With this test design, if a module does not respond as expected, the error can be easily identified and remedied. In addition, these tests allow positively ensuring the entire functionality of the CC before its final assembly and usage.

V. Sample Data Acquisition and FV

The FV refinements, such as satellite transponder, State Determination System (SDS), Inertial Navigation System (INS), rechargeable batteries, wireless and serial data communications, etc., were field tested in the waters south of La Parguera, PR near the UPRM Department of Marine Sciences Field Station on Magueyes Island during the years 2011 to 2014. The early tests focused on the SDS which is critical in ballast release, signaling, and overall power optimization. As it was impossible to simulate actual conditions in the laboratory, repeated deployments were made to 1000 m to collect INS sensor data. The FV as used in the field tests is presented in Fig. 9. Analysis showed definite indications of descent initiation, reaching bottom, ascending, and reaching the surface (Fig. 10). This allowed algorithms to be constructed that could automatically detect the transitions and turn on/off different systems such as ballast release and signaling. The SDS and INS systems will be the subject of future papers.

VI. CONCLUSION

The concept and evolution of subsea oceanographic research platforms in the form of untethered free-vehicles were discussed. In particular, the design of the DMS-ECE FV was analyzed to highlight the need for robust solutions in this type of applications. By using a modular design approach, our research team was able to produce a functional redesign of the said vehicle, overcoming shortcomings of previous designs. A new CC was designed with the aid of DSM analysis resulting in a reduced number of sharing connections between modules. A detachable-acrylic frame was developed for accommodating the PCB modules and batteries. The combination of modules and frame produced a versatile structure that allowed for easily replacing components, facilitating the testing process, and reducing the risk of malfunctions due to human errors in the assembly and set up process. This new FV version was successfully tested in 1000 m ocean depths, were collected accelerometer, magnetometer, and gyroscope data demonstrated the functionality and correctness of this design.

Fig. 9. FV deployment test at the Parguera, PR

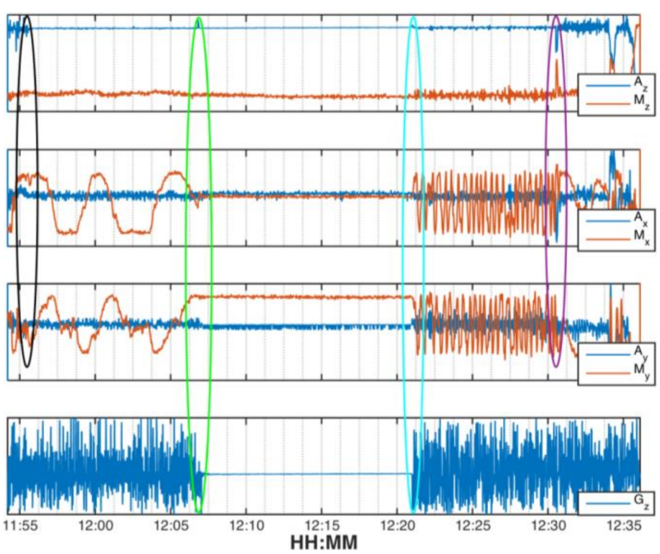

Fig. 10. 2014 Unscaled FV INS sensor data from 1000 m test (A, accelerometer; M, magnetometer; G, gyroscope. Subscripts indicate axis). Ovals indicate FV state transitions, (black) descent, (green) on bottom, (cyan) ascent, (violet) at surface.

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REFERENCES

[1] R. Kamal, “Embedded systems 2E,” Tata McGraw-Hill Education, 2008.

[2] S. Farritor, S. Dubowsky, N. Rutman and J. Cole, "A systems-level modular design approach to field robotics," *Proceedings of IEEE International Conference on Robotics and Automation*, Minneapolis, MN, USA, 1996, pp. 2890-2895 vol.4.

[3] M. S. Salerno and A. V. C. Dias, “Product design modularity, modular production, modular organization: the evolution of modular concepts," Automotive Industries, 1999.

[4] T. Lehtonen, “Designing modular product architecture in the new product development”, 2007.

[5] T. D. Miller and P. Elgard, “Defining modules, modularity and modularization," *Proceedings of the 13th IPS research seminar*, Fuglsoe, 1998.

[6] R. Zurwaski, “Embedded Systems Handbook: Networked Embedded Systems,” CRC Press, 2009.

[7] B. R. Page, S. Ziaeefard, P. Morath, V. Stumbris and N. Mahmoudian, "ROUGHIE 2.0: Improving performance using a modular design approach," *OCEANS 2017* – Anchorage, AK, USA, 2017, pp. 1-5.

[8] G. Antonelli, F. Caccavale and S. Chiaverini, "A modular scheme for adaptive control of underwater vehicle-manipulator systems," *Proceedings of the 1999 American Control Conference (Cat. No. 99CH36251)*, San Diego, CA, USA, 1999, pp. 3008-3012 vol.5.

[9] I. G. Priede and P. M. Bagley, “In situ studies on deep-sea demersal fishes using autonomous unmanned lander platforms,” *Oceanography and Marine Biology, An Annual Review*, 2003, pp. 357-392 vol.38.

[10] M. Ewing, A. Vine, “Deep-sea measurements without wires or cables,” *Eos, Transactions American Geophysical Union*, 1938, pp. 248-251 vol.19.

[11] M. J. Hvorslev, and H. C. Stetson, “Free-fall coring tube: a new type of gravity bottom sampler,” *Geological Society of America Bulletin*, 1946, pp. 935-950 vol.57

[12] J. D. Isaacs, and G. B. Schick, “Deep-sea free instrument vehicle,” *Deep Sea Research (1953)*, 1960, pp. 61-67 vol.7.

[13] C. F. Phleger, and A. Soutar, (1971), “Free vehicless and deep-sea biology,” *American Zoologist*, pp. 409-418 vol.11.

[14] P. F. Worcester, K. R. Hardy, D. Horwitt and D. A. Peckham, "A deep ocean data recovery module," *OCEANS '95. MTS/IEEE. Challenges of Our Changing Global Environment. Conference Proceedings.*, San Diego, CA, USA, 1995, pp. 1225-1231 vol.2.

[15] R. Weiss, O. Kirsten and R. Ackermann, "Free vehicle instrumentation for the in situ measurement of processes controlling the formation of

deep-sea ferromanganese nodules," *OCEANS '77 Conference Record*, Los Angeles, CA, USA, 1977, pp. 616-619.

[16] W. E. Schmidt and E. Siegel, "Free descent and on bottom ADCM measurements in the Puerto Rico Trench, 19.77° N, 67.40° W," *Deep Sea Research Part I: Oceanographic Research Papers*, 2011, pp. 970-977 vol. 58.

[17] K. Hardy, M. Olsson, A. A. Yayanos, J. Prsha and W. Hagey, "Deep Ocean Visualization Experimenter (DOVE): low-cost 10 km camera and instrument platform," *OCEANS '02 MTS/IEEE*, 2002, pp. 2390-2394 vol.4.

[18] K. Hardy, J. Cameron, L. Herbst, T. Bulman and S. Pausch, "Hadal landers: the DEEPSEA CHALLENGE ocean trench FVs," *2013 OCEANS - San Diego*, San Diego, CA, 2013, pp. 1-10.

[19] O. Pfannkuche, and P. Linke, "GEOMAR landers as long-term deep-sea observatories," *Sea Technology*, 2003, pp. 50-55 vol.44.

[20] W. Schmidt, D. Rojas, H. xu, R. Veitnen, Z. Fuentes, and M. Jimenez. "An untethered free vehicle for oceanographic research. *J. Atmos. Oceanic Technol*, unpublished.

[21] T. J. Van Beek, M. S. Erden, and T. Tomiyama, "Modular design of mechatronic systems with function modeling,". *Mechatronics*, 2010, pp. 850-863 vol. 20.