A Vehicle for Science and Exploration:
Bringing Offshore Industry Advances and Experience to the Oceanographic Community

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***Abstract* - The defining characteristics of a new NOAA ROV and its enabling technologies are explored. The NOAA system is rated to a depth of 6000 meters and can be configured as either a two body ROV and smart camera platform or as a camera platform only, depending on mission risk and sea conditions. Both the ROV and camera platform carry broadcast quality high definition cameras capable of providing high-resolution images critical to the scientist's mission. These high definition video feeds as well as vehicle data will be available for satellite transmission for real time collaboration with scientists at shore-based locations**.

I. INTRODUCTION

Phoenix International Inc., (Phoenix) is in the final production stage of a Remotely Operated Vehicle (ROV) built specifically for the National Oceanic and Atmospheric Administration (NOAA) Office of Exploration [1]. The system is designed for permanent installation aboard the *EV Okeanos Explorer* and will become one of NOAA's primary tools for scientific exploration of the world's oceans. While most science vehicles of a similar caliber have been built internally by oceanographic institutions, this vehicle system design represents a collaborative effort between the science community and a subsea industry technological leader to develop an exploration vehicle employing the latest advances in subsea technology.

II. SURVEY OF COMMERCIAL VEHICLES DEDICATED TO SCIENCE

Oceanographic institutions have historically developed advanced ROV's internally, employing the experience and expertise of the scientists and engineers that would operate, maintain and further develop those vehicles. Indeed, many of these vehicles have significantly advanced the role of ROV's in both the scientific and commercial arenas have employed often-revolutionary advanced technologies.

Prominent institutionally designed and built vehicles that have set the standard for the technological edge of the ROV world include the Woods Hole Oceanographic Institute *Jason* and *Jason II* vehicles, MBARI's first generation *Tiburon* vehicle, and the Institute for Exploration/University of Rhode Island's *Hercules*. Each of these systems has made significant contributions to both science, and the science and technology of ROV's.

Independently, the commercial sector of the ROV community has pushed the envelop of ROV capabilities through the needs of the oil and gas, search and recovery, cable laying, and film industries.

MBARI was the first scientific institution to capitalize on the advances of the commercial sector with its acquisition of *Ventana* – an International Submarine Engineering work class system designed for subsea intervention and inspection duties. Since that time there has been a hiatus on the further incorporation of commercial vehicles in the science sector. NOAA's acquisition of a 6000 meter science ROV from Phoenix represented the first move toward a growing trend by oceanographic institutions to capitalize on the experience of commercial operators and vendors for science ROV's. Subsequent groups to also employ vehicles from commercial manufacturers include IFM-Geomar's purchase of a modified Schilling Quest vehicle and MBARI's replacement of the in-house built *Tiburon* with a Soil Machine Dynamics (SMD) vehicle.

III. COMMON ATTRIBUTES OF COMMERCIALLY BUILT 'NEW' SCIENCE VEHICLES

The ROV's currently being designed and delivered by commercial entities for the scientific community share common examples of leading edge technology. Many of these technologies have long been employed in other disciplines, but are only now trickling down to the ROV world. While some of these advanced technologies are incorporated in commercial work class vehicles, most are not yet common, indicating that the demand for these capabilities by science users continues to drive the technological forefront of current ROV technology.

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A. High Definition Video

High Definition (HD) video has become mainstream among broadcasters and filmmakers, but is only now making headway into the subsea arena. Two factors – camera size and fiber multiplexer compatibility - have greatly impeded its inclusion to date but both are quickly being overcome.

Until recently, the only HD cameras available to the subsea community have been large, broadcast quality systems that at times have time proven unreliable in the maritime subsea environment. The large size of these cameras has made them difficult to integrate into existing vehicles, and while some science institution vehicles have incorporated them, the ability to freely pan and tilt those units has proven problematic. The housings employed to enable operation at significant depth is also a severe weight impact and can dramatically affect vehicle design.

While HD smaller cameras have recently become available, Phoenix elected to incorporate a broadcast HD camera to maximize the optical quality of the lens and matching dome port for the highest quality image possible.

The incorporation of this large and heavy camera had a profound impact on the mechanical design of the vehicle. Phoenix believed that limiting the ability to pan and tilt the HD camera would negatively affect operations. To properly accommodate the HD camera and pan and tilt, Phoenix incorporated a large bow in the vehicle design. This approach provides excellent pan and tilt range and also minimizes the possibility of the manipulators contacting and damaging the camera. The bow also increases the separation of the HMI lights and the HD camera, reducing backscatter in images.

Fiber multiplexer advances have allowed and will continue to allow more integration of high definition signals. Previously, the inclusion of HD meant dedicating a fiber to the high bandwidth HD signal. The NOAA vehicle is a national asset that will need to adapt and grow with technology for years to come. In initial system design, Phoenix determined that moving to a Coarse Wavelength Division Multiplexed (CWDM) fiber multiplexer system would provide the long-term path for growth desired by NOAA.

CWDM multiplexes many wavelengths on one single-mode fiber, drastically increasing the bandwidth and signal carrying capacity of a single fiber, and thus the umbilical connecting the ROV to the ship. While the .680” electro-optical cable employed in the NOAA ROV system incorporates three fibers, all signals are passed on only one of the three. This frees the two remaining fibers to serve as spares or to be dedicated to other high bandwidth systems that may be incorporated in the future.

The broadcast television market has standardized on the High Definition Serial Digital Interface (HD-SDI) standard signal format. The current availability of HD-SDI cards for the fiber multiplexer enable the direct injection of broadcast standard HD-SDI, eliminating the need for special converters and their associated signal degradation.

B. Dynamic Positioning

Dynamic Positioning of vessels has become standard practice in oil and gas support. Several companies that have well proven vessel DP systems have also begun development on similar systems for ROV’s. Science class ROV systems, such as WHOI’s JASON pioneered ROV DP [2][3][4][5][6][7]. Fortunately for ROV end users, commercial ROV providers have leapfrogged those third party DP providers and, like select science ROVs, have developed ROV DP systems on their own, tightly coupled to the ROV control system [8].

While not quite the same as the DP systems found on vessels, the ROV DP systems are functionally similar. Vessel DP systems are referenced to real world coordinate systems (lat/long, UTM) while current ROV offerings are referenced only to some relative point on the seafloor. While it is possible to reference the ROV to real world coordinates in real time, the cost (generally in time) of developing the reference point to above water satellite systems (GPS) is not cost effective for the today’s ROV DP needs.

Current ROV DP systems employ a Doppler Velocity Log (DVL) to accurately measure vehicle transit over the seafloor. By incorporating the DVL transit and inertial movement calculations with closed loop control of the vehicle, ROV DP systems are able to provide standard DP functions including position hold, return to home, incremental moves, and transits of the vehicle for specified distances. Certainly the transition of these first ROV DP systems to those incorporating real world coordinate systems is on the horizon.

C. Depth

Most commercial ROV’s are specifically designed and built for work in the oil and gas industry. “Deep water” in the oil and gas world has an entirely different significance when compared to the terminology as applied to the scientific community. Deep water in oil and gas roughly means drilling and recovery operations in depths up to 3000m. In the science world, deep water implies 6000 meters, and sometimes more.

At first glance, the issue of developing a deep water vehicle appears to be related to the ability of the vehicle and its components to withstand pressure, and indeed, designing the vehicle to operate at 10000 psi (the nominal pressure at 6000m) can significantly add to the system cost.

In designing the system however, it quickly becomes apparent that the real challenge is in cost effectively delivering enough power to ensure that the vehicle is useful at that depth.

Several manufacturers are now pushing the depth envelope, but none have the experience in delivering systems to 6000 meters and beyond that Phoenix does. Phoenix has been designing and operating their own Remora ultra deep vehicles for search and recovery operations for many years.

Recognition and application of several enabling technologies allowed Phoenix to develop an ultra deep work class science vehicle for NOAA.

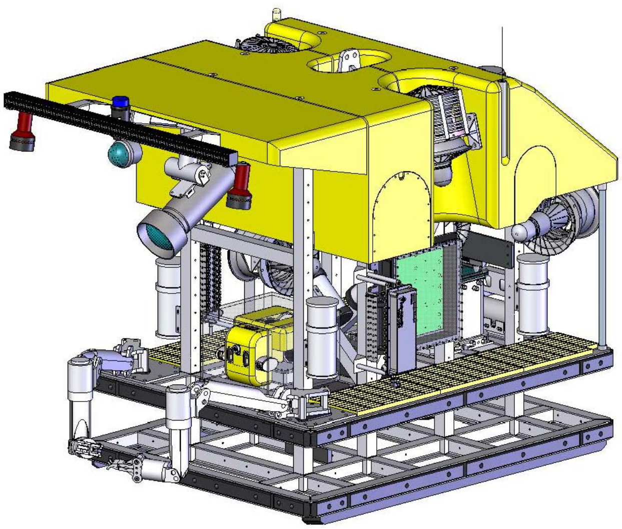

Fig. 1 Phoenix International's NOAA ROV

IV. Defining Characteristics of the Phoenix built NOAA ROV

While the commercial science vehicles currently being designed and built share many common attributes, there are several characteristics of the Phoenix NOAA ROV that make it a very different system. This is a direct result of other vendors basing their offerings on existing machines, while the NOAA ROV is only loosely based on previous designs. In fact, it is designed specifically to meet NOAA's unique needs. The characteristics that differentiate the NOAA ROV from other commercial offerings are described below.

A. Two Body, Separable System

The most obvious feature that separates the Phoenix design from other commercially provided solutions is that it is a two-body system. In this it resembles science systems like the Hercules/Argo pair developed by the Institute for Exploration and University of Rhode Island.

The NOAA ROV system is actually comprised of two vehicle systems – an ROV and a Camera sled. The ROV is connected to the Camera Sled via a flexible electro-optic tether, which is, in turn, connected to the support vessel via an armored electro-optic-mechanical cable. Each carries a separate subsea computer and is controlled independently of the other in the topside control system.

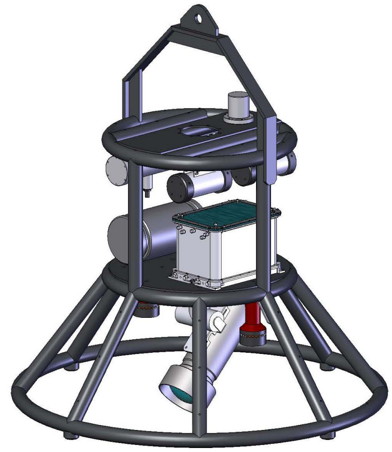

Fig. 2 The NOAA ROV Camera Sled

The ROV operates in a traditional manner, employing lights, cameras, manipulators, thrusters and other science equipment to explore its surroundings. The Camera sled serves two primary purposes, to decouple the ROV from any ship movement, and to provide an alternative point of observation for ROV operations.

Both the Camera Sled and ROV carry HD cameras and HMI lights. The Camera Sled will be used to film the ROV in operations and to provide additional lighting to the ROV from a vantage that will significantly reduce backscatter into the ROV HD camera.

During the design of the system, it became apparent to NOAA that the ability to physically disconnect the two vehicles and deploy only the Camera Sled would greatly improve the flexibility of the NOAA system. An independently deployed camera sled would provide NOAA the ability to explore high risk environments such as historically significant shipwrecks and increase the operations envelope of the *EV Okeanos Explorer* to permit subsea exploration in moderate to heavy weather conditions.

To meet this request, Phoenix worked with third party vendors to develop a robust yet quickly detachable connector that would allow the tether that connects the Camera Sled and ROV to be easily removed. This will provide an additional operational benefit in that tether length may be adjusted easily any time the ROV is on deck. Thus the operational radius of the ROV, from the camera sled, may be adjusted to fit the subsea task without "breaking open" cable terminations.

B. Payload Specific Workskids

NOAA had the foresight in recognizing that the ROV itself is a core platform that will support a variety of different operations. Accordingly, one of the primary specifications set forth was the inclusion of interchangeable workskids on the ROV for mission specific payloads.

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The NOAA ROV system is therefore based on a core vehicle that provides common functionality - thrusters, cameras, lights and a central control system – mated to workskids that will carry instrumentation for specific tasks. While the workskid payloads are at this time undefined, possibilities include multibeam and sidescan sonar, benthic sampling, coring or drilling, and photo mosaicing.

A workskid interface is provided to allow peripheral devices and instruments to be quickly connected and patched directly through the fiber multiplexer, using robust subsea connectors. This interface allows an array of RS232, RS422, Ethernet, and analog signals to be interfaced and provides switched power to each connector port. The details of the available ports are provided in Table 1.

Table. 1 NOAA ROV Spare IO

Type	**Topside**	**Sled**	**ROV**	**WorkSkid**
Video Upload	5	1	4	
Fiber Link	2	2	2	
Ethernet	2	2		2
PC USB	3	2	2	
PC RS232	2		4	
PC Analog In	5	16	16	
PC Digital IO	18	24	24	
PC Analog Out	4	4	4	
Mux RS232	2	2		12
Mux RS422	10	2	8	6
CAN Analog In		4	7	2
CAN Analog Out		1	3	
CAN Digital In		3	14	
CAN Digital Out		4	10	
+24V Switch		1	5	22
Camera Control			4	
Motor Control			4	
Spare CAN Slot			3	
Spare Pwr Supply			2	
Leak Sensors			2	
Proportional Power				1
440 AC				1

C. *Design for Growth*

The expected operating life of the NOAA ROV is in excess of ten years. For that reason, Phoenix has developed the vehicle system from the ground up to be flexible and accommodating of future technological advances.

In addition to the workskid interface described in the previous section, abundant spare IO is provided - pre-wired out to the junction boxes. This IO is accessible through various systems including the fiber multiplexer, subsea computer, and the CAN bus system that provides low priority control of ROV subsystems and components.

Additionally, both the fiber multiplexer and PC-104 control stack are designed to accommodate expansion modules. The fiber system design allows for the use of additional wavelengths and also inclusion of the spare fibers, effectively providing NOAA the option of locating a second, completely independent fiber multiplexer on the vehicle for science payloads.

D. *Substantial Power at Depth*

The combination of extreme depth and a large array of peripheral devices present a considerable challenge to designers trying to balance a heavy demand for power. In order to provide over 40kW of subsea power, Phoenix engineers first modeled the 7km umbilical cable [9][10] to optimize the operating voltage for which both the topside and subsea transformers would be designed.

Phoenix also selected electric motors as opposed to hydraulic motors for improved power efficiency and precise closed loop control of thrusters and hydraulic functions. High current motor controllers and associated electronics in pressure housings are seawater cooled to provide sufficient heat dissipation in warm operating environments.

Finally, by employing the use of ‘operating modes’ in the control system, the NOAA ROV can be adapted to operational needs. For example, a “positioning’ centric control mode allocates full power to thrusters for work in currents, whereas a ‘hydraulic tool’ mode reduces total thruster power for maximum hydraulic pump power. Similarly, a workskid mode might be configured for a payload package that needs a large amount of power for some critical operation. Currently, Phoenix expects to deliver approximately 43kW subsea.

E. *Pressure Tolerant Electronics*

One of the significant cost drivers on modern ROV’s is the pressure housings used to isolate electronics from the high-pressure operating environment. With rapidly rising costs of titanium, this is only a becoming a more critical concern to system designers.

Phoenix has employed a cost effective mix of proprietary designed and tested pressure tolerant electronics and commercial-off-the-shelf (COTS) components to achieve the specified depth rating and performance. COTS components in the NOAA ROV include the fiber multiplexer, subsea control computer and Attitude and Heading Reference System (AHRS). This equipment and the electric thruster motor controllers are housed in two large titanium pressure housings. Nearly all other components, including power supplies and many small microcontroller modules, are located in delrin junction boxes that ‘equalize’ the internal and external pressures via an oil compensation system. These ‘pressure tolerant’ electronics have been extensively tested in both laboratory test chambers and real world operating environments on Phoenix built ROVs.

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F. *Telepresence*

From its initial conception, the NOAA ROV is designed to be integrated with shore based telepresence systems that permit scientists from locations all over the world to participate in real-time ROV operations. NOAA specified this capability as a direct result of their successful telepresence operations with IFE/URI's *Hercules.*

While Phoenix, first and foremost a subsea operations company, was initially resistant to shore based remote operation of the vehicle, our continued development of subsea control systems has brought us to the point that we feel that we can provide the ability to remotely control many of the ROV operations, including lights, cameras, and DP functions. Those functions that do not lend themselves to remote control include human-in-the-loop (real time joystick) control and manipulator operation. The limiting ability to provide this functionality is the inherent delay present in satellite communications that could result in damage to the vehicle system.

All secondary vehicle system control functions have been removed from the hardware control panels and are accessed via the control system Graphical User Interface (GUI). This functionality as well as future specialized payloads might also be easily integrated into telepresence control systems via a similar, remote ROV control GUI.

Fig. 3. The NOAA ROV GUI

G. *xBot*

In addition to being a two body system, the ROV will also carry one of Phoenix International's xBot micro ROV's. This 7000 meter vehicle will operate from the host ROV and provide a third perspective on operations, as well as allow NOAA to probe high risk environments such as chemically hostile subsea vents and wreck sites. NOAA does not penetrate wrecks but they still present significant challenges to larger ROV systems.

Phoenix is currently in development of its third generation xBot. This evolution leaves fundamental capabilities as originally designed but makes significant changes to the vehicle mechanical layout to capitalize on our operations experience with the vehicle. The third generation xBot will be highly modularized to simplify assembly and field maintenance. Refinements also include upgrading the fiber multiplexer to be HD ready, significantly brighter LED lamps, larger fiber spool capacity and more powerful thrusters.

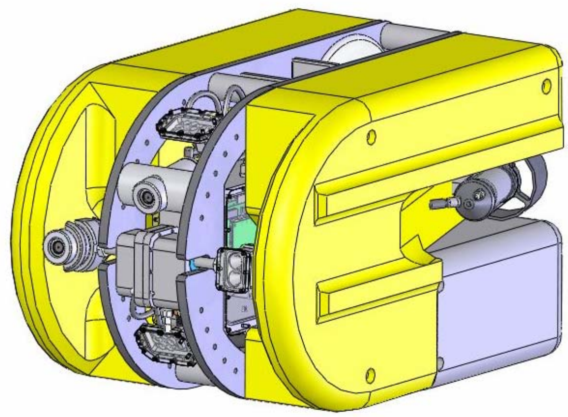

Fig. 4. Phoenix International's 7000m xBot Gen III

V. Conclusions

Many, if not all, of the features of the NOAA ROV have been employed in other ROV's from both the commercial and science sectors, but Phoenix's solution is unique in its system design and in the combination of advanced technologies it employs. HD video, extreme depth capability, multiple camera vantage points, significant subsea power, interchangeable workskids for mission specific payloads and a robust and flexible design with significant capacity for growth show that commercial providers have the operations experience and technology and well as an understanding of the science mission to provide extremely advanced yet cost effective tools to the scientific community.

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