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Development of an Adaptable Monitoring Package for Marine Renewable Energy

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Abstract

Monitoring of early demonstration projects will benefit the industry of marine renewable energy by reducing uncertainty around environmental risks and informing sustainable commercial implementations. The Adaptable Monitoring Package (AMP) and Millennium Falcon deployment vehicle described here are designed to address the need for integrated, cabled instrumentation. By incorporating a flexible suite of instrumentation into a shrouded body with a single wetmate connector, the AMP has the power and data bandwidth afforded to cabled deployments while remaining easy to maintain. Instrumentation included in the initial AMP implementation will allow for monitoring of marine animal interactions, noise levels, current profiles and turbulence, and water quality in the near field of marine energy converters. The Millennium Falcon deployment vehicle, along with the docking station and launch platform, provides the support infrastructure for deployment and recovery of the AMP in the energetic conditions that are typical of marine energy sites. Operational procedures are designed to minimize risk to instrumentation and marine energy converters and the time required for deployment. Future potential for instrument integration and algorithm development makes the AMP well-suited to face the evolving needs of environmental monitoring around marine energy converters.

Keywords—Marine Renewable Energy, Hydrokinetics, Environmental Monitoring, Instrumentation, ROV

1. Introduction

Marine renewable energy is a developing industry that is rapidly advancing towards commercialization. As foundational demonstration projects are entering the water around the world, crucial information may be gained about the features that contribute to a project's success. The extent of information gained is often limited by the monitoring capabilities available to a project team. Each demonstration site or project to date has involved a unique set of monitoring requirements based on site-specific environmental concerns (Polagye et al., 2014). While it may be desirable to engage in comprehensive monitoring, this generally leads to impractical costs. Recent workshops (Polagye et al., 2014, 2011) have prioritized research areas by the risk, significance, and uncertainty of potential impacts and identified the instrumentation suitable for evaluating those impacts.

a. Potential Environmental Impacts

Environmental effects of marine energy converters (MECs), such as wave or tidal energy converters (WECs or TECs, respectively), can be described in terms of interactions between stressors and receptors. Stressors are the factors that occur due to the installation and operation of a MEC and receptors are the elements of the marine environment that are affected by stressors (Boehlert and Gill, 2010; Boehlert et al., 2008; Polagye et al., 2011). Stressor-receptor interactions considered by Polagye et al. (2011) for TECs are ranked as a function of the significance that the potential impact would have if it were to occur, the probability of the impact occurring, and the current level of uncertainty surrounding that impact. Together, these first two factors define the risk associated with the potential impact and the current level of uncertainty helps to determine the priority level for study. The high priority potential impacts observable at the pilot scale include dynamic interactions between marine animals and MECs (e.g., collision, strike, and evasion), reef effects of MECs, and behavioral changes caused by converter sound.

The objective of environmental monitoring, as discussed in Polagye et al. (2014), is to collect sufficient information about an environmental risk to either identify and mitigate impacts or responsibly "retire" the risk by proving it insignificant. Decisions regarding the handling of these risks are made by regional or national resource agencies based on the scientific information available and regulatory mandate. The potential of "retiring" risks would allow monitoring missions to evolve over time and could reduce the cost of MEC deployment.

b. Monitoring Instrumentation Needs

Capabilities of currently available instrumentation to satisfy monitoring goals around marine energy sites, along with the desired advances for future research, are discussed in Polagye et al. (2014). Collecting sufficient information to monitor for risks with low probability of occurrence but severe outcomes (e.g., animal mortality due to collision) is the greatest challenge to current instrumentation. Theoretically, the most expedient approach to monitoring for these rare interactions is through spatially comprehensive and temporally continuous data collection. Even if the cost of instrumentation required for spatially comprehensive monitoring is neglected, the volume of data produced through this type of approach would likely result in a "data mortgage", whereby data are collected at a rate faster than they can be processed. For monitoring plans that require species level taxonomic classification of marine animals (e.g., optical or acoustical imaging), this problem is particularly acute. Neither pure hardware nor pure software solutions are likely to be practical, but integrated instrumentation packages may be a viable approach (Polagye et al., 2014). For example, an instrument with omnidirectional, real-time target detection capabilities (e.g., a localizing hydrophone array listening for marine mammal vocalization) could be used to trigger an instrument with higher-bandwidth and lower-aperture that requires archival data collection for interpretation (e.g., optical camera). While some instrument integration is currently in development, many future possibilities exist which suggests that instrumentation packages should be adaptable to support a wide range of instrument combinations.

One benefit of deploying monitoring instrumentation in the vicinity of MECs is the availability of the converter's power export cable to shore. If the instrumentation can be connected to the export cable, ancillary circuits can provide sufficient power and data bandwidth to operate a wide range of instruments that would be otherwise infeasible for autonomous deployments. Through the shore connection, instruments can be operated in real time with targeted sampling and data processing to meet monitoring plan objectives. While this addresses the power and data bandwidth limitations of traditional

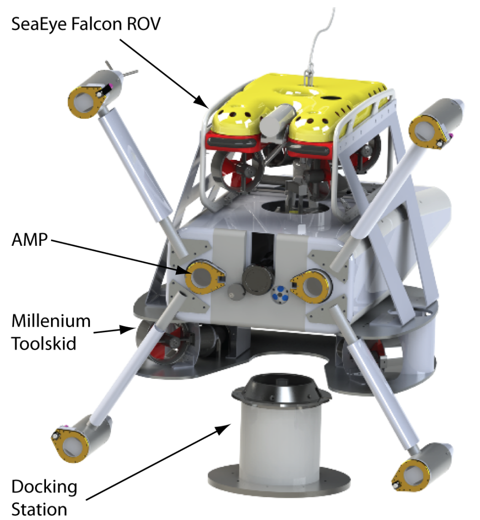


Fig. 1: AMP AND MILLENNIUM FALCON DEPLOYMENT ROV

autonomous deployments, maintenance of the instrumentation becomes more difficult. For experimental monitoring technologies, ease of maintenance is particularly important due to the high probability of malfunction or need for adjustment after relatively short periods (e.g., several weeks between maintenance interventions). Potential maintenance strategies are summarized in Joslin et al. (2014b).

In response to these instrumentation needs, we are developing two systems to enhance capabilities and reduce the cost of environmental research: 1) the Adaptable Monitoring Package (AMP) to integrate a flexible suite of instrumentation into a single, streamlined body and 2) the infrastructure to allow an inspection class remotely operated vehicle (ROV) and custom tool skid to deploy the AMP at marine energy sites. Figure 1 shows the current design model of the AMP and the deployment system, a SeaEye Falcon ROV and custom tool skid referred to as the "Millennium." With a docking station incorporated into the MEC design or located near by, the AMP employs a "plug and socket" architecture, whereby the AMP ("plug") mates with the docking station ("socket") with a power and data connection to shore. Over the lifetime of a project, only the "socket" remains in the water while the "plug" (AMP) is readily maintained or reconfigured at a shore facility. The AMP conceptual design lends itself to rapid deployment in a precise manner, reliable connection to shore power and data, and recovery with similar facility all of which minimize the duration of a maintenance operation and surface vessel operational costs. This approach captures both the benefits of a cabled connection to shore and the adaptability of an autonomously operating package.

2. TIDAL CURRENT AND WAVE ENERGY SITE HYDRODYNAMIC CONDITIONS

The AMP's hydrodynamic performance is evaluated in the context of forces associated with deployment and operation at the Pacific Marine Energy Center's South Energy Test Site (PMEC-SETS) of the coast of Newport, OR and in Admiralty Inlet, WA. PMEC-SETS is a proposed wave energy test site affected by both waves and ocean currents. Admiralty Inlet is a potential commercial tidal energy site affected primarily by currents. While tidal and ocean currents act throughout the water column, wave orbital velocities decay exponentially with depth, such that the loads during opteration at a wave energy site are a strong function of package depth. Wave energy converter monitoring needs (e.g., reef effects of anchors, diving seabed activity) can generally be met by a package deployed near the seabed.

For Admiralty Inlet, the maximum loads on the AMP during operation are given by the superposition of mean currents, turbulence, and an allowance for currents in a storm surge. For a deployment depth of 10 m above the seabed, the maximum horizontal mean currents in Admiralty Inlet approach 4 m/s(Polagye and Thomson, 2013). The maximum storm surge current at this location is likely no greater than 0.4 m/s and unlikely to occur during the epoch maximum tidal currents (as a matter of probability). Consequently, a storm surge current with half this intensity is included in the design loads. Turbulence intensity in Admiralty Inlet is approximately 10% (Thomson et al., 2012) meaning that turbulent perturbations up to 1.3 times the mean current velocity are probable, assuming that turbulent perturbations follow a normal distribution. These considerations lead to a design current of approximately 5.4 m/s for AMP operation (with substantially lower currents during deployment around slack water). For bottom mounted deployments of the AMP at PMEC-SETS (maximum 2 m above the seabed in a minimum of 55 m of water), operational loads will peak during extreme wave events. At PMEC-SETS an extreme wave case would be a 15 m wave (trough-to-crest) with a 16 s period, resulting in horizontal orbital velocities of approximately 2.3 m/s (vertical orbital velocities go to 0 m/s near the seabed). This is less than half of the velocity associated with extremes at the tidal current site.

To be effectively utilized for adaptive management, hydrodynamic conditions amenable to recovery and redeployment should occur with relatively high frequency (e.g., at least one per week). For deployment at a tidal energy site, the AMP would be deployed with the currents fully set in one direction (either on a tide falling towards slack or rising towards peak currents), but with currents less than the operating limit for the deployment system. For Admiralty Inlet, if the AMP is able to operate in mean currents of at least 0.7 m/s, the criteria for deployment window frequency can be met. This operating criterion would also allow the AMP to be deployed under most conditions at PMEC given weather conditions appropriate for surface vessel operations (e.g., less than sea state 3).

3. System Component Descriptions

a. The Adaptable Monitoring Package

Instrument integration has the potential to expand the capabilities of individual sensors while reducing

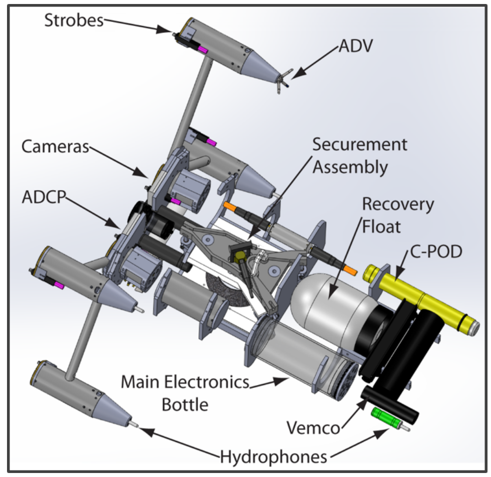


Fig. 2: AMP INTERNAL COMPONENT LAYOUT WITH FAIRINGS AND FRAME REMOVED

the costs associated with environmental monitoring (Polagye et al., 2014). As a platform, the AMP allows for a flexible suite of instrumentation by providing up to 1 kW of power and 2 Gbps of data bandwidth (depending on the capacity of the MEC export cable). The instruments incorporated into the initial AMP design are listed in Table I with their internal layout in the AMP structure shown in Figure 2. Most of these instruments, with the exception of the stereo-optical camera system, are commercially available. The development and initial evaluation of the camera system are described in Joslin et al. (2014a). The leading constraints on the AMP layout are due to the minimum separation distance between hydrophones in the localizing array and between the strobes and optical cameras. Practical experience suggests that time-delay-of-arrival (TDOA) localization methods for mid- and high-frequency cetacean vocalizations will be most effective with at least one meter separation between the hydrophone elements in either a tetrahedral or three-dimensional “L” configuration (Wiggins et al., 2012). Similarly, camera-strobe separation of one meter has been shown to reduce backscatter from biological flocculent (Jaffe, 1988; Joslin et al., 2014a). Both the optical and acoustical cameras, as well as other active acoustic instruments (e.g.,

Instrument	Manufacturer	Monitoring Capabilities	Layout and Orientation
Stereo-Optical Camera System	Integrated System – UW Custom, Cameras – Allied Vision Tech., Strobes – Excelitas	Near-field marine animal interactions with turbine with potential for species-level identification	0.5 m camera separation, 1 m strobe/camera separation, must face region of interest
Acoustical Camera	BlueView P900-2250	Near-field marine animal detection with capabilities for optical camera triggering	Must face region of interest
Hydrophone Array	Integrated System - UW Custom, Digital Hydrophones - OceanSonics iCListen	Marine mammal localization and converter sound monitoring	$\geq$1 m separation between hydrophone elements
Acoustic Doppler current profiler	Nortek Aquadopp 1 MHz	Near-field current profiling to study inflow and wake	Must face towards profile of interest
Acoustic Doppler velocimeter	Nortek Vector	Near-field current point measurement to study inflow and wake turbulence	Sensor head unobstructed
Water quality	SeaBird 16+ v2 CTDO	Water quality and property observations	Unobstructed intake
Cetacean click detector	Chelonia C-POD	Harbor porpoise click detection	Exposed hydrophone element
Fish tag receiver	Vemco VR2W	Tracking of tagged fish	Exposed hydrophone element

TABLE I: MONITORING INSTRUMENTATION INCORPORATED IN THE INITIAL AMP DESIGN

echosounder, Doppler profiler), must also be oriented to face the regions of interest. The remaining instruments generally require a clear line of site for a receiving element (e.g., C-POD click detector, Vemco fish tag receiver) or pump intake (e.g., CTDO) and do not have strict separation or directional requirements. Each of these instruments has been integrated into the structure of the AMP in a way that respects their layout and orientation constraints while optimizing hydrodynamic performance and maintaining a favorable distribution of mass and buoyancy.

The power and communications architecture for the AMP, shown in Figure 3, is similar to that employed by cabled ocean observatories such as Neptune Canada (Barnes et al., 2010) and the Regional Scale Nodes (Cowles et al., 2010). All of the instrumentation in the AMP is either autonomous (e.g., the C-POD and Vemco), or connected to the central node that converts power and data for the cabled connection to shore. Power is converted

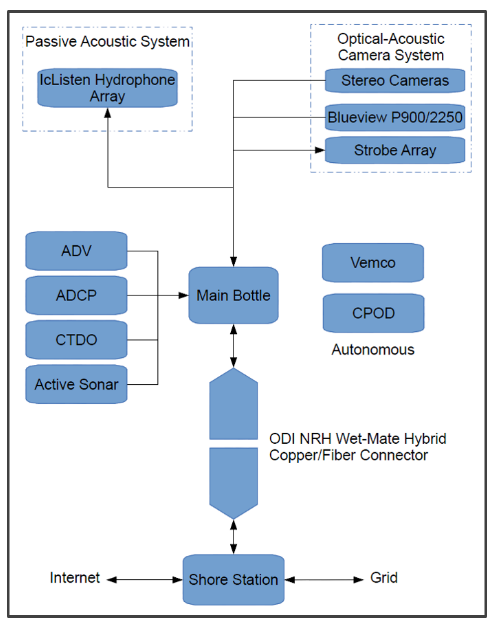


Fig. 3: SYSTEM ARCHITECTURE FOR THE AMP WHILE DOCKED

in the main bottle from the 48 VDC supply to switchable instrument connectors at 12, 24, and 48 VDC. All data from instruments is converted and aggregated to two Gigabit Ethernet channels from native Ethernet or network addressable serial converters. The wet-mate hybrid copper/fiber connector (ODI NRH) is housed at the center of the docking station and is the link between the AMP and shore power and data.

Combining instrumentation into a single shrouded body simplifies maintenance and reduces the drag loads from currents. The mechanical structure of the AMP consists of a streamlined outer hull over modular internal bulkheads. These bulkheads support the loads on the external shrouds while providing mounting surfaces for the instruments. Instrumentation layout, and thereby control of the mass and buoyancy distribution is adaptable due to the modularity of this internal structure. At the center of the AMP body is the docking station securement system and wet-mate connector. The securement assembly consists of conical platform for alignment and three over-center clamps that are engaged by a centrally-located actuator on the ROV. By changing the orientation of the wet-mate connector and securement system alignment key, the AMP can be deployed in orientation angle of 0°, 50°, or 90° relative to the docking station to achieve different viewing angles of a MEC or surrounding ocean.

b. Millennium Falcon Deployment ROV

The commercially available SAAB SeaEye Falcon inspection class ROV forms the base of the AMP deployment system. Weighing approximately 60 kg in air with a payload capacity of 14 kg and having dimensions of 1 m long by 0.6 m wide by 0.5 m tall, the Falcon represents a balance of cost, performance, and ease of customization. The four vectored horizontal thrusters and single vertical thruster are capable of generating 50 kg of force in the surge direction and 13 kg of force in the heave direction. The initial hydrodynamic analysis, discussed in Section 4, shows that the Falcon alone lacks sufficient thrust to deploy the AMP in the currents likely to be encountered at marine energy sites. In collaboration with SeaView Systems, a custom tool skid, shown in Figure 4, was developed that includes additional thrusters (four additional horizontal, one additional vertical), actuators, and cameras to meet the needs for deployment of the AMP.

Fig. 4: MILLENNIUM FALCON DEPLOYMENT ROV

The SeaView Systems power and communication distribution node operates in a Master/Slave configuration with the Falcon's surface control unit. Pilot commands for the Falcon are transmitted via a RS485 serial bus to all of the vehicle's thrusters, actuators, cameras, and lights. At the heart of the Millennium is SeaView's thruster control board, which receives the Falcon commands and emulates them to control the appropriate thrusters on the tool skid. These additional thrusters are mounted in a mirrored configuration to the Falcon but within the structure of the tool skid, which is connected to the Falcon but beneath the AMP during deployments. With thrusters positioned both above and below the AMP, the center of thrust is collocated with the center of pressure from drag. In this manner, the ten thrusters on the Millennium Falcon operate

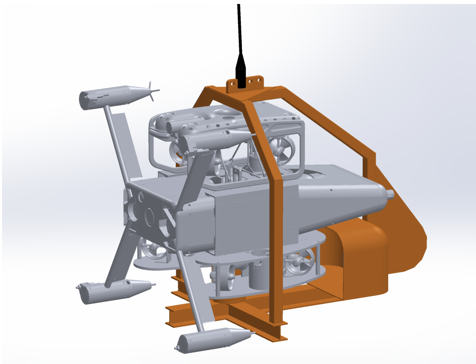


Fig. 5: LAUNCH PLATFORM FOR DEPLOYMENT TO DOCKING STATION DEPTH

on the same commands as the Falcon alone while minimizing pitch and yaw moments from drag forces during maneuvers. Preliminary tank testing indicates that this configuration is able to produce 70 kg of forward/reverse thrust, 60 kg of lateral thrust, and 23 kg of vertical thrust.

c. Launch Platform and Docking Station

A launch platform for the AMP and deployment ROV increases the acceptable current range during deployments by decreasing the umbilical drag that must be overcome by the ROV. Figure 5 shows the current design model of the launch platform that will deploy the system from a surface vessel to the approximate depth of the docking station. This platform is supported by a load-bearing umbilical. A junction bottle on the platform connects the power and data lines from the load bearing umbilical to a neutrally buoyant ROV umbilical. As the system drives off the launch platform, this second umbilical pays out from a passive tether management system on the platform so that the ROV is not exposed to drag on the load-bearing umbilical.

The docking station for the AMP, shown in Figure 1, is designed to facilitate docking and reduce operational time in adverse conditions. On approach, the ROV is guided into alignment with the docking station by cameras, lights, and an ultra-short baseline (USBL) positioning system on the Millennium tool skid. The horseshoe shape of the tool skid is used to achieve a coarse alignment with the vertical axis of the docking station. Fine alignment, required for the wet-mate connector, is achieved by the conical shape of the dock for the vertical axis and a keyway for the system angle. Securement clamps on the AMP are engaged by a linear actuator on the Falcon ROV and designed to withstand the hydrodynamic forces generated by peak loads (Section 4). Mating of the AMP's power and data connection is performed by a second linear actuator on the ROV and monitored by a vertically oriented camera.

d. Deployment and Recovery Operations

Deployment of the AMP with the Millennium Falcon ROV is possible from small vessels with basic station keeping capabilities, an A-frame or crane with appropriate load capacity, and 220 VAC power availability. The operational steps for deployments are as follows:

- Prepare AMP instrumentation and docking clamps for desired deployment orientation. Load AMP and Millennium Falcon on to launch platform.
- Maneuver ship into position down current from docking platform and confirm that currents are within an acceptable range for ROV operations.
- Lower the system to the depth of the docking station on the launch platform and connect power and fiber on the winch for ROV operation through the load bearing umbilical (this order of operations obviates the need for a slip ring to support ROV operations).
- Confirm separation distance and orientation of the system with the docking station using a USBL, disengage from the launch platform and drive towards docking station.
- Maneuver into coarse alignment using Millennium docking features and forward facing cameras.
- Thrust down onto the docking cone and partially engage the docking clamps in the initial

"soft-lock" position.

- Rotate the ROV for angular alignment with the keyway on the docking station and engage docking clamps in the final "locked" position.
- Plug in wet-mate connector and bring the AMP online from a shore station to confirm instrument operations.
- Disengage the ROV from the AMP and return to surface for recovery.
- Disconnect ROV power and fiber on winch to recover the launch platform.

Recovery operations for the AMP are designed around an autonomous system, leaving ROV intervention as a backup. The operational steps for recovery are as follows:

- Maneuver recovery vessel into position and confirm the current range and direction.
- Power down AMP systems.
- Trigger the acoustic release of recovery float and messenger line from the AMP.
- Retrieve recovery float and place tension on the messenger line to sequentially disengage wet-mate connection and docking clamps.
- Raise the AMP to the surface for recovery.

4. System Development and Testing

a. Hydrodynamic Analysis

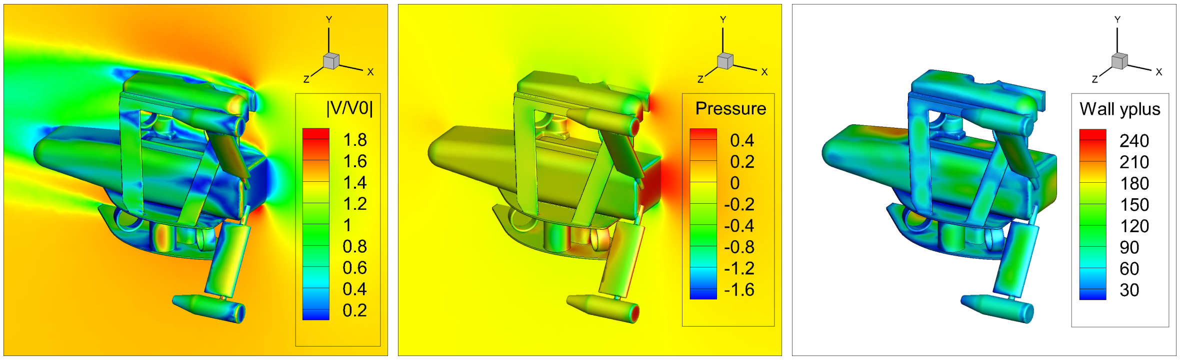
During the design process, a hydrodynamic analysis of the system components is used to estimate system performance. Drag loads on the AMP and deployment ROV during operations determine the acceptable current range for operations. Similarly, the drag forces on the AMP due to peak currents at a site determine the design loads for the internal structure and securement system. Computational fluid dynamic (CFD) simulations estimate the drag forces on the system components and allow rapid iteration on design options (Eng et al., 2013; Jagadeesh et al., 2009). Figure 6 shows sample visualizations of CFD results for a 1 m/s fluid flow over the AMP and Millennium Falcon in the forward direction.

While CFD simulations are useful in a relative sense for making design decisions, the results should be verified experimentally whenever practical. For this purpose, free-decay pendulum experiments in a salt-water test tank are performed on a rapid-prototyped quarter-scale model of the system components (Eng et al., 2013). An analysis of the pendulum motion allows for the derivation of the added mass and drag coefficients. The methods used for this analysis and the results for this system are described in Joslin et al. (2014b).

These experimental results, along with the center of pressure from the CFD simulations, and centers of thrust, mass and buoyancy from the solid model (SolidWorks) allow for an evaluation of the ROV's stability. Given the turbulent component of the site currents, the ROV and AMP should have a buoyant righting moment to remain passively stable on the pitch and roll axes during operations. Dynamic simulations of the system operating in turbulent currents with these hydrodynamic coefficients will be used to determine the limits of stability in the fall of 2014.

b. Tank and Open Water Testing

Prior to deployment in support of marine energy projects, a rigorous testing regimen is needed to thoroughly validate the design and operation of the AMP and Millennium Falcon. Testing will begin as the first full scale prototype components are completed in the fall of 2014. Initial tank tests will allow confirmation and trimming of the system buoyancy and measurement of the bollard thrust output of the ROV and tool skid. Following the tank testing, open water testing will begin in the calm waters of Lake Washington with a test docking station to practice deployment, docking and recovery operations. Testing will then progress to Puget Sound, WA in locations with wave and current conditions similar to those expected for early adoption projects. In



(a) NORMALIZED VELOCITY VISUALIZATION **(b) PRESSURE [MPA] FIELD VISUALIZATION** **(c) WALL y^+ VALUES ON BODY SURFACES**

Fig. 6: CFD SIMULATION RESULTS FOR A 1 M/S MEAN FLOW IN THE FORWARD DIRECTION

addition to these operational tests, the AMP, with a full complement of instrumentation, will undergo a 3-6 month endurance test in early 2015 to evaluate effects of biofouling and corrosion during extended deployments and develop integrated triggers for the instrumentation payload.

5. Summary and Conclusions

Improving monitoring capabilities for marine renewable energy converters will reduce uncertainty around environmental risks and inform design decisions for sustainable commercial implementations. The AMP and Millennium Falcon ROV offer a platform for deploying a wide range of instrumentation in the energetic environmental conditions that are typical of marine energy sites. The initial instrumentation deployed on the AMP will monitor for marine animal interactions, sound levels, current velocities and profiles, and water quality. As monitoring goals and requirements evolve, the AMP's configuration can follow suit through the addition of new instruments or the development of innovative instrument integration methods.

Addressing environmental risks around marine energy converters is essential for sustainable development but the cost to do so must be in line with other project costs. For this reason, developing monitoring plans with practical site specific goals for early demonstration projects is crucial. Collecting sufficient information to responsible "retire" risks will help reduce costs for future projects and for scale up to commercialization.

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