Development of an unmanned mobile current turbine platform

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Abstract— **The design and development of a prototype unmanned mobile floating platform, equipped with a custom low-flow marine current turbine for autonomously seeking and harnessing tidal/coastal currents is described. The platform is an unmanned surface vehicle in the form of a catamaran with two electric outboard motors and capabilities for autonomous navigation. An undershot water wheel, aided by a custom flow concentrator, has been selected as the basic design for the marine current turbine, which is mounted on the stern of the unmanned surface vehicle platform. The concept of operation is that the platform would navigate to a designated marine current resource, autonomously anchor at the location, align itself in the current and deploy the current turbine using a custom cable-lift deployment mechanism. As the turbine harnesses the local current, an onboard power-take-off device converts the harnessed mechanical energy to electricity which is stored in onboard batteries. Considerations of deployment in tidal and coastal waters required obtaining the necessary environmental permits for conducting in-water testing; developing required mitigation measures in protecting local wildlife and their habitats; and identifying potential in-water test sites and surveying them for their suitability in terms of the current resource, bottom type, water depth, and local boat traffic. The design and development of the turbine and the results of initial in-water testing are discussed. The potential for scaling up the system for extended capacity is presented.**

Keywords— **Low-flow current turbine, unmanned surface platform, power take-off device**

I. INTRODUCTION

WHILE there is a rapidly growing global market in commercial, military, and scientific research applications of unmanned marine and aerial vehicles operating in coastal areas, the market for at-sea recharging stations for these vehicles is in its infancy. For example, aerial drones or unmanned aerial vehicles (UAVs) are increasingly being considered for coastal surveillance and monitoring; shoreline mapping; search and rescue; and aerial surveys. The UAVs need to return to land-based recharge stations to recharge. For small battery-operated aerial drones, such a mode of operation is very limiting. These drones can therefore benefit significantly from floating at-sea recharge and data transfer stations that would result in the extension of their at-sea presence and offshore operational ranges at reduced costs. In the absence of the availability of a subsea-cable-based power supply, marine hydrokinetic energy (MHK) as well as solar and offshore wind are good potential renewable sources of power for such floating at-sea recharge stations, providing continuous power as the resources allow. A mobile autonomous platform has several advantages in serving as a recharge station for other unmanned marine and aerial vehicles. First, wave, tidal, and ocean current resources are optimal near the ocean surface, while a surface station can also 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. A surface platform can accommodate the recharging of UAVs on demand, either at its anchored location or when the resource abates, at a more desirable location where the platform can autonomously navigate to. The recharge station can also power monitoring instruments or recharge other autonomous unmanned marine vehicles. We consider providing partial power for such a recharge station from harnessing tidal/riverine/estuarine/coastal ocean currents.

Large-scale in-stream floating platforms that harness marine currents include Orbital Marine Power's O2 [1] platform in Orkney waters, UK for harnessing tidal currents, ORPC's pontoon-based Rivgen platform [2] for harnessing rivers, and a mono-hull ship-based platform developed by *Sustainable Marine* in the Bay of Fundy [3] to harness tidal currents in the bay. Making some of the functions of such platforms autonomous would be beneficial.

Here we describe our effort to design, build and test a prototype-scale unmanned mobile floating marine

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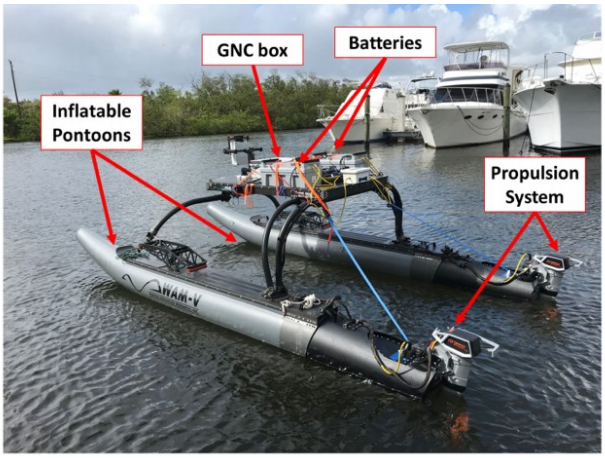

Fig. 1. The 16' WAM Unmanned Surface Vehicle to serve as the Platform.

hydrokinetic (MHK) platform that is autonomous and equipped with a custom low-flow (~0.5 – 1.5 m/s) current turbine to harness current energy and convert it to electrical power for storage in onboard battery banks, in support of providing partial power to an onboard charging station for aerial drones. The design and development of the system and associated subsystems are described in section II, the performance characteristics of the turbine are discussed in section III, field testing is described in section IV, the results of preliminary testing are provided and discussed in section V and concluding remarks are provided in section VI.

II. System Design and Development

The goal is to develop a small prototype unmanned mobile floating marine hydrokinetic (MHK) platform to assess the feasibility of such platforms to serve as recharge stations for other unmanned vehicles, including aerial drones. The platform utilizes a custom low-flow (~0.5 m/s) marine current turbine to provide partial power to recharge onboard battery banks.

A. *Unmanned surface vehicle (USV) platform*

A small wave-adaptive-modular autonomous unmanned surface vehicle (WAM 16-USV, Fig. 1, [4]), with two 16 ft inflatable pontoons, each with an electric outboard engine and connected to an elevated deck, serve as the base platform. The specifications of the USV are:

Length (m)	4.88
Beam (m)	2.44
Payload (Kg)	113
Propulsion	2 x outboard electric motors
Batteries	2 x 105 Ah Li NMC
Draft (m)	Up to 5.66
Weight (Kg)	181
Draft (m)	0.15 - 0.45

The USV is controlled from its guidance and navigation control (GNC) box. It is a catamaran vehicle with two inflatable pontoons, two rigid motor mounting pods, an articulated structural framework, two batteries, an interface control box, and two steerable electric outboard motors. By design, the vehicle requires the provided radio frequency controller to be in range during operations. The USV is appropriately modified to accommodate the turbine, an anchoring system, and a helipad for aerial drones as well as a supporting structure, battery banks, and onboard electronics.

B. *Low-current turbine and flow concentrator*

A trade study between a horizontal axis, a vertical axis, and an undershot waterwheel (USWW) turbine was conducted to determine the best option for the WAMV 16-USV platform; details of the trade study are provided in [11]. Based on the merits of each turbine option, and the requirement to maintain platform stability, the USWW (Figs. 2, 2a), aided by a custom flow concentrator, was selected as the turbine of choice for the WAMV-16 USV platform, significantly as it was considered to have the least impact on the platform stability. Through design iteration, 7, 9, 10, and 11-blade waterwheel configurations for the turbine were chosen for consideration [5], and a diffuser-type flow concentrator [6-8] was deemed optimal.

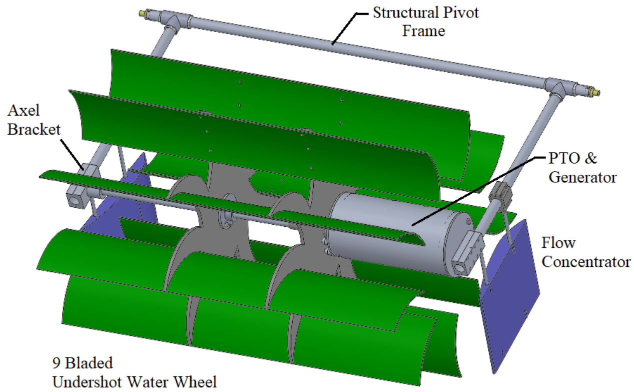

Fig. 2. The undershot waterwheel (USWW) turbine and diffuser-type flow concentrator.

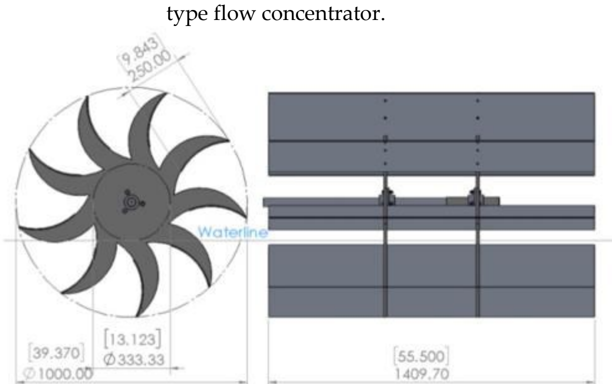

Fig. 2a. Basic dimensions (in/mm) of the USWW

C. *Power take-off device (PTO)*

A spur drivetrain/gearbox coupled with a ball-type continuously variable transmission (B-CVT) system [9], a Freedom 3 sealed permanent magnet generator, and an associated controller, constitute the power take-off device (PTO, Fig. 3). The B-CVT was selected primarily because of the easy commercial off-the-shelf availability for our small-scale prototype MHK system. Its low weight, good performance, and low cost were other considerations. The B-CVT facilitates optimization, particularly when operating in constantly varying tidal currents, translating the relatively low speed of the MHK device to higher speeds required by most generators using a pair of linked configurable pulleys to smoothly transition the gear ratio between input and output shafts. The PTO unit is custom-built and housed in a shielded container on the turbine shaft (Fig. 2) so that it is suitable for near-free surface marine operations. The powertrain structural framework attaches to one arm of the deployment frame to resist rotation and provides the support and connections used by this subsystem's environmental shielding.

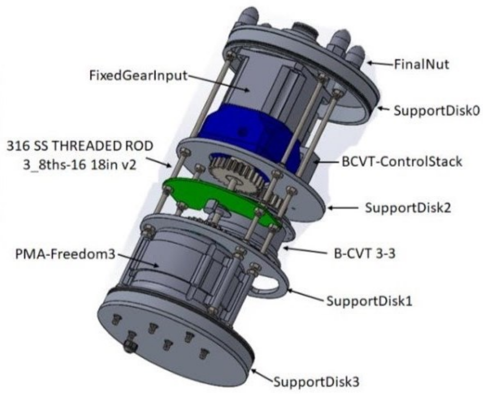

Fig. 3. The power take-off (PTO) device.

The B-CVT gear ratio is controlled by an instrumented motor stack (B-CVT Shifter Stack) driving a pair of spur gears. The torque required for shifting the CVT was measured at 0.35Nmm. The proportional–integral–derivative (PID) controller is used with a maximum power point tracking (MPPT) algorithm to maximize power transfer between the MHK device and the electric generator. The driving and driven gears have a pitch diameter ratio of 0.5:1.25. The controller is housed on a custom motherboard and is supported by a Teensy 3.6 microcontroller unit (MCU). This selection allows for the expected multiple communication protocols between it and the other systems onboard the platform. The controller output drives two stepper motors to vary the actuation of the CVT ratio. Charge control is monitored through a universal asynchronous receiver/transmitter (UART) serial communications port. Health inside the controller box is monitored using two temperature sensors and a humidity sensor. Acquired data and health monitoring sensor record is communicated to the computer of the main system through the MCU's universal serial bus (USB) port.

The gearbox has a 35:1 gear ratio and the B-CVT facilitates variation of this ratio by a factor of 0.5 to 1.9. The waterwheel turns at a rate of 3 – 5.5 rpm in 0.5 – 1.0 m/s current. Thus, the B-CVT-based gearbox provides an output of between 52 and 365 rpm.

D. *Turbine deployment subsystem*

The turbine deployment subsystem (Fig. 4) controls the deployment of the turbine into and out of the water. When not in use, the turbine is out of the water and stowed on the platform (Fig. 5a). Once the USV platform navigates to a current flow resource, and successfully anchors, the turbine is deployed (Fig. 5b) for harvesting marine current energy. The deployment mechanism's position information is monitored and relayed to the autonomous unmanned platform's controllers. The deployment subsystem structure is designed to mechanically support the weight of the turbine with the requirement that the subsystem can actuate deployment and recovery of the turbine. The deployment/recovery of the turbine is controlled by a linear actuator.

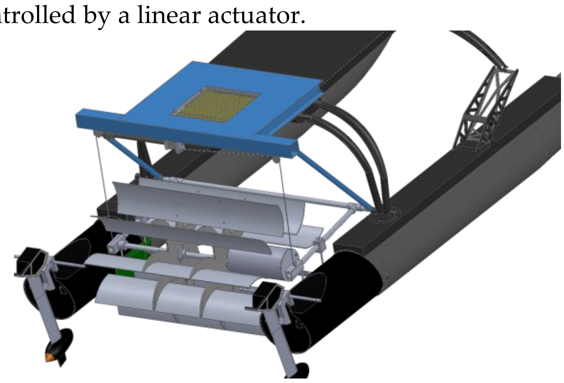

Fig. 4. The swing arm turbine deployment subsystem.

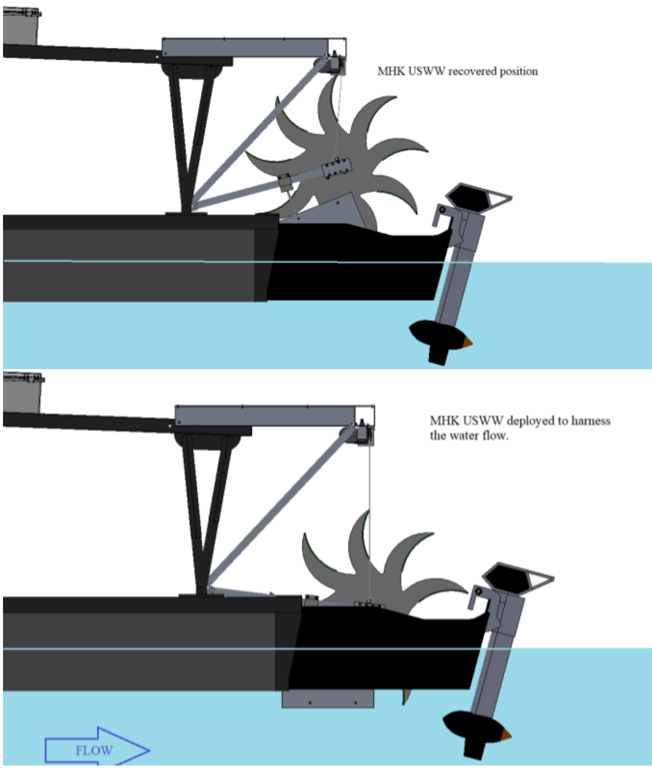

Fig. 5. The turbine in (a) recovered position and (b) deployed position.

E. *The automated anchoring subsystem*

The floating unmanned platform needs to anchor autonomously in the current stream to enable the harvesting of the marine current energy by the onboard turbine. This is accomplished using an automated anchoring system, consisting of a Rocna anchor, an anchor line, a line locking cleat, and a winch (Fig. 6) that automatically pays out the anchor line to a 7:1 scope when positioned in the current stream. The vehicle performs station-keeping while being anchored so that the platform is appropriately oriented when the turbine is deployed. The automated anchoring system, an analysis of its feasibility, and laboratory testing are described in detail in [10]. The anchor system was successfully tested in the field as part of a mooring system in a 1 m/s tidal current.

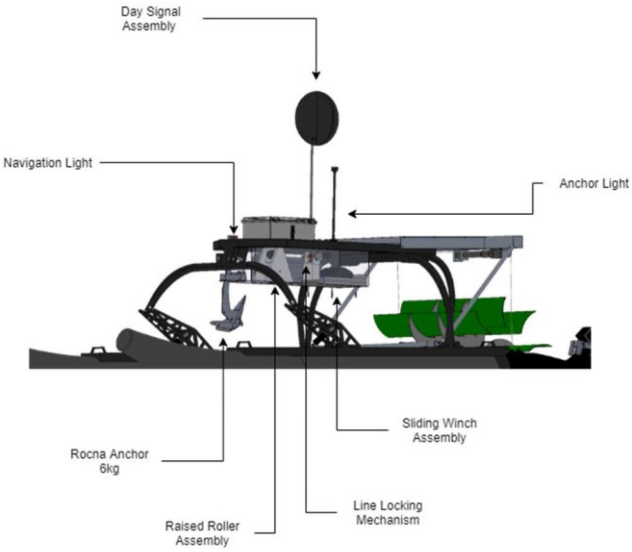

Fig. 6. Automated anchoring system assembly

F. *The MHK platform*

The schematic of the MHK platform with its subcomponents is shown in Fig. 7. In addition to the above subcomponents, the platform includes a flight deck with capabilities for the launch, recovery, and charging of aerial drones (see [11] for details).

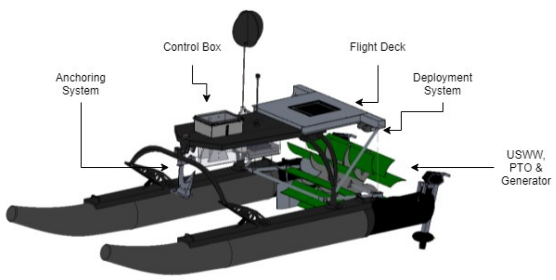

Fig. 7 The schematics of the complete platform with all the subsystems

The turbine, the PTO, the turbine deployment subsystem, and the automated anchoring system have been fabricated and assembled. The flight deck is being assembled. The assembled platform to date is shown in Fig. 8.

Fig. 8 Assembled MHK platform as of March 2023

III. PERFORMANCE CHARACTERIZATION

The performance of undershot waterwheel has been well studied. Significant previous and recent investigations include those by [12-14]. Quaranta and Revelli [12] provide a comprehensive study of large-scale undershot and overshot waterwheels. Cleynen et al. [13] conducted a 2-D numerical study, coupled with a model scale laboratory investigation, of the USWW to characterize its performance. Zhao et al. [14] examined the effect of blade submergence depth on turbine performance. Here we present the results of a high-fidelity computational fluid dynamics (CFD) investigation of the performance characteristics of our undershot waterwheel with its custom curved blade design. Parameterized two-dimensional, multiphase CFD simulations were conducted using a refined mesh (Fig. 9) for a range of flow speeds and tip-speed ratios, 7, 9, 10, and 11-bade turbine configurations, and a range of blade-submergence depths.

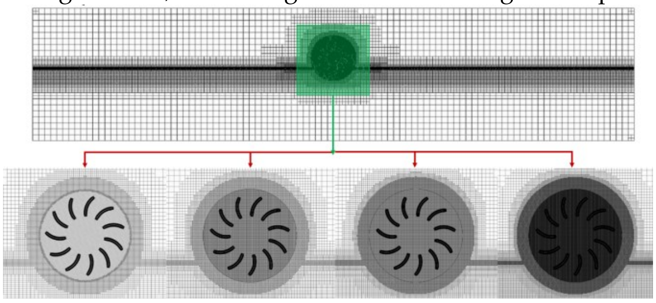

Fig. 9. An example of computational mesh resolution

The accuracy of the CFD simulations was quantified using convergence studies of the computational scheme, aiming to obtain acceptable modeling accuracy for a modest computational cost. Predicted coefficients of power generated at the waterwheel, based on the 2-D numerical simulations, which imply a 100% blockage ratio, are provided in Fig. 10; the values shown also do not include the impact of the loss of mechanical and electrical efficiencies at the shaft and in converting mechanical power to electrical power. They suggest that optimal performance is achieved for a tip-speed ratio in the range of 0.6 - 0.7. For very low flow rates, the best performance is achieved using a 7-blade configuration while for higher speeds the performance is approximately similar for all configurations among the ones considered. The computational study was complemented with laboratory experiments using a scaled model of the 9-blade configuration [5] that confirmed the computed turbine characterization. Work is in progress to extend the computational work with a 3-D CFD study to characterize the effects of the 3-D aspects of the flow as well as consider the impact of including a diffuser for flow enhancement.

The performance of the PTO was characterized through modeling and simulation using SIMULINK in MATLAB and supported by bench tests of the PTO assembly and an emulated USWW (Fig. 11). The results of the performance characterization, described in [15] and [11], suggested that the design would provide an acceptable level of power conversion.

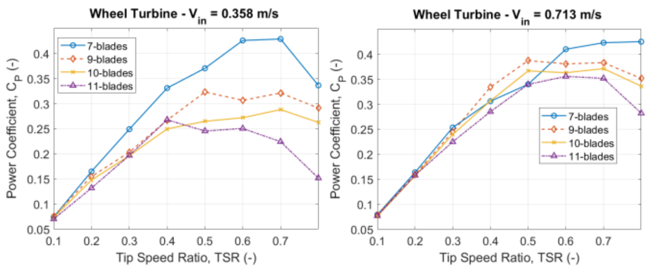

Fig 10. See the caption below.

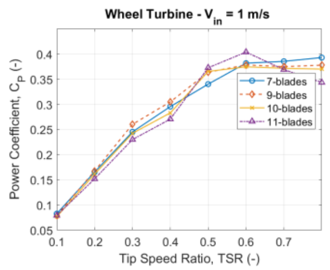

Fig. 10. Predicted power coefficient vs. TSR for three different inflow speeds for various turbine blade configurations – these results are based on 2-D simulations, which effectively represent a 100% blockage ratio and do not include the effect of losses at the shaft and in converting mechanical power to electrical power.

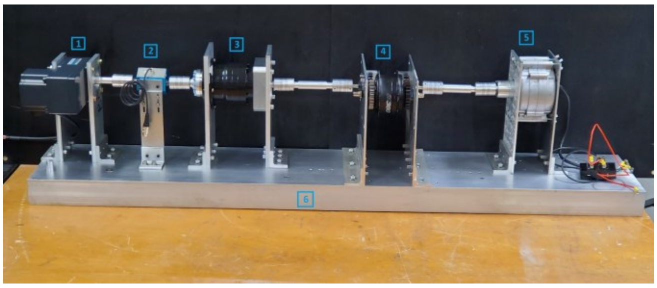

Fig 11. Benchtop PTO and USWW emulation assembly [15]. 1: motor for USWW emulation; 2: torque sensor; 3: gearbox; 4: B-CVT; 5: generator

IV. Field Testing

Obtaining necessary environmental permits for testing the system in the field requires a biological evaluation of the test site to address the potential effects of operating the MHK system in open waters on marine species and their habitat.

G. Biological Evaluation

A biological evaluation of the designated project area in southeast Florida, between latitudes 26.0514° N and 26.2358° N, was conducted by Ecological Associates, Inc. The project area is composed of the Intracoastal Waterway (ICW) and the nearshore Atlantic Ocean, a tidal system comprised of terrestrial, estuarine, and marine habitats for juvenile sea turtles and many other species. The area encompasses some of the busiest urban waterways in Florida. The evaluation identified a list of endangered and threatened animal and plant species in the region. However, it determined that direct, indirect, interrelated, interdependent, and cumulative effects on listed species are projected to be rare or minimal based on the small size and careful design of the MHK platform and that planned in-water testing and demonstration of the platform and its current turbine are not likely to adversely affect listed species, provided compliance with the conservation measures outlined in the NOAA's Vessel Strike Avoidance Measures and the NMFS' Sea Turtle and Small tooth Sawfish Construction Conditions are met.

H. Mitigation measures

Specific mitigation measures that are taken include (1) restricting field testing to periods outside of the sea turtle nesting season in southeast Florida; (2) having two lookouts present during in-water operations, one to monitor for the local presence of marine animals and to require stopping of in-water operations and retrieval of the turbine if an animal is spotted, and a second lookout to monitor for boat traffic; and (3) avoiding anchoring in areas where seagrass is present. The design of the diffuser system for enhancing the speed of the in-flow to the turbine was modified to exclude a bottom plate in order to prevent potentially trapping an animal.

I. Site selection

In selecting sites for testing the prototype platform, consideration is given to the availability of the local current resource; the local water depth; the bottom type; the local boat traffic; the regulatory and permitting requirements; proximity to the location of the vehicle launch; and requirements for the staging of the response team if operations need to be stopped. With these considerations, two sites in the ICW and two sites in the coastal waters off the coast of southeast Florida have been identified.

J. Instrumentation

The MHK platform is currently equipped with a sensor suite consisting of an Airmar ultra-sonic current flow sensor for measuring the speed of the near-surface current, and a BlueRobotics depth sensor for measuring the local water depth, together with a supporting electronics package for power and data acquisition and storage. Experiments are supported with video-based observation of the rate of rotation of the waterwheel. The WAM-V USV has sensors to aid navigation and control of the platform. We are in the process of installing a Hall-effect sensor for measuring input rpm at the gearbox and load sensors for measuring tension in the anchor line and are exploring ways to install a small torque sensor for directly measuring the generated torque.

K. Preliminary testing

Preliminary tests were conducted in the ICW prior to the start of the 2023 turtle nesting season using the MHK platform as assembled to date (Fig 8), including the USWW, the turbine deployment subsystem, and the PTO. In the absence of its autonomy functionalities, which are being completed, the unmanned MHK platform was piloted to the site via remote control and manually anchored to the bottom in a 4m water depth instream in the ICW in Dania Beach, Florida. The turbine was lowered into the water via remote control to initiate the harvesting of the tidal current. The sequence in Fig 12 illustrates the lowering of the turbine into the water and the sequence in Fig. 13 illustrates the USWW turning in the tidal current with flow speeds in the range 0.5 – 1.25m/s. The results of the preliminary testing are described in section V.

Fig. 12. See caption below.

Fig.12. Automated lowering of the turbine into the water

Fig. 13. USWW turning sequence at 0.05s interval.

V. Results and discussion

The partial results of the three days of preliminary testing are discussed here. Fig. 14 illustrates the measured flow speed of the tidal current and the correspondingly generated electric power on February 23, 2023, in approximately three hours of operation for the case of the 9-blade turbine configuration with a 10in blade submergence depth.

As expected, there is, in general, a good correlation between flow speed and power generated. A total amperage of 4.6Ahr was generated corresponding to 42Whr of power. Further parametric-level testing and demonstration of the full capabilities of the platform will resume at the end of the 2023 turtle nesting season.

The operations in the ICW were effective in highlighting some robust aspects of the prototype platform. During the testing period, the platform was exposed to spurious waves of significant magnitude produced by passing boats. Although designed to operate in low sea states, the platform operated normally through the passage of the waves.

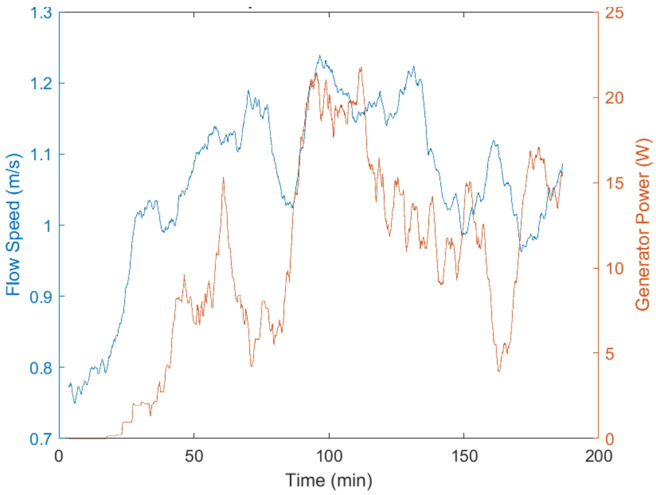

Fig. 14. Flow speed of the tidal current and correspondingly generated electric power.

The preliminary testing has helped to identify areas of improvement in the performance of the PTO through the use of a lower RPM generator and a more robust charge controller. The latter would aid in better capture of the electric voltage produced by the generator. These improvements are being pursued.

VI. Conclusion

A prototype mobile floating unmanned MHK platform comprised of an autonomous unmanned surface vehicle, an undershot waterwheel, a B-CVT-based PTO, and supporting subsystems has been designed and work is in progress in the development of its subsystems and their implementation on the platform. Current-resource sites in the Intracoastal Waterway (ICW) in southeast Florida and in coastal waters off the coast of southeast Florida have been identified and characterized for meeting permitting requirements. Preliminary tests of the partially assembled system in tidal flows of the ICW are encouraging and provide support for the concept. Identified areas of improvement during the preliminary testing are being addressed before further tests are undertaken.

The power captured by small-scale platforms of the type described here is primarily limited by the swept area of the turbine and it is linearly dependent on it. The present prototype can be expanded with additional undershot waterwheels on either side of the pontoons of the platform, all supported by a single shaft. The concept can be expanded to larger platforms, the feasibility of which would be dependent on the choice of location of operation.

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