

# A Low-Flow Marine Hydrokinetic Turbine for a Floating Unmanned Mobile Platform

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**Abstract**—Design and fabrication of a marine hydrokinetic turbine for deployment from a floating unmanned autonomous mobile catamaran platform is described. The objective is to develop a low-flow current turbine for deployment from a floating mobile catamaran USV platform. An undershot water wheel has been selected as the turbine of choice and a WAM-V 16 catamaran has been selected as the USV platform. The concept of operation is that the USV platform would autonomously seek and navigate to a coastal location where coastal or tidal currents may be present, anchor at the location, and deploy the turbine to harness the current energy, convert it to electricity and store it in onboard battery banks. The prototype system being developed is targeted at supporting development of self-powered autonomous mobile recharge stations for unmanned aerial vehicles in coastal zones. Once implemented on the vehicle, open water tests are planned for a range of environmental conditions, involving tidal and coastal currents, and system configurations. The status of the ongoing effort will be discussed.

**Keywords**—renewable energy; marine hydrokinetic turbine; autonomous; PTO; USV; UAV

## I. INTRODUCTION

There is a rapidly growing global market in commercial, military, and scientific research applications of unmanned marine and aerial vehicles operating in coastal areas. Unmanned aerial vehicles (UAVs) are increasingly being considered for coastal surveillance and monitoring; shoreline mapping; search and rescue; and aerial surveys. Small UAVs are typically battery-operated and are therefore limited by their battery capacity and availability for recharging. They and other unmanned systems would benefit significantly from floating at-sea recharge and data transfer stations.

In the absence of availability of subsea-cable based power supply, marine hydrokinetic energy (MHK) as well as solar and offshore wind are good potential renewable sources of power for a floating at-sea recharge station, providing continuous power as the resources allow. Several types of MHK turbines of various scales are in use, based on their demonstrated performances with wind power generation [1]. Horizontal-axis, vertical-axis and horizontal transverse-axis turbines have been well studied and are being commercially utilized for power generation [2]. Each of these configurations has its merits, particularly in deployment from fixed or moored platforms. For consideration of their application from a mobile floating platform, these systems would need to be evaluated in terms of weight and size

requirements, ease of deployment from the platform, associated anchoring requirements, and its expected performance characteristics. In low-flow currents, the inflow to the turbines may be enhanced through use of ducts and diffusers [3-5].

Commercial-level development of unmanned surface vehicles (USVs) is underway, and strides are being made in the level of autonomy of these vehicles. A USV has several advantages in serving as a mobile autonomous, recharge station for UAVs as well as for other unmanned systems. First, tidal and coastal current as well as wave energy resources are optimal near the ocean surface, while a surface can also simultaneously harness solar and offshore wind energy resources. Second, in view of its mobility, the recharge station can navigate to and anchor in hot spots of MHK energy resources to optimize its harnessing potential. It can recharge UAVs on demand while anchored, or when the resource abates or as otherwise required, it can autonomously retrieve its anchor and navigate to a desirable location, while being continuously available to the UAVs for recharging. The recharge station can also power monitoring instruments or recharge other autonomous unmanned surface vehicles. Small UAVs are typically battery-operated and are therefore limited by the battery capacity and the capabilities available for readily recharging these batteries. While typically the UAVs may be retrieved onto manned surface ships or shore stations for recharging and data transfer, they can benefit significantly from stations that are unmanned and autonomous, in terms of significant cost savings, as well as increasing the at-sea presence and offshore operational ranges of the drones and associated missions.

Here, we describe development of a low flow marine hydrokinetic (MHK) current turbine for deployment from a mobile unmanned surface vehicle (USV). The concept of operation is that the USV platform would autonomously seek and navigate to a coastal location where coastal or tidal currents may be present, anchor at the location, and deploy a selected MHK turbine to harness the local current energy. An onboard power take-off (PTO) device would convert the harnessed energy to electricity for storage in onboard battery banks. The power will be stored in onboard battery banks. The USV includes a flight deck with a wireless charging platform connected to the battery bank to support landing, takeoff and recharging of small UAVs. Once the current harnessing cycle is completed, the MHK turbine would be raised out of the water, the anchor would be retrieved and the USV would return to a

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desired location. The system has been designed and is being fabricated and implemented on the USV. Environmental permits have been obtained to carry out field testing and demonstration in tidal currents in the Intracoastal Waterways and coastal currents off South Florida.

## II. SYSTEM DESIGN AND METHODOLOGY

The USV is a WAM-V 16 catamaran with two 16 ft inflatable pontoons, each with an electric steerable outboard engine and connected to an elevated deck. The navigation system onboard the USV enables it to autonomously navigate along designated pre-programmed field paths, avoiding obstacles. The USV is being developed at FAU for additional levels of autonomy, including adaptive navigation [6]. It includes an articulated structural framework and two batteries. The specifications of the USV are:

Length	4.88m
Beam	2.44m
Draft	0.15 – 0.45 m
Platform weight	181 kg
Payload	113 kg
Batteries	2 x 105 Ah Li NMC

Once fitted with the supporting subsystems, the USV would constitute a mobile, floating MHK Platform (Fig. 1). The subsystems would include the MHK turbine, a flow concentrator, a PTO and generator, an automated anchoring system, a health monitoring system, and a flight deck with autonomous direct-contact charging platform for UAVs. The design and the methodology for selection of these subsystems are described here.

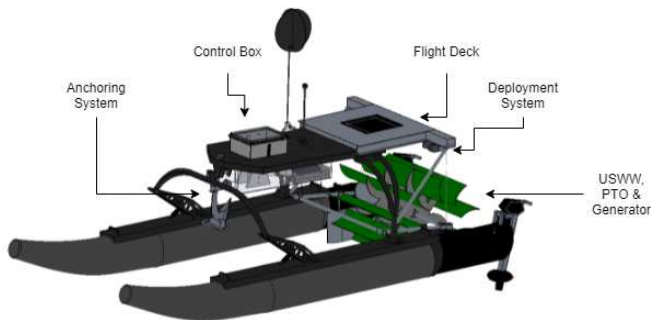


Fig. 1 WAM-V 16 USV and USWW turbine based MHK Platform.

### A. Low-current MHK turbine

A trade study with seven different requirements (Table I) was conducted between a horizontal-axis and vertical-axis turbines as well as a horizontal transverse-axis solution, in the form of a Poncelet undershot water wheel (USWW). A Poncelet undershot water wheel [7] exploits the kinetic energy of the water while being partially immersed in water.

USWW was selected primarily for its low submergence level that would facilitate operation in any location, smaller moment

arm/lower mounting point for better platform stability, low startup speed due to non-lift-dependent operation, and superior clearance in its stowed position. Further, a risk analysis suggested that USWW was the lowest risk design compared with the others, in terms of impact on platform stability, and likelihood in being impacted by debris in the water. Siting the turbine between the pontoons at the stern of the USV restricted the length of the wheel to 1.3m and its diameter to 1m, providing a swept water area of  $A = 0.45m^2$ . To enhance the inflow to the turbine, a flow concentrator in the form of side and bottom fins were considered. Laboratory experiments were conducted with a 1/5<sup>th</sup> scale model of the turbine, configured with nine and eleven blades and fitted with scaled model of the flow concentrator to characterize their performances [8]. A nine-blade turbine was deemed optimal. However, subsequent two-dimensional CFD analysis suggested better performance may be attained with a seven-blade configuration. Final evaluations of seven, nine and eleven blade configurations of the USWW would be determined via field-testing. Consideration of environmental conditions during operations dictated removal of the bottom fin. The designed USWW and the flow accelerator are shown in Fig. 2a and the fabricated wheel is shown in Fig. 2b. The USWW will be implemented on the aft of the USV and will be automatically deployed using a linearly actuated swing arm and cable (Fig. 2c). The inferred performance characteristics of the USWW are shown in Fig. 3.

TABLE I: TRADE STUDY REQUIREMENTS

Requirement Number:	Description:
1	The system must operate in the low-speed current flow of a coastal marine environment (~0.5 m/s)
2	The system must reach a power output of 300 W
3	The power output for the final device must be at least 50% of the predicted value for a given flow speed.
4	The system must be autonomously deployable from the WAM-V platform.
5	The MHK, PTO, generator, and associated mounting structures must weigh less than 140 lbs.
6	The MHK device must completely clear the free surface in its stowed position.
7	The device should deflect/avoid environmental debris such as plastic bags and coconuts.

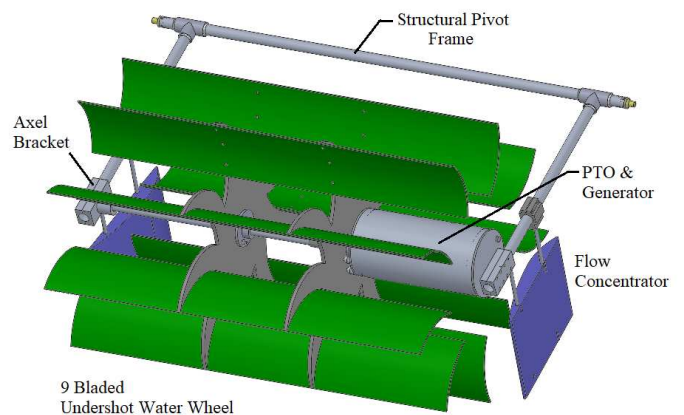


Fig. 2a. USWW and flow concentrator design



Fig. 2b. Fabricated and assembled 9 blade USWW.

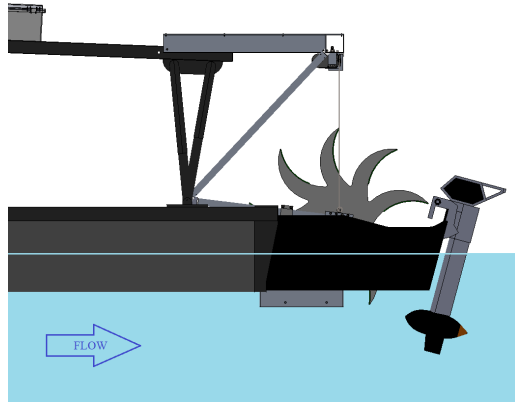


Fig. 2c. USWW in its deployed configuration.

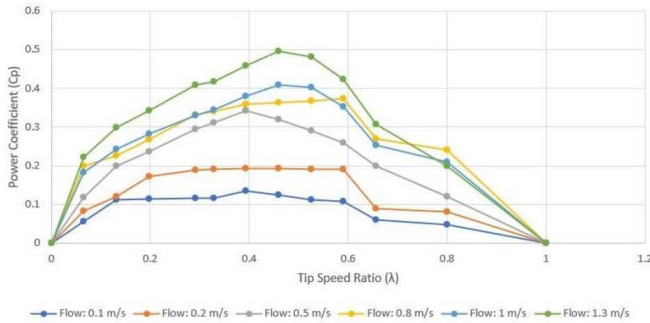


Fig. 3. Estimated USWW full-scale performance based on laboratory experiments.

### B. Power Take-off Device

The power take-off (PTO) device transforms the mechanical power of the rotating USWW shaft to electrical power. It also ensures that the USWW and the generator both rotate at their respective peak efficiencies individually as well as a coupled system, in support of optimal power extraction. The designed PTO has three main components, a step-up gearbox, a ball-continuously-variable transmission (CVT), and a permanent

magnet synchronous generator. Based on the results of a trade study, a 1-to-35 planetary gearbox, a NuVinci ball-CVT, and a Freedom-3 sealed permanent magnet generator were selected. The PTO subcomponents are assembled in a compact package for implementation onto the USWW assembly (Figs. 2 and 4). Modeling and simulations were conducted to develop baseline performance expectations for the full MHK turbine system and to verify the selected PTO components. The full system models and simulations were based on the approach by Rex and Johnson [9], with modification to how the turbine is modeled and taking account of the specific component characteristics and parameters of this turbine/PTO design. The USWW was modeled using equation (1) for the extracted power, equation (2) for the associated torque, and the rigid body equation of motion (3), with the power coefficient  $C_p(\lambda)$  based on laboratory/computationally predicted data; here  $U$  is the speed of the stream,  $A$  is the swept area of the USWW,  $\rho$  is the density of the water,  $\lambda = \frac{\omega R}{U}$  is the tip speed ratio,  $\omega$  is the angular speed of the turbine,  $R$  is the radius of the water wheel,  $J$  is the moment of inertia of the water wheel and  $T_c$  is the generator torque. These equations were used to develop a lookup table of input data for the MHK model simulations

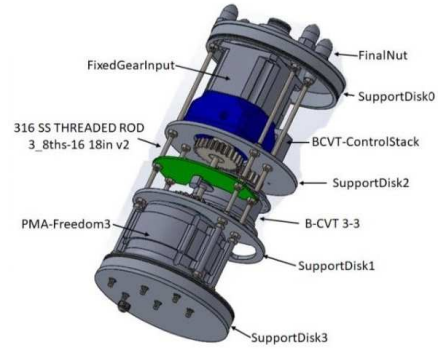


Fig. 4. The PTO assembly.

$$P_m = \frac{1}{2} \rho A C_p(\lambda) U^3 \quad (1)$$

$$T_\gamma = \frac{P_m}{\omega} \quad (2)$$

$$\dot{\omega}_\gamma = \frac{1}{J} (T_\gamma - T_c) \quad (3)$$

Simulations of the full system were conducted in MATLAB/SIMULINK, modeling each of the subsystems, MHK turbine, gearbox, CVT & controller, and generator, modeled each individual component using their respective characteristic and dynamics equations. A PID controller was utilized for the simulation of the CVT ratio control system. Time series of multiple water current flow profiles were used as input to the simulations, including  $\sim 5\%$  variance in flow speed, centered around 0.5, 0.7, and 1.0 m/s. The simulations targeted maximum power point tracking (MPPT) of the MHK power production at the varying current flow using the PID-controlled CVT ratio. The results of the MPPT controller, comparing the optimum versus actual rotation rates of the USWW, are shown in Fig. 9(a-c), and the power produced through this MPPT control are shown in Fig. 10(a-c). The results of the simulations

suggest that the mechanism for MPPT is more than adequate for maximum power capture using the applied controller, with near identical plots of the optimal versus actual rotation rates of the USWW. The power generation results confirm that the PTO design, comprised of the selected components, are a feasible configuration for power capture at the targeted low water current flow rates. Experimental validation of the design and prediction of the performance of the PTO was carried out using a laboratory benchtop system (Fig. 5), based on emulation of the USWW. The aims of the benchtop tests were to assess the functionality and performance of the PTO through evaluation of the component efficiencies, to verify the control method that is utilized, and to confirm generation of electrical power at targeted low current flow rates. The results of the tests showed that the bench setup matched the simulated MHK response with correlated stepped response and torque curves with an average 0.94 correlation for each tested flow rate. Testing of the PTO component efficiencies indicated that the losses throughout the system would not inhibit the performance of the overall system to the extent of unfeasibility. Tests confirmed the MPPT and power production expectations, with the method of characterized system ratio command providing better control over the PID controller for MPPT. Detailed description of the PTO and results of these tests are provided in [10].

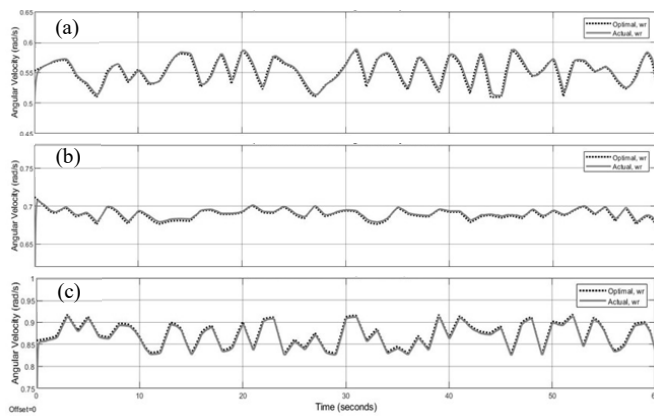


Fig. 5. Rotational rate of the USWW and MPPT for each current profile: (a) 0.5 m/s, (b) 0.7 m/s, (c) 1 m/s

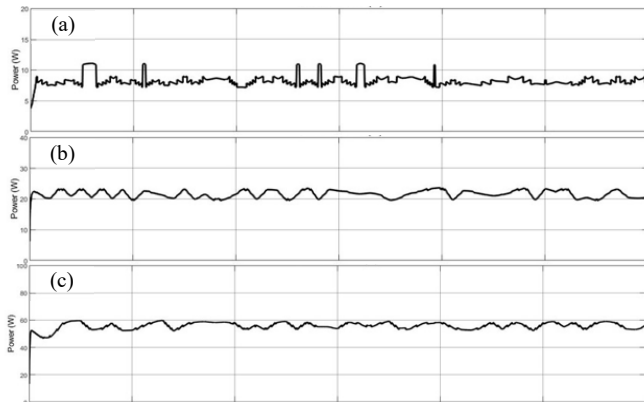


Fig. 6. Electrical power generated for each current velocity profile: (a) 0.5 m/s, (b) 0.7 m/s, (c) 1 m/s

### C. Automated Anchoring System

Operations in waters of depth 1 – 5m is planned. An automated anchoring system (AAS), consisting of a Rocna

anchor, an anchor line, a line locking cleat, a raised roller and a winch, has been designed (Fig. 7) to automatically pay out the anchor line to a 7:1 scope when in position to deploy the USWW and to retrieve it following retrieval of the USWW. The automation is based on sensing the tension in the anchor line and commands from the USV. It is expected that the anchor and the anchor line would experience additional tension due to the added drag of the deployed USWW in the current. Consideration is given to the impact of this tension on the platform stability. The expected maximum tension and the associated angle of the anchor line at the vehicle were determined using an Orca Flex simulation to be 710N and 12 degrees to the vertical respectively [11]. These forces dictated the selection of the anchor line, the winch and the load cells that are built into the design to monitor the real time tensions on the anchor line. A custom cam cleat is incorporated in the design for secure easy cleating and easy release of the anchor line.

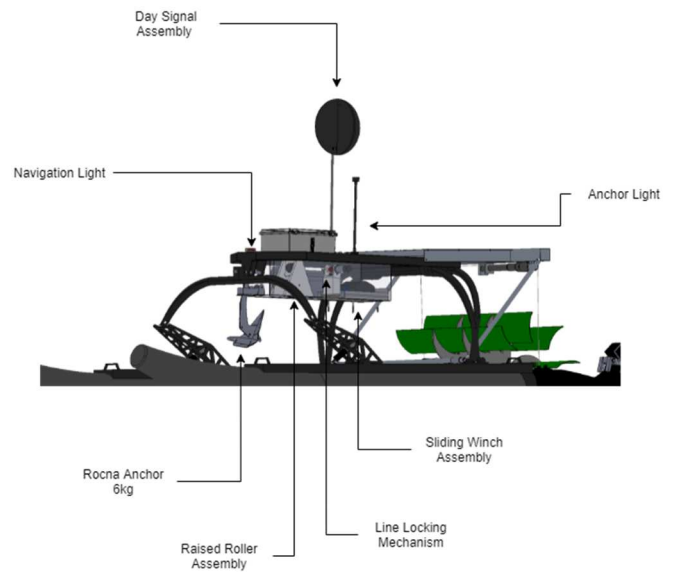


Fig. 7. Automated anchoring system assembly

COLREG requirements for anchoring and nighttime operations were then taken into considerations. The requirements for the black day shape, an anchor light, and a navigation light were identified and incorporated into the design (Fig. 7). The AAS system, including an electronic control board, was assembled and tested in the laboratory for its proper functionality. The all up test certified that the AAS worked once each feature was integrated into the whole system. A sled test was then conducted to ensure that the AAS would hold the anchor in place while under a load and that the selected anchor line was adequate. The anchor line was paid out with the anchor attached to a sled which held an additional 150lbs of weight and the AAS was then pushed 100ft while weighted. The holding power of the anchor was also tested by placing it on the surface of saturated mason sand at the end of a 10'x2'x3' box and the anchor line was pulled until it set itself in the sand. Then it was subjected to increasing load until it pulled free from the set position in the sand. The tests suggests that the anchor would take approximately 2m to set itself and that it would remain anchored under the maximum applied force of 1,100N, well above the expected load.

#### D. UAV Flight Deck

The USV can accommodate small unmanned aerial vehicles (UAVs). It is planned to demonstrate the UAV recharging capability of the prototype MHK Platform with a small, unmanned helicopter. The flight deck (Fig. 1) consists of two main subsystems, a UAV restraint system and a charging pad [12]. The restraint system is designed as a parallel pusher that uses two motors to actuate four rods to the center of the charging pad which then slip over custom UAV landing gear, holding the UAV in place for the duration of its charge. The restraint system has been fabricated inhouse (Fig. 8). The two driving motors have been programmed to close to the desired distance in relationship to the edges of the charging pad. The restraint system was tested in the laboratory for its functionality. In view of the small size of the fabricated components of the restraint system, the machined rods and slider u-channels did not glide sufficiently smoothly for robust autonomous operation. A redesign utilizing t-slotted framing rails and matching slides is underway.

To facilitate autonomous recharging, wireless, direct-contact charging is needed [13]. Such a charging pad developed by SkyCharge has been selected for implementation on the flight deck. The pad uses conductive contacts and proprietary DC to DC battery charging electronics in charging an UAV. The pad and its electronic box have been modified so that they are better suited for application on the USV. The functionality of the pad was successfully tested in the laboratory.

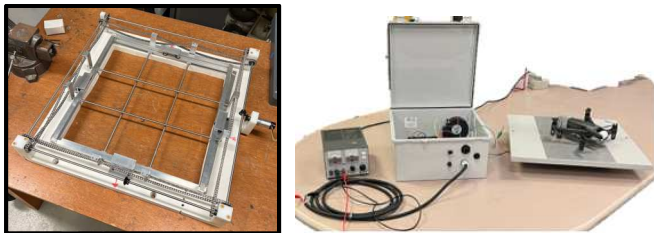


Fig. 8. The fabricated UAV restraint system (left) and the UAV charging pad and electronics box (right)

### III. PLANNED FIELD TESTING

#### A. Permitting

The project underwent a National Environmental Policy Act (NEPA) review for the planned fieldwork. A field work plan was prepared and a third-party biological evaluation of the identified potential test sites was conducted. Tests are planned to be conducted in the Intracoastal Waterways in South Florida which is subject to tidal currents and in coastal waters off Port Everglades, Florida. The biological evaluation determined that the planned activities at the proposed test sites are likely to have no adverse effect on at-risk wildlife and their habitats, provided appropriate mitigation procedures are followed. The steps include not conducting field testing during the turtle nesting season in South Florida, as well as following all posted no-wake and speed limit signs and stopping testing if any animals are sighted within a fifty-foot radius of the test site and deploying the anchor so as to minimize damage/disturbance to the bottom.

#### B. Field Testing

Open water tests of the MHK Platform are planned for a range of environmental conditions and system configurations, including current speeds, sea state conditions, USWW blade submergence, USWW blade configuration, and harvesting location (tidal flows vs longshore coastal currents), in support of assessing its power generation capabilities. Test sites have been selected based on the local current resource; the local water depth; the bottom type; local boat traffic e) the regulatory and permitting requirements; proximity to FAU - SeaTech, and staging of the response team. Data from these test sets will be used to assess the performance of the MHK Platform and its subcomponents and developed optimized standard operating procedures for such mobile MHK platforms to ensure peak performance and in support of transitioning the prototype MHK Platform to the commercial market.

### IV. DISCUSSION

The flight time, range and mission of small UAVs and other unmanned autonomous systems are limited by the availability of onboard power. At-sea mobile recharge stations for such systems, supported by renewable power sources, can serve to extend the mission and operation time of these systems. For example, a UAV can only fly as far as half the battery life allows before having to turn around and return to base. However, strategic placement of recharge stations along its intended flight route can significantly extend its autonomous reach and missions.

A USWW turbine, a PTO, and supporting systems have been designed for low current flow applications and deployment off the aft of a small USV. Simulations and laboratory experiments confirm feasibility of the concept and the simulations suggest extraction of approximately 9, 24, and 58 Watts of power at 0.5, 0.7, and 1.0 m/s current flow rates respectively [2]. The turbine and the supporting systems are being fabricated, assembled and implemented on the WAM-V 16 USV for testing and demonstration in open waters.

### ACKNOWLEDGMENTS

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