Final Technical Report

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Executive Summary

A prototype low-flow marine current turbine for deployment from a small unmanned mobile floating platform has been developed for autonomously seeking and harnessing tidal/coastal currents. The support platform is an unmanned surface vehicle (USV), in the form of a catamaran with two electric outboard motors and with capabilities for autonomous navigation. The USV utilized is a WAM-V 16 vehicle that has been developed separately with support from the Office of Naval Research (ONR) [1]. The marine current turbine is based on a freestream waterwheel (FSWW), also known as an undershot waterwheel (FSWW), mounted on the stern of the USV. The concept of operation involves the USV autonomously navigating to a designated marine current resource. Upon arrival, the USV anchors itself, aligns with the current, and deploys the FSWW turbine using a custom cable-lift mechanism. The turbine harnesses the local current, and an onboard power-take-off (PTO) device converts the mechanical energy into electricity, which is stored in an onboard battery bank. When energy harvesting is completed, the turbine and the anchor are retrieved and the USV navigates to a selected location. These unmanned at-sea platforms can provide power to other unmanned maritime systems. Specifically, in this project, the power generated onboard can be used to charge aerial drones via a custom flight deck that has been developed for the USV. The recharging capabilities offered by a fleet of such strategically placed recharging stations can significantly benefit aerial drones operating in the maritime domain by eliminating the need to travel back and forth to land or ship based charging stations. The project has resulted in the development of subcomponents, including the FSWW turbine, a novel PTO, an automated anchoring system for the USV, an automated turbine deployment system, and a flight deck with capabilities onboard the USV for landing, direct-contact charging and takeoff of aerial drones. The design and development of these subsystems have culminated in the overall prototype marine hydrokinetic platform (MHK Platform, Fig. 1). Comprehensive lab and field testing have been conducted to validate the functionality and performance of the platform and its components. The project demonstrates the potential for autonomous, unmanned systems to harness renewable energy from marine currents, and provide sustainable power solutions for maritime applications such as coastal surveillance and environmental monitoring; shoreline mapping; search and rescue; oceanographic research; inspection and maintenance of offshore energy installations like wind turbines and oil rigs; oil spill response; maritime disaster response; and aerial surveys, as well as facilitation of data transfer drones and shore stations.

Fig. 1. The completed MHK Platform in operation in tidal waters of the Intracoastal Waterway in South Florida

Summary of work performed during the project.

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 not developed. Unmanned marine vehicles, including unmanned surface vehicles and aerial drones are increasingly being considered for coastal surveillance and environmental monitoring; shoreline mapping; search and rescue; oceanographic research; inspection and maintenance of offshore energy installations like wind turbines and oil rigs; oil spill response; maritime disaster response; and aerial surveys, as well as facilitation of data transfer drones and shore stations. Unmanned systems lead to reduced personnel requirements and a significant reduction in associated costs. Small aerial drones are typically battery-operated and are therefore limited by their battery capacity and availability for recharging. These drones can benefit significantly from floating at-sea recharge and data transfer stations, through resulting increase in their at-sea presence and offshore operational ranges at reduced costs. In the absence 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. As they provide continuous power for as the resources is present. A low profile mobile autonomous, low-surface-expression recharge station has several advantages in serving as a recharge station for aerial drones. First, tidal, ocean current, and wave energy resources are optimal near the ocean surface. Additionally, a surface station can subsequently 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 potentially recharge aerial drones on demand while anchored, or when the resource abates or as otherwise required, it can autonomously retrieve its anchor and navigate to a more desirable location, while being continuously available to the aerial drones for recharging. The recharge station can also power monitoring instruments or recharge other autonomous unmanned surface vehicles. The focus of the present effort is to consider providing partial power for such a recharge station from harnessing coastal (tidal/river/estuarine/open ocean) currents.

A prototype MHK Platform has been developed that is based on an available USV at Florida Atlantic University. The vehicle serves as a good developmental platform for the FSWW turbine system as it accommodates the turbine well between its pontoons and in view of the vehicle's stability, autonomous navigation, precise control, customizable design, and reliable development support. However, once established, the FSWW system could easily be migrated to alternative custom platforms for larger turbine capacity. The concept of operation is shown schematically in Fig. 2.

The work performed in developing the MHK Platform is described here in terms of the work carried out in the development of its principal subsystems, and their implementation on the USV platform. The complete Platform is schematically shown in Fig. 3.

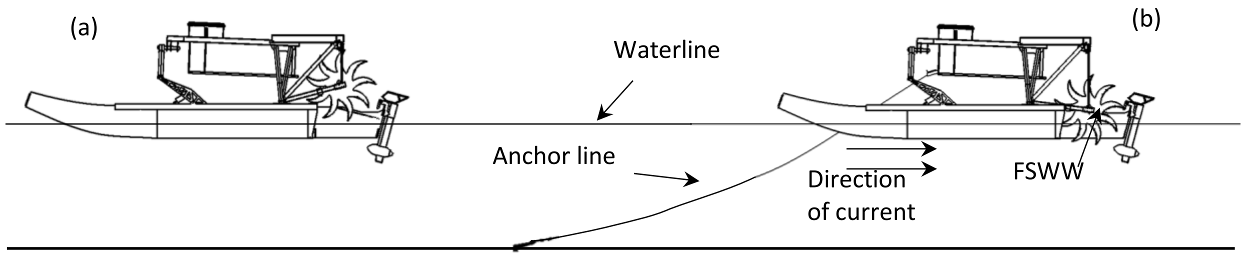

Fig. 2. Concept of Operation of the WAM-V USV MHK Platform: (a) the Platform with the FSWW stowed onboard the vehicle transits to a site of a current resource and (b) anchors at the site and deploys its FSWW to harness the currents. An onboard PTO converts the mechanical power of the FSWW to electric power for storage in onboard batteries.

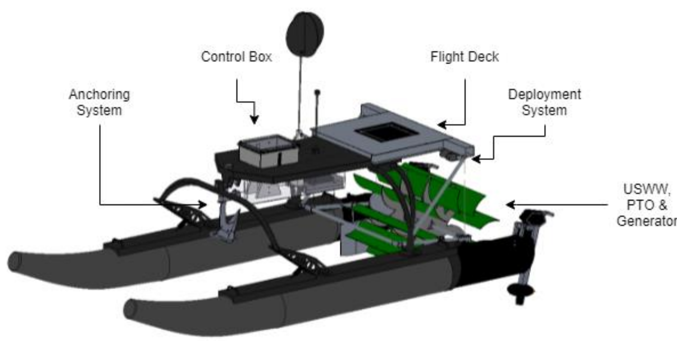

Fig. 3. The schematics of the complete platform with all the subsystems

The subsystems that make up the MHK Platform are:

- <u>A Freestream Waterwheel (FSWW)</u> that harnesses the marine current and convertes it to mechanical energy. Low-flow prototype-scale FSWWs, consisting of 7, 9 and 11 blade configurations were designed and built with the aim of determining the optimal configuration through field testing. The FSWW design was adopted based on a trade study comparing the pros and cons of the FSWW with horizontal-axis and vertical-axis turbines (HATs and VATs) in ensuring platform stability when the turbine is deployed (Fig. 5). The FSWW offers significant advantages over HAT and VATs in terms of platform stability during operation; ease of deployment and retrieval of the turbine from the platform; operational robustness in low-flow conditions; reduced impact on marine life due to its lower profile in the water, with the turbine not extending as deeply or widely as VATs or HATs; and ease in scaling up and adapting to different sizes of USVs and varying operational requirements. The FSWW is driven by the drag force on its blades induced by the flow in the direction of the flow (compared with HATs and VATs, which are driven by the lift force on their blades induced by the flow in the direction perpendicular to the flow). Therefore the FSWW was designed to have curved blades to maximize wetted surface area. The turbine blades were fabricated from aluminum and the supporting spoke discs were fabricated using high-density polyethylene (HDPE) plastic. Aluminum was selected for the turbine blades as it is a high-strength yet lightweight material, and in view of its resistance to corrosion in marine environments; good resistance to fatigue; ease in fabrication and customization; relatively low cost; and its recyclability. The performance characteristics of the selected design were determined through numerical simulations and a 1:5 model-scale laboratory investigation [2, 3].

- Flow accelerator that is designed to increase speed of the inflow to the turbine. A diffuser-type flow augmentation device was designed to enhance the speed of the flow through the turbine, and its functionality was evaluated through a 1:5 model-scale laboratory investigation [2] and subsequently through a numerical simulation [3]. While the laboratory investigation suggested some benefit in including such a device, particularly at very low current flow speeds, the numerical study did not show measurable difference in performance. The device was not implemented on the prototype in view of environmental concerns that a small animal could get trapped between the turbine blades and the device. However, there is merit in a further investigation of augmentation of the inflow to the turbine as part of the consideration for market transformation of the overall system.

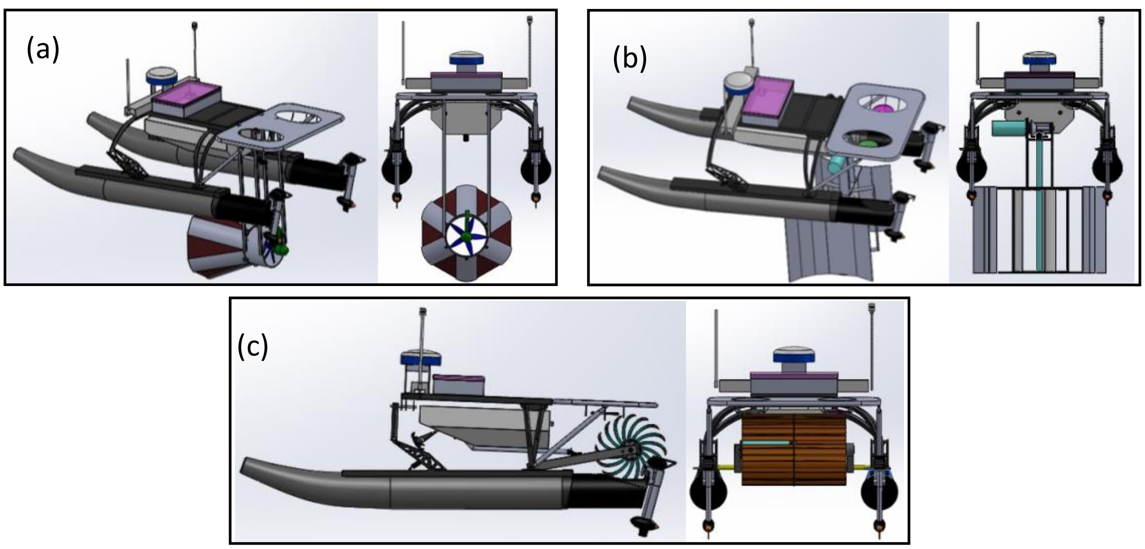

Fig. 5. Possible turbine options for the WAM-V USV platform: (a) horizontal-axis, (b) vertical-axis and (c) freestream waterwheel. Left: 3-D view. Right: front-on view

- A Power-Takeoff (PTO) Device that converts the mechanical energy of the FSWW to electric energy (Fig. 6). The PTO was custom designed and built using commercial off-the-shelf (COTS) parts and housed in a protected environmental shielding so that it was suitable for marine operations. It consists of an input shaft that is driven by the FSWW and is connected via a 1:35 gearbox and a NuVinci Ball continuously variable transmission (B-CVT) to a Marsrock permanent magnet synchronous generator. The B-CVT ratio ranges from 0.5:1 to 1.9:1 and is controlled via a servo motor, while speed measurements are taken by sensors placed on its input and output shafts. The generator is rated at 100 W when driven at 600 rpm. The generator has a cut-in speed of 0.42 - 0.46 m/s although the waterwheel starts turning at approximately 0.4 m/s; the cut-in speed is the minimum flow speed at which the PTO generates electric power. The generated electric power charges an onboard 12V lead-acid battery bank via a charge managing controller. The concept of energy conversion is depicted in Fig, 7. The speed of the waterwheel is controlled by modulating the torque load imparted by the generator on its rotor[4 - 7].

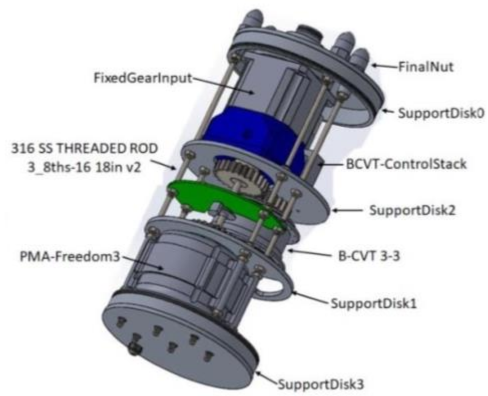

Fig. 6. The power take-off (PTO) device.

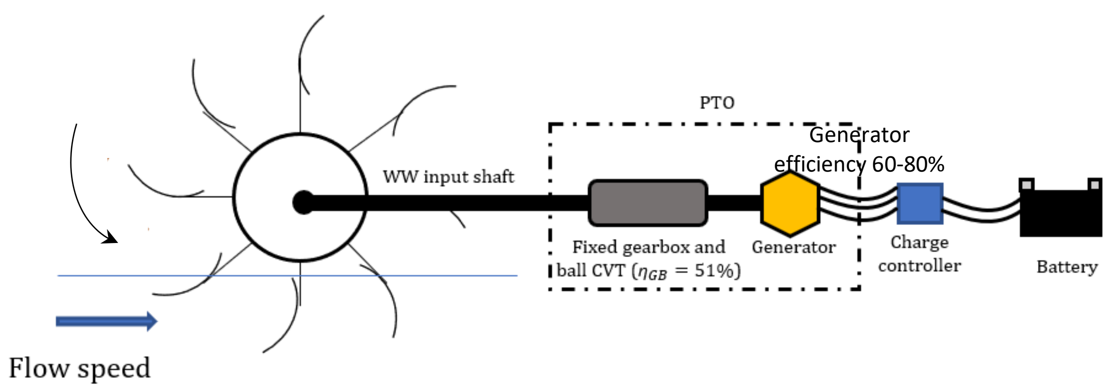

Fig 7. A system diagram of the PTO

- <u>An Automated Turbine Deployment System</u> that enables automatic deployment and retrieval of the FSWW (Fig. 8). An automated deployment system was designed, fabricated, and implemented on the MHK Platform. The system uses a linear actuator driven cable-lift mechanism for deploying and retrieving the turbine upon receiving an appropriate command from the central platform computer [2]. The linear actuator cable interface block rides on a rail and linear bearing combination to insure smooth motion with no binding due to the off-axis loading. Motion end points are detected with contact switches.

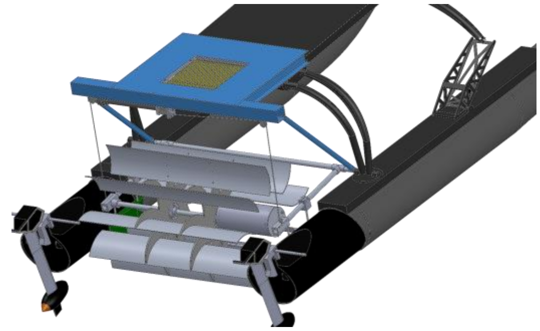

Fig. 8. The swing arm turbine deployment subsystem.

- An Automated Anchoring System that enables anchoring the mobile platform so that the marine currents can be harnessed (Fig. 9). A custom system, consisting of a TRAC Fisherman 25 electric winch, a 6kg Rocna anchor, a 47m anchor chain/rode, and a line-locking mechanism for taking tension off the winch, was designed, assembled and implemented on the MHK Platform. The design enables anchoring the platform in up to 5m water depth in tidal currents up to 1m/s. The novelty of the system is that the operation is performed autonomously. For this purpose, the system includes a BlueRobotics sonar depth sensor onboard the platform to enable the system to determine the required scope of the anchor line (7:1 line length/depth ratio), a Hall effect sensor mounted on the drum of the winch to measure the length of the anchor line as it is paid out, and a load cell mounted on the anchor line to measure the tension in the line [8, 2].
- A Flight Deck to accommodate landing, re-charging, and take-off of an aerial drone from the MHK Platform was custom designed and developed (Fig. 10). The deck consists of a Skysense charging pad, modified to reduce its weight and enable its functionality using a DC (instead of AC) power supply, a set of mini laser light beams to detect the presence of the aerial drone on the deck, and an articulated restraining system to restrain and guide the drone onto the charging pad. Power is supplied to the charging pad from the battery bank onboard the MHK Platform and the aerial drone is charged through direct contact with two plates on the charging pad. The drone restraining system consists of a set of articulated rods that are activated through interruption of the laser light beams on the deck by the landing drone. The rods move in and linearly shift the drone, guiding it appropriately onto the charging plates. The rods retract when the drone is ready for takeoff [9, 10]. Further work is needed to test and determine the limiting environmental conditions for operations and make improvements towards weather-proofing the flight deck.

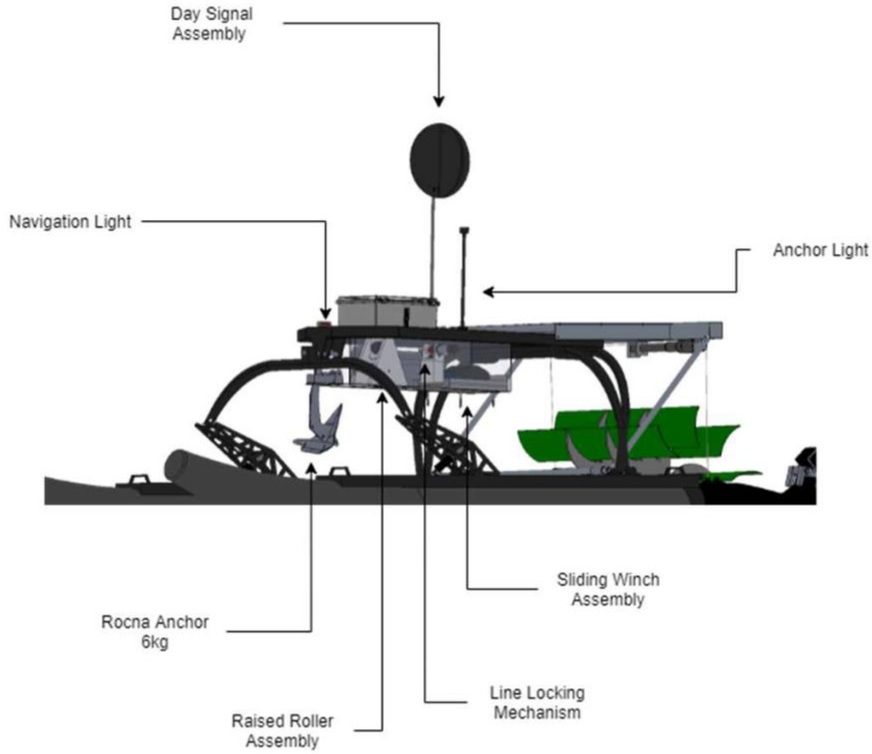

Fig. 9. The automated anchoring system assembly

Fig 10a. See caption below.

Fig. 10. Flight Deck: (a) Full view of the flight deck onboard the WAM-V16 platform; (b) View of the flight deck before drone landing; (c) View following the drone landing

- Data Acquisition and Auxiliary Electronic Systems to support USV and turbine operations. Custom data acquisition systems were designed, developed and implemented on the MHK Platform with custom electronics and appropriate electrical interfaces, including for generation, storage, and management of harnessed electricity onboard the platform; for facilitating automated operations, and for acquiring and storing environmental and turbine performance data for analysis of turbine performance. [1, 4]. The USV uses Velodyne Puck Hi-Res LIDAR sensor, and a Zed 2i stereovision camera for obstacle avoidance and vision-based navigation. The LIDAR provides a detailed 3D point cloud of the environment, representing the distance and shape of objects around the USV, thereby serving to detect these obstacles. The Zed 2i camera allows perception of depth and creation of 3D maps of the environment. It also provides high-resolution color images, which are used for object recognition and classification using computer vision algorithms. The LIDAR and the camera software drivers facilitate the retrieval, interpretation, and publishing of point cloud/image data from the sensors to the USV's Robot Opertaing System (ROS). Fusing these data, the USV distinguishes between different types of obstacles and enhance the accuracy of depth perception. The USV's path-planning algorithm, which constantly receives new data from these sensors in a feedback loop, calculates an alternative route If an obstacle is detected in the USV's planned path. The algorithm considers the USV's maneuverability, speed, and the surrounding environment to avoid collisions. The USV's low-level control system receives the updated path and executes the necessary maneuvers, such as turning, slowing down, or stopping, to avoid obstacles.
- Support structures were designed and fabricated for installation of the turbine, the PTO, the Flight Deck, and peripheral hardware onboard the MHK platform, including appropriate environmental shielding.

Laboratory Testing: Laboratory subcomponent-based testing and evaluation was conducted prior to application of the MHK Platform in the field. This included the following:

- Numerical modeling and simulation, which was validated using model-scale laboratory testing, was conducted in evaluating and characterizing the performance of the FSWW, [2, 3]. Once fabricated, the turbine and the turbine deployment system were tested in the laboratory to evaluate functionality.
- A purpose-built laboratory benchtop setup was developed for bench testing the PTO. This involved a motor that mimicked the FSWW turbine connected via a gearbox and Ball-CVT to the generator and included sensors for measurement of torque, rpm, voltage, and amperage. The benchtop setup provided data for evaluating the performance of the PTO, including its gearbox, generator, and the Ball-CVT system. The setup was used to design and develop the charge and turbine-speed controllers for the PTO in support of performance optimization [4, 5].
- The operations of the automated anchoring system were numerically modeled and simulated in ORCAFLEX to estimate the forces the anchor line and platform would experience during operations under various current and wave conditions. A pull test was conducted on the anchor to confirm its holding strength and laboratory verification tests were conducted to ensure proper functionality [8]. The automated functionality of the system, as installed on the MHK Platform, was also tested in the lab and verified.
- The functionality of the Flight Deck, including the drone landing, charging and takeoff, and the operation of the drone restraint system, were evaluated in the laboratory for their functionality and were deemed satisfactory for deployment in the field.
- The electronics and electric interfaces that were developed were tested for functionality in the laboratory prior to field applications.

Field Testing: The following efforts were undertaken in testing the final MHK Platform.

- NEPA Review and Biological Evaluation. Preliminary step to conducting field testing was acquiring the required environmental permits for the related activities in open waters, including tidal waters of the Intracoastal Waterway and coastal areas in South Florida. Potential test sites were identified, and a comprehensive field test plan was developed [9, 11]. The criteria for selection of a specific site is based on consideration of a) the local current resource; b) the local water depth; c) the bottom type, including avoidance of marine habitats; d) local boat traffic; e) the regulatory and permitting requirements; and f) proximity to FAU-SeaTech, and g) staging the response team. A National Environmental Policy Act (NEPA) review was conducted on the field work plan created for the planned testing activities. Following the NEPA review, a third-party biological evaluation of the region was conducted to determine if at-risk or endangered species and their habitats around the Intra-coastal Waterway (ICW) and coastal regions off Fort Lauderdale and Dania Beach, Florida would be affected by our planned activities. The biological evaluation [12] determined that field-testing associated with this project was not likely to adversely affect the environment provided that proper mitigation steps were taken during testing. The required mitigation steps included educating all field-testing staff on the endangered species that could be present in the testing area; stopping operations if any of these animals entered a 50 ft test radius established around the MHK Platform; and refraining from conducting fieldwork during sea turtle nesting season in South FL (March 1st through October 31st). Issues that were considered for safe operations included: a mechanism for manual emergency shutdown of the turbine was implemented; the USV has a manual remote control capability to override autonomous navigation in case of an emergency; the platform has LIDAR and stereovision camera to avoid collisions; a bottom plate on the waterwheel, initially designed to augment the flow, was removed to ensure no entanglement with marine animals; the anchoring system was tested in the lab and verified to hold securely under various tension forces; the automated turbine deployment system was tested in the lab for safe operation; before each outing, inspections were carried out to check for the structural integrity platform and its subcomponents and after the outing, the platform was cleaned; testing under adverse weather conditions were nor permitted; and finally all FAU and local and state safety protocols for marine operations, including using a qualified boat captain for the support vessel, were followed. This permitting process was completed mid-way through 2021.

- Site Selection. Surveys of the identified eight potential field-test sites were conducted, making assessment of their suitability in terms of local water depth, seafloor conditions, current flow resource, and local boat traffic. The methodology and procedures for site surveying were developed and provided in detail in [9, 11]. Due to their overall performance in meeting the site requirements, two tidal flow sites in the ICW were selected for final field-testing. At these sites there was absence of endangered seagrasses, the current flow speeds ranged from 0.5 to 2.25 m/s and there was moderate nonintrusive boat traffic [9]. ICW SeaTech Dockside also provided good land-based observation capability. The water depth at ICW SeaTech Dockside site exceeded the 5m limit required for anchoring, so an auxiliary mooring line was employed in securing the MHK Platform to the site; this arrangement allowed testing and evaluation of the low-flow turbine, the turbine deployment system, and the PTO. Field testing was carried out in stages to ensure each of the subcomponents functioned as intended, followed by a final test and demonstration of the complete MHK Platform in its autonomous mode of operation. Test site 1.3 was selected for the full MHK Platform autonomy demonstration, as it met the depth requirements. Site selection was finished by January of 2023. Survey of the identified coastal sites suggested that the sites either lacked adequate current resource or were in environmentally sensitive regions involving presence of sea bottom habitats. All testing was therefore carried out in the tidal waters of the Intracoastal Waterway, leaving testing in coastal waters for future consideration.
- Preparation for Field Testing. Following selection of the test sites, detailed plans for testing were developed [9]. Two periods, February 2023, and November 2023 – February 2024, were identified for field testing as these periods excluded the local turtle nesting season. The first phase served to provide preliminary data and to establish operational procedures. The period in between the two phases was used to 1) analyze the data and

make improvements to the system; and 2) develop and laboratory test various algorithms for autonomously operating the platform and its subsystems.

- Field Testing and Data Analysis. The bulk of the field testing took place in Jan – Feb 2024. The MHK Platform functioned over extended periods for several days in the tidal waters of the Intracoastal Waterways. The tests were scheduled during rising or ebbing tides when the speed of the currents is relatively high. The 7, 9, and 11 blade configurations of the turbine were tested for full and half submergence. The turbine operated continuously over extended periods harnessing tidal currents and providing electric power, and analysis of the data led to the development of a turbine speed controller that allows the turbine to operate at its optimal tip speed ratio. Fig. 11 summarizes the data recorded during seven days of field testing for three different blade-configurations and two blade submergence levels. The left panel shows the power of the tidal flow stream that is available at the turbine blades during each of the seven days of testing in January-February 2024. The center panel shows the corresponding mechanical power harnessed by the FSWW and the right panel shows the corresponding power converted to electricity for storage in onboard batteries. The top two rows depict the data for the 7-blade configured FSWW, with full and half blade submergence levels; rows 3 and 4 depict the data for 9-blade configuration for the two submergence levels; and rows 5 and 6 depict the data for the 11-blade configurations for the two submergence levels. The available power depends on the speed of the flow current, and the area of the blade exposed to the flow. The mechanical power harnessed depends on the induced torque on the FSWW and its speed of rotation. The electric power conversion is governed by the gearbox, the CVT and the generator in the PTO. Details of the experiments and the data and the turbine speed controller are reported in [5-7, 9, 13].
- MHK Platform Autonomy. Once the components of the MHK Platform were tested for their functionality, the complete MHK Platform with all its components onboard was tested for its autonomous operations, involving the platform autonomously navigating to a site with known current resource, anchoring at the site, deploying the turbine at the site, harnessing energy from the current resource, and subsequently retrieving the turbine, and returning to the starting point. The operations were demonstrated in February 2024. The autonomous functionality of the Flight Deck, completed and implemented on the MHK Platform, was tested in open waters at the end of June 2024 for facilitating landing, charging and takeoff of an aerial drone (See Fig. 10).

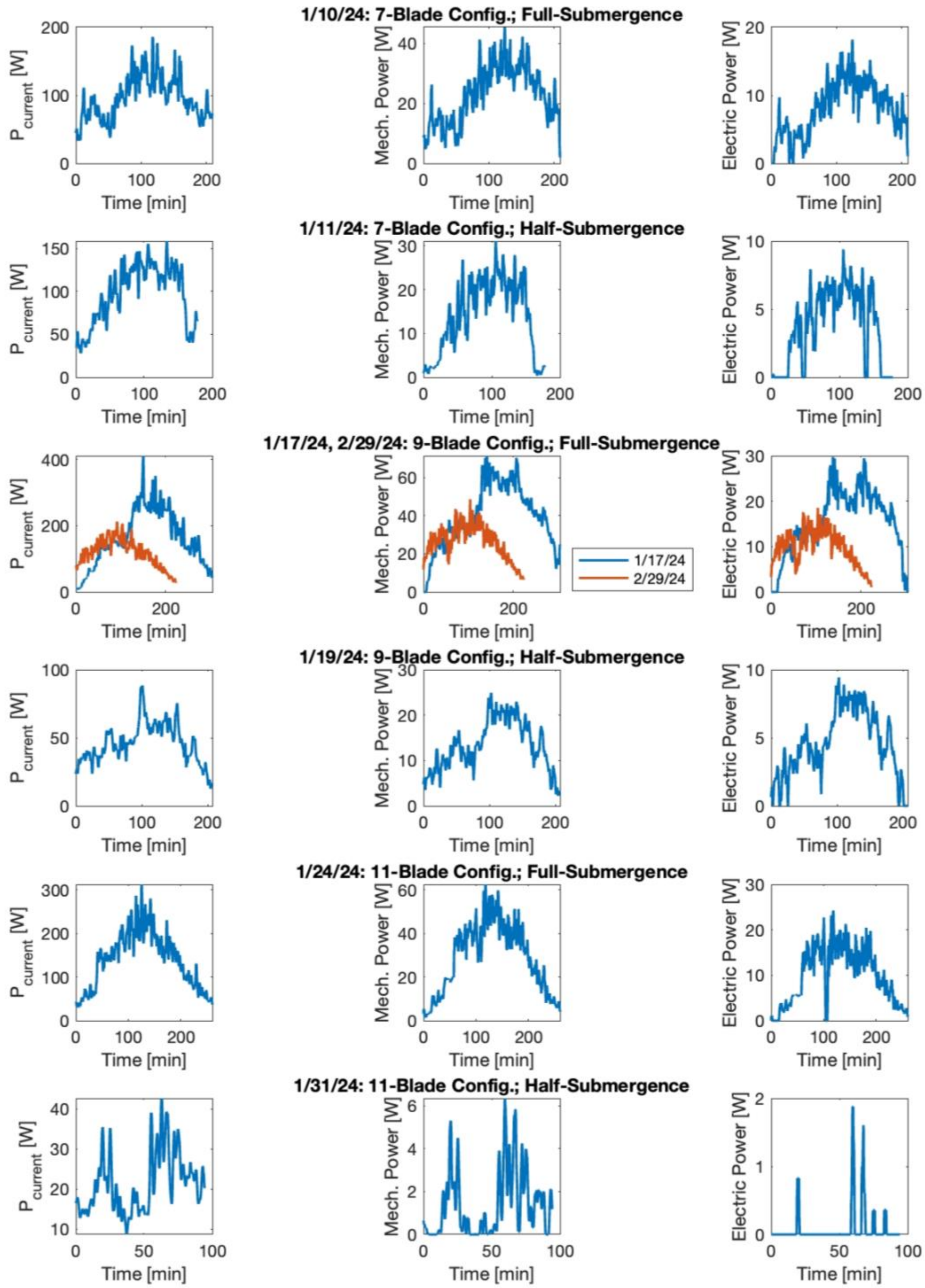

Fig. 11: Summary of data acquired during seven days of field testing using three different blade configurations and two blade submergence levels. Left panel: MHK Power Potential, $P_{current} = \frac{1}{2}\rho A U^3$, where ρ is water density, A is swept area, and U is flow speed; Center panel: Harnessed mechanical power; Right panel: Converted electric power

Techno-economic potential: With the support of NREL, the techno-economic potential of unmanned, autonomous MHK Platforms was studied, based on consideration of an extended version of the prototype MHK Platform developed here; the extension is in terms of the size of the turbine and number of such unmanned platforms employed. The details of the study are provided in an Appendix.

Work accomplished against the technical objectives as outlined in the award SOPO

Objective	Accomplishments	Comments
Design and develop		
○ A low-flow prototype turbine	Completed	A freestream waterwheel turbine (FSWW) was designed and fabricated with aluminum blades and HDPE plastic spoke discs.
○ A CVT-based power take-off (PTO) unit and a controller system.	Completed	A PTO, comprising of an input shaft driven by the FSWW and connected via a 1:35 gearbox and a NuVinci Ball CVT to a generator, was designed and fabricated
○ Support structures for installation of the turbine, the PTO and the generator onboard the mobile floating platform, including appropriate environmental shielding	Completed	
○ An automated anchoring system (AAS) for the floating platform	Completed	The AAS, consisting of an electric winch, a 6kg Rocna anchor, a 47m anchor chain/rode, and a custom line-locking mechanism, was custom designed, assembled and implemented on the MHK Platform.
○ Electronics and appropriate electrical interfaces for generation, storage and management of harnessed electricity onboard the floating platform; for facilitating automated operations, and for acquiring and storing environmental and turbine performance data	Completed	Custom electronics in support of this objective were designed, developed, and implemented on the MHK Platform. They served as the lynchpin to the successful execution of the project tasks.

○ A health monitoring sensor system	Partially completed	Temperature sensors were implemented in enclosures housing the electronics. A precautionary leak sensor could have been added to the PTO for even though it remains above the water surface and is securely shielded, it operates fairly close to the water.
• Develop plans for installation, operation and maintenance (iO&M)	Completed	The IO&M plans were developed, and the subsystems were accordingly implemented onto the USV platform, and operation and maintenance procedures followed during field work.
• Test the above components and subsystems		
○ Laboratory testing	Completed	The subcomponents were tested and verified for functionality in the lab prior to fieldwork. The PTO was extensively tested on the custom benchtop setup.
○ Conduct NEPA review and obtain environmental permits	Completed	A Biological Evaluation of the region was conducted and it was determined that the project related water activities will not adversely affect the environment provided mitigation measures were taken during the operations, including avoiding testing during the turtle nesting season in South Florida
○ Field testing in tidal waters	Completed	The FSWW turbine with 7, 9 and 11 blade configurations was tested over extensive continuous periods (3-4 hours) during several days in Feb 2023, and Jan – Feb 2024. Full autonomous operations involving the platform autonomously navigating to a desired location, anchoring,

		deploying/retrieving the FSWW into/from the water for harnessing tidal currents. The in-water demonstration of the Flight Deck and landing, charging and takeoff of an aerial drone is planned for late June 2024.
○ Field testing in coastal waters	Not undertaken	Survey of the identified coastal sites suggested that the sites either lacked adequate current resource or were in environmentally sensitive regions involving presence of sea bottom habitats. Testing in coastal waters was therefore not conducted and is left for future consideration
○ Obtain environmental and turbine performance data	Completed	Data for measured speed of the prevailing inflow currents, and noted tidal levels, wave and wind conditions, as well as the turbine rpm, and voltage and electric current generated were acquired during the testing.
• Analyze the performance of the prototype MHK turbine system from the acquired laboratory and field data	Completed	The data were analyzed and compared with predicted models. The results are described in detail in references [5, 9].
○ Conduct numerical modeling and simulation studies in support of design optimization of the system, and prediction of techno-economic potential, and other quantities of interest.	Completed	This was carried out with the support of NREL. A discussion of the techno-economic potential is provided in the Appendix. Further, a Teamer project is underway between FAU and NREL that involves 3-D simulations of the FSWW, including various measures to augment the speed of the inflow to the turbine.

○ Develop a risk management plan	Completed	This was developed in conjunction with NREL
• Mature design readiness in support of commercialization of the prototype system	In Progress	Numerical simulation studies of the FSWW turbine with NREL, as described above, will lead to optimization of the performance of the turbine. Various measures to optimize the performance of the PTO and the overall system are proposed in [5, 7]

Critical Success Factors	Minimum Accomplishment	Achievement
Regional Navigation		
Deployment	Given an area of expected operation successfully navigate to the final waypoint using published data and avoiding unforeseen obstacles.	Achieved.
Recovery	Return to a pickup point after mission end	Achieved
Site Survey	Before each anchoring perform a current resource survey to locate areas of high potential accessible while anchored.	Achieved. This was carried out prior to undertaking the field-testing using flow and bathymetry sensors mounted on a custom platform
Anchoring		
Selection	Locate the optimal anchor position and navigate over it	Achieved.
Mechanics	Deploy the anchor	Achieved.
Verification	Determine that the anchor is properly set for the current conditions	Achieved.
Monitoring	Periodically confirm anchor effectiveness and status	Achieved.
Recovery	Successfully recover the anchor to end the mission	Achieved.
Reset	Successfully recover and re-deploy the anchor based on current conditions	Achieved.

Shedding	If ordered to abandon a trapped anchor, successfully break the connection	This was demonstrated in anchor testing.
MHK		
Stowed configuration	The MHK and flow concentrator are clear of the free surface while in the stowed position.	Achieved.
Deployment	The MHK and flow concentrator move smoothly into their active configuration	Achieved with a custom automated turbine deployment system onboard the MHK Platform
Generation	With the ambient water velocity above the bottom threshold, the MHK/PTO/Generator begin operating.	Achieved. The cut-in speed of the turbine, when the generator starts producing power, is in the range 0.42-0.46 m/s, depending on the blade configuration
Debris shedding	The flow concentrator bypass operates to let coconut sized debris past the MHK device without damage	The flow concentrator was not used in the field for environmental concerns of trapping an animal. Its impact was demonstrated in the lab.
Effectiveness	Power generation of at least 50% of the predicted level for any particular flow velocity	Achieved. Power generation capability may be measured in terms of the power coefficient C_p. As illustrated in Figs. 12a and 12b for two different flow velocities, C_p is 50% or higher than predicted by theory based on 2-D modeling. When compared with the results predicted through model scale laboratory studies (Fig. 13), C_p achieved in field tests exceeded 80% of the expected value.
Power management		
Hotel load	The power expended monitoring health, operations, and position do not exceed 20% of the MHK output over a tidal flow cycle	MHK monitoring, positioning, and USV maneuvering were not powered by MHK output. MHK monitoring and positioning, while not powered by the MHK output, consumed <5% of MHK captured power.
Charging	Using 60% of the power captured by the MHK chain, operated the unmanned aerial vehicle (UAV) charging station	Achieved. 100% of the captured power was available for UAV charging
Ops charging	Deliver 20% of the power captured by the MHK chain to the operational battery bank for maneuvering etc.	Captured power was not delivered to the USV battery bank.

Performance and health monitoring		
Environmental input	Use a low power device to measure water velocity incident to the MHK device and record wind speed and direction from the navigation suite to synced data	Achieved. An acoustic flow meter was used to measure the flow speed. Wind speed and direction in the region of operation were recorded.
MHK dynamics	Measure the rotation rate of the hydrokinetic converter and record synced data	Achieved
Performance monitoring	Record voltage and current flow at the generator and record synced data	Achieved.
Enclosure environments	Monitor the environmental conditions being maintained in the electronics enclosures recording synced data and flagging out of range values	Achieved. All electronics enclosures have internal environmental monitoring circuitry. All data is recorded and out of range conditions flagged.
Platform power storage	Monitor the power storage systems and record synced data	Achieved.
Platform dynamics	Monitor and record platform motions due to waves, wind, and other disturbances	Achieved. This was recorded in the USV control box.
Drone Operations		
Retention	The drone should be positively constrained while on board against moderate amounts of platform motion due to environmental factors	Achieved.
Clean release	Drone takeoff should be unimpeded by the platform	Achieved.
Navigation	The location of the platform should be available to the drone while it is in flight	Achieved.

Successes or challenges and how those challenges were addressed/overcome

Principal success is that the overall MHK Platform and the FSWW turbine operates robustly in the field, harnessing MHK power from currents, converting it into electric power, and storing it in onboard batteries. An innovative custom Ball-CVT-based PTO device for conversion of mechanical power to electric power has been developed. The project has led to development of several major subcomponents of the system which have enhanced the USV capabilities, including automated deployment of devices from the USV, automated anchoring, and a flight deck for landing, takeoff and recharging of aerial drones. Further, fabrication and field-testing operations were completed safely. The major successes may be listed as:

1. <u>Harnessing tidal currents in the field and its conversion to electric power</u>

   The FSWW turbine performed robustly during the testing period of January – February 2024, enabling harnessing of energy of the tidal currents over extended periods, and converting it into electricity, as depicted by the data provided in Fig. 6. The results of the field experiments for the case of full blade submergence levels are compared with theory [5] for two different flow speeds in Fig. 12a and 12b, and with laboratory experiments [1] in Fig. 13.

   In general, the theory overpredicts the performance of the turbine (Fig 12) and is likely because it is based on 2-D CFD simulations, so that it effectively represents a 100% blockage ratio and does not include the effect of losses at the shaft. Over a range of tip speed ratios, the performance among the different blade configurations is similar, with the 9-blade configuration at full submergence providing optimal performance.

   Laboratory experiments using 1/5 scale model of the turbine were conducted using Froude scaling of the flow velocity. The results of these lab experiments for the 9-blade configuration are compared in Fig. 13 with the results of the field experiments and with the theory. The case considered is for a full-scale flow speed of 1 m/s. The agreement between the data sets is reasonable over a range of tip speed ratios. However, at higher values of the tip speed ratios, the results of the 2-D theory again diverge from both the results of the laboratory and the field experiments.

   Fig. 14 shows the mean electric power produced during the field experiments as a function of the current flow speed. The results suggest that the 9-blade configuration with full blade submergence provides optimal power in the velocity range 0.4 – 1.1 m/s, producing approximately 22W of mean electric power at a speed of 1.1m/s. Thus, for a sustained 1.1 m/s current, in say coastal or river location, 66Whr of electricity maybe generated over 3 hours. In the Intracoastal tidal stream on 1/17/2024, when the speed of the current varied from 0.4 to 1.1m/s with a flow speed probability distribution given by Fig. 15, the power generated is tabulate in Table 1. This corresponds to an average power of 14W. This would result in 42Whr over a 3-hour period or 168Whr over a full tidal cycle. Small aerial drones need approximately 20 – 30Whr for a full charge. Thus the prototype MHK Platform can adequately support recharging of aerial drones and provide power for instruments onboard the USV, such as for say monitoring water quality.

2. <u>Development of a Custom CVT-based PTO Device</u>
   An innovative PTO device, based on a custom continuously-variable-transmission-based gearbox, has been developed that overcomes the challenge that available COTS generators have significantly high rotational rates for MHK applications. The success of this device has been demonstrated through its application in the field experiments.
3. <u>Development of a a Laboratory Benchtop Turbine Testing System</u>
   A custom benchtop turbine testing system (Fig. 14) has been developed that enables component-wise characterization of the PTO, and modeling and prediction of its performance as well as troubleshooting problems that may be encountered in the

physical system in the field. The benchtop system was instrumental in the development of the final PTO and the charge controller.

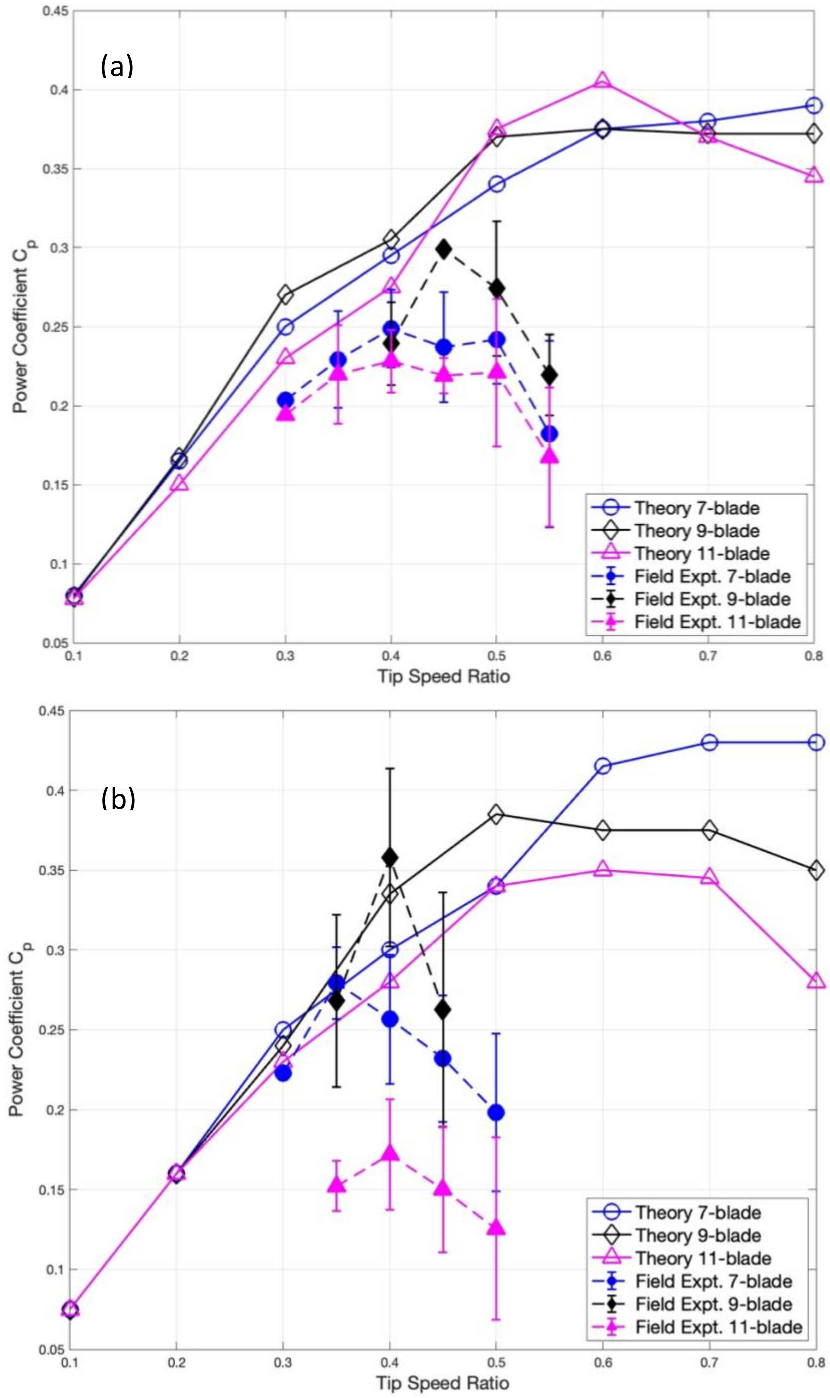

Figure 12. Comparison of the field data for the power coefficient C_p with theory [5] based on 2-D CFD simulations for the cases of flow speed of (a) 1m/s, and (b) 0.7 m/s

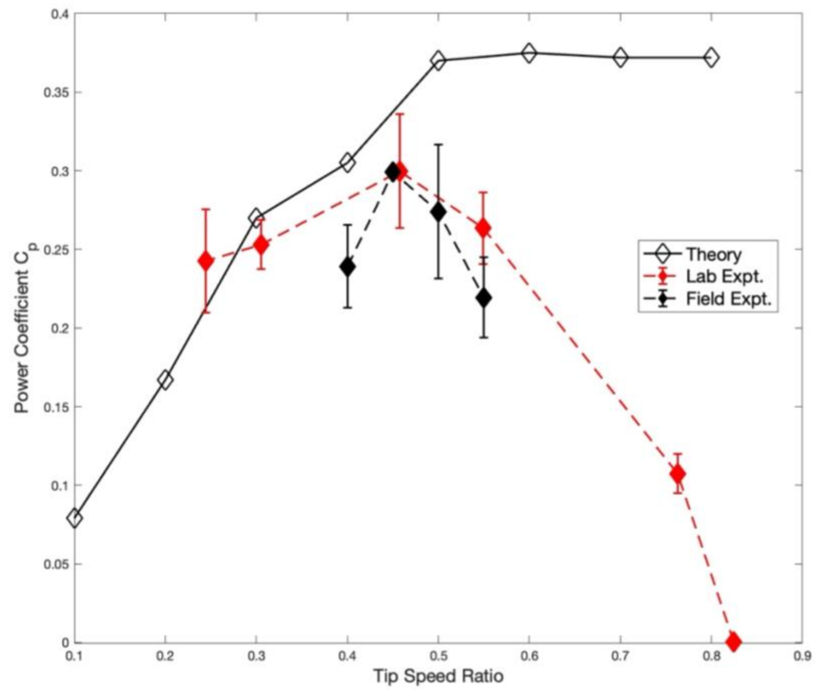

Fig. 13. Comparison of the field test data with the results of laboratory tests of a 1/5-scale model of the 9-blade configuration FSWW turbine, corresponding to full-scale operating condition (based on Froude scaling) of current flow speed of 1m/s. The results of the 2-D numerical simulations are also included in the figure.

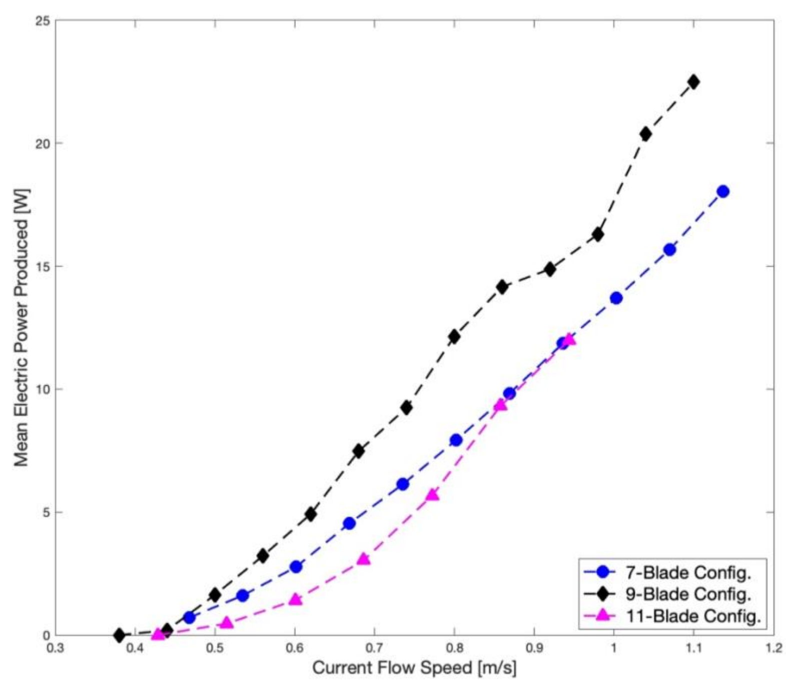

Fig. 14. Mean electric power produced as a function of current flow speed.

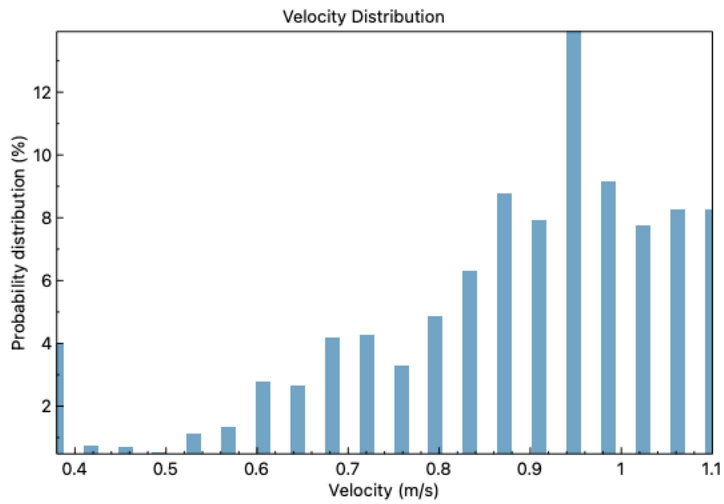

Fig. 15. Probability distribution of the velocity of the tidal flow over 3-hr period for 1/17/2024

Flow Speed [m/s]	Probability Distribution([%]	Electric Power Generated [W]
0.38	3.9	0
0.42	0.7	0
0.46	0.6	0.3
0.49	0.5	1.1
0.53	1.1	2.5
0.57	1.3	3
0.61	2.8	4.3
0.65	2.6	5.7
0.68	4.1	7.5
0.72	4.2	8.4
0.76	3.2	9.9
0.8	4.8	11.5
0.83	6.3	13.6
0.87	8.7	14.3
0.91	7.9	14.9
0.95	13.9	14.9
0.99	9.1	16.5
1.02	7.7	18.9
1.06	8.2	21.4
1.1	8.2	22.3

Table 1. Marine current Flow Speed, probably distribution of the flow speed and generated electric power for operations in the tidal current on 1/17/2024 for the case of the 9-blade configuration with full blade submergence

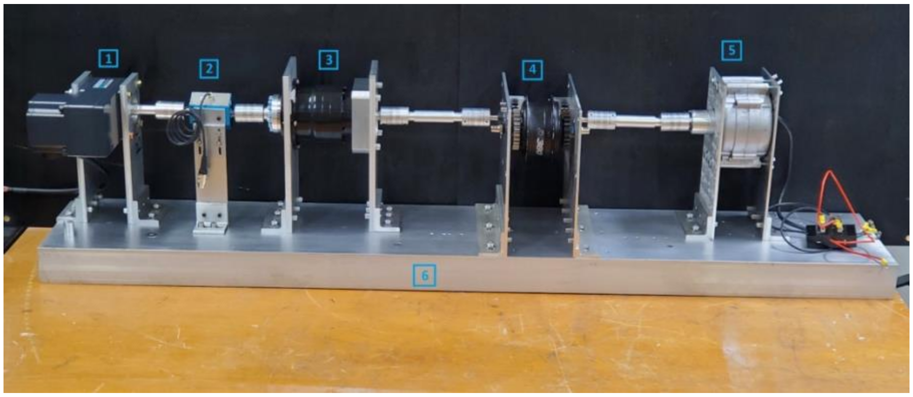

Fig 14. Benchtop PTO and FSWW emulation assembly [15]. 1: motor for FSWW emulation; 2: torque sensor; 3: gearbox; 4: B-CVT; 5: generator

4. An Automated Turbine Deployment System
   The custom linear actuator driven cable-lift mechanism has been developed for automatically deploying and retrieving the turbine from the MHK Platform. The system has been demonstrated to operate robustly in the field over several cycles of operation. It is transferable to any USV for deployment of other devices, such as instrument packages, thereby enhancing the USV capability.
5. An Automated Anchoring System for the USV Platform
   Platform anchoring is necessary for harnessing the MHK currents. This is enabled for the unmanned platform through the development of a custom automated anchoring system. The development is transportable to USVs in general, leading to enhancement of their capabilities for a range of applications.
6. A Flight Deck for Recharging Aerial Drones
   A custom flight deck onboard the MHK platform has been developed that accommodates automated landing, re-charging, and take-off of an aerial drone from the USV platform. The flight-deck operations have been successfully demonstrated in the laboratory and in the field. The novelties are that the deck enables (i) restraining an aerial drone on the deck and (ii) battery-based recharging of drones onboard the USV. The application is transferrable to any USV and would enhance the USV capabilities for cooperative applications between the USV and aerial drones.

Among the challenges, the restriction that in-water operations be limited to between Nov and Feb, which includes the holiday season, to avoid the turtle nesting season in South Florida (Mar 1 – Oct 31) may be regarded as a significant challenge. In addition, challenges were encountered in technology development and field operations. These challenges and successful solutions to overcoming them are listed as follows:

1. Fabrication of the PTO Device
   a. Mechanical Power Transfer. The initial design included two pairs of 1:1 transfer gears to reduce the housing diameter to fit within the FSWW blade inner boundary. These were modified COTS gears selected to take maximum input torque on either side of the Ball-CVT. The meshing of the gears was loose which

resulted in a noisy gearbox. The solution was to build up a much finer toothed plastic gear set on the higher RPM lower torque region between the B-CVT and generator. The smaller teeth meant less absolute cogging behavior and less noise. Custom fabricated gears could be used to decrease the susceptibility to shock and provide a smoother transfer of torque.

b. Precision and rigidity. The prototype PTO housing was designed and built as a stacked structure held tightly together by four tensioning threaded rods with cylindrical spacers. While easier to fabricate, this proved overly flexible leading to sealing issues under load and unanticipated loading of the transfer gears. The solution was a switch from cylindrical spacers to flat plate spacers with snug pass-through holes. An alternate, more refined solution would involve a custom 3D fabricated part set with keying features, whereby custom fabricated gears could be fabricated to decrease the susceptibility to shock and provide a smoother transfer of torque. This can be accomplished by machining a solid stock piece, or rough casting to have the necessary features for mounting the internal components. Alternately, components designed with keying features such as peg in hole or ridge in slot can be assembled with reduced opportunities for motion between the pieces.

c. Suitable COTS generator: Most COTS generators are high rpm devices which is a challenge for typical low shaft rpm input associated with the MHK turbine. A Marsrock generator rated at 100W when operating at 600rpm, coupled with a 1:35 ratio gearbox was found to be an acceptable solution. The pros of the solution is that it enables working with available COTS generators. The cons are that the system has more moveable parts and leads to loss in efficiency. However, we believe there is a need for generators that are specifically made for low-rpm MHK turbines. The use of an existing asset set the scale of the energy harvesting device which in turn limited the selection criteria for the generator selection. Nothing in that size range was found that could operate at low rpms.

d. The charge management system on the flight deck had to be customized for reduction of weight of the COTS Skysense charging pad and converting from its power requirements from AC to DC. The modifications made are performing well.

2. Fabrication of the Flight Deck Drone Restraint System. The initial design of the double two-bar retention system was prone to hanging up on its own components. The chain drives placed at each end of the bar pair to insure they remained parallel had excessive texture and would catch themselves and the dividers that were meant to reduce that occurrence. The solution was a redesign to a much more engineered system using COTS linear motion rails and bearings and Left-Right ACME threaded rods to open or close a particular pair of restraining rods with a single motor. Initially susceptible to friction lock for off center loads, this issue was cleared with a threaded bracket that moved contact points further apart on the ACME rods. The benefit of this higher precision approach is a smoother operation overall, but at a substantially higher cost in parts.

3. Custom Electronics and Electrical Interfaces. These are lynchpin elements of the multi-component MHK Platform and performed well, having gone through iterations in development. They enabled the PTO in converting mechanical power to electrical power as well as enabled power and communications between the USV control system and the turbines.
4. Integration of Instrumentation. There were unanticipated interface and format issues that had to be overcome to knit the collected data into a synchronized time stamped data set. There were also issues caused by newer versions of the hardware not designed to be 1 to 1 replacement of the previous version. To overcome such issues, it was necessary to test the purchased components against specific specifications to verify ther behavior. In addition, greater than minimum component purchases are required so that identical backups are available should there be a failure.
5. Laboratory Testing of the PTO. The benchtop PTO system that was developed, involving (i) use of a small motor to mock the low rpm MHK turbine, (ii) placement of torque and rpm sensors between the motor and the gearbox and between the gearbox and the generator, and (iii) a battery charge management system, worked well in characterizing the components of the PTO, providing necessary data for modeling and predicting the performance of the PTO and trouble-shooting issues encountered in the physical system in the field.
6. Field Testing Operations.
    a. Anchor pullout. Several small boat anchor styles were considered based on scant published holding capacities. Testing this capacity on substrates typical to the local area was delayed, then halted, by the need to have an environmental survey conducted before hand. Then the extended length of sea turtle season in the area became an issue for operations. To overcome this and obtain the required data on anchor pullout, a wet box was constructed in which construction sand was used to roughly approximate the bottom substrate in a moderately energetic flow environment. An alignment frame was used to approximate the anchor line lay given a 7:1 scope to accommodate on-landing tests of the anchor holding capacities. The original plan was in situ testing in areas where energetic flows exist, thus providing actual substrates influenced by those flows. The simulated testing involved only a single grade of uniform substrate that does not necessarily reflect actual conditions.
    b. Anchoring Limits. The COTS anchoring winches available for vessels of this size were limited to approximately 30m of anchor line. Any chain used in the anchor rode would have to remain external to the winch. This limited the self-anchoring capability to depths of 5m or less. Areas with both enough current resource, and shallow enough waters are harder to identify and do not usually occur close to convenient shore observation areas. The ICW SeaTech Dockside has the needed current resource, but the water depth is approximately 7m. To overcome the limitations, pre-deployed mooring buoys and operations area warn-away buoys

were used to conduct tests to determine the performance characteristics of the FSWW turbine with a high degree of safety.

Lessons learned and best practices

1. Planning does not substitute for training. Working as a team toward achieving the goals and milestones of a project is much more than a calendar of events, a checklist of tasks, and timeline for the day. Effort is needed to train and verify the skills that have been learned. Execution of tasks may not exactly follow the plan. When team members executing field work are confident of their abilities and understand the goals to be achieved, they can adapt to surprises and setbacks. When they understand the tools and equipment, they are better prepared to take on troubleshooting.
2. If it doesn't feel right, don't. Pushing to execute a plan when something is off increases the chance for failure. Whether it is weather conditions, equipment, personnel, or an issue with the planning, stop and evaluate what the risks are of proceeding regardless.
3. Have a checklist. For each stage of operations, from planning and preparing to cleaning up after, have a tangible checklist of tasks, tools, equipment, and procedures.
4. Keep notes as you go. Take good notes to better remember and analyze the operational performance and condition of the instruments and support equipment. Writing notes in the process of performing a task are more helpful in performing follow up tasks than working from memory.
5. Keep complexity as low as possible. More complexity means more ways to have a failure, mechanically, electrically, or in software. This also applies to the tasks to be carried out by team members.

Products

Publications:

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2. Fosbrook, A. "An Automated Anchoring System for an Unmanned Surface Vehicle". 2021. MS Thesis. Ocean Engineering. Florida Atlantic University.
3. Hall, Adam, "Design, Simulation, and Testing of a CVT Based PTO and Controller for a Small Scale MHK-Turbine for Low Flow Speed Operation", 2022, MS Thesis, Ocean Engineering, Florida Atlantic University.
4. A. McKinney *et al.*, "A Low-Flow Marine Hydrokinetic Turbine for a Floating Unmanned Mobile Platform," *OCEANS 2022, Hampton Roads*, Hampton Roads, VA, USA, 2022, pp. 1-6, doi: 10.1109/OCEANS47191.2022.9977141.
5. Hugo Pimentel, Adriana McKinney, Edward Henderson, John Frankenfield, Pierre-Philippe Beaujean, Manhar Dhanak, "A Power Take-off Device for a Small Marine Hydrokinetic Turbine Deployed from an Unmanned Floating Platform", IEEE/MTS OCEANS 2023 - MTS/IEEE U.S. Gulf Coast, pp.1-6, September 2023.

6. Dhanak, M. R., Beaujean, P.-P., Frankenfield, J., Hall, A., Henderson, E., McKinney, A., Pimentel, H., and Tran, T. T. Development of an Unmanned Mobile Current Turbine Platform: *Proc. EWTEC*, vol. 15, Sep. 2023.
7. McKinney, Adriana. "Small Unmanned Marine Hydrokinetic Platforms for Power Generation in Coastal and Tidal Waters." 2024. PhD Dissertation. Ocean Engineering. Florida Atlantic University.
8. Pimentel, Hugo. "Modeling, Implementation and Control of a CVT Based PTO for a Small Scale MHK-Turbine in Low Flow Seed Current." 2024. PhD Dissertation. Ocean Engineering. Florida Atlantic University.
9. A. L. McKinney, et al., "Site Selection for Field Testing of a Marine Hydrokinetic Turbine Platform to Serve as a Floating Unmanned Mobile Recharging Station for Aerial Drones." *Offshore Technology Conference, Huston Texas, 1-4 May 2023.*
10. Dhanak, M, Beaujean, P-P, Fosbrook, A, Frankenfield, J, Hall, A, Hess, S, McKinney, A. *Low-Flow Current Turbine for a Small Unmanned Mobile Recharge Station*, Poster, International Conference on Ocean Energy 2021 (ICOE, 2021). Virtual Conference.
11. McKinney, Adriana, "Design & Development of a Secure Self-Leveling Wireless Recharging Platform for an Aerial Drone on an Unmanned Surface Vessel", 2021, MS Thesis, Ocean Engineering, Florida Atlantic University.
12. A. L. McKinney, et al. "Full-Scale Experimental Verification of a Mobile Marine Hydrokinetic Platform for Power Generation in Tidal Flows." In preparation.
13. Hugo Pimentel, Adriana McKinney and Manhar Dhanak, "Development of a Speed Controller for a Low-Flow Marine Hydrokinetic Turbine Deployed from an Unmanned Floating Mobile Platform", Submitted to International Marine energy Journal.

Invention disclosure

The following invention disclosures are being filed:

11. MHK Platform

    Title: An Autonomous Marine Hydrokinetic Current Energy Harvesting Platform

    Description: This invention relates to a marine hydrokinetic (MHK) turbine designed to be deployed from an autonomous unmanned surface vehicle (USV) platform. The platform autonomously navigates to a location of marine current energy resource, deploys an anchor at the location, then deploys a freestream water wheel (FSWW), harnesses the energy from the currents, and converts it into electrical power via an onboard power take-off (PTO) system. The generated electricity is stored in integrated onboard battery banks. When complete, the FSWW and the anchor are retrieved, and the platform returns to a designated location. Key features include autonomous operation in various maritime conditions, adaptive energy harvesting efficiency based on real-time current monitoring, and integration with renewable energy sources such as solar and wind. The platform also supports various maritime applications, including the recharging of aerial drones, and autonomous environmental monitoring. The platform has been developed and tested in the field.

11. Automated Anchoring System

    Title: Automated Anchoring System for Unmanned Marine Energy Platforms

    Description: This invention relates to an Autonomous Anchoring System designed for securely positioning a USV. The system includes a custom assembly featuring a TRAC Fisherman 25 electric winch, a 6kg Rocna anchor, a 7-meter anchor chain/rode, and a line-locking mechanism specifically designed to alleviate tension on the winch. The anchoring system is capable of securing the platform in water depths of up to 5 meters, in tidal currents reaching speeds of 1 meter per second. The key innovation of this system lies in its fully autonomous operation. The system utilizes a BlueRobotics sonar depth sensor to accurately determine the required scope of the anchor line based on a 7:1 line length-to-depth ratio. A Hall effect sensor is mounted on the winch drum to precisely measure the length of the anchor line as it is deployed, while a load cell on the anchor line monitors the tension, ensuring secure anchoring under varying current conditions. This automated approach allows the platform to efficiently anchor at the selected location without the need for manual intervention, significantly enhancing its operational capabilities and reliability in dynamic marine environments.

11. Automated Device Deployment and Retrieval System

    Title: Automated Device Deployment and Retrieval System for Marine Platforms

    Description: This invention involves an automated system for deploying and retrieving a large device, such as a freestream water wheel (FSWW) from an unmanned surface vehicle platform. The system ensures the safe and efficient lowering of the device into the water and its secure retrieval when not in use or during adverse conditions. The principle of operation is a cable hoisting arrangement driven by a single COTS linear actuator that is oversized in load and range capacities to allow for experimental reconfiguration. One end uses a simple pully to redirect the force vertically, the other uses a two-pully arrangement for the same purpose so both ends lift together. In addition to manually configured stop sensors, it includes automated controls that respond to real-time environmental data, ensuring that the device is deployed at optimal depths and angles. The system also features a fail-safe mechanism for emergency retraction to protect the device from damage.

11. Power Take-Off (PTO) System

    Title: Onboard Power Take-Off System for Marine Hydrokinetic Platforms

    Description: The Power-Takeoff (PTO) device is specifically designed for converting the mechanical energy generated by a Free-Stream Water Wheel (FSWW) into electrical energy. The PTO is custom-built using commercial off-the-shelf (COTS) components and is encased in a protective environmental shield to ensure durability and functionality in marine environments. The PTO system consists of an input shaft, directly driven by the FSWW, which is connected to a 1:35 gearbox. This gearbox is coupled with a NuVinci Ball continuously variable transmission (B-CVT) that offers a ratio range from 1:0.5 to 1:1.9. The B-CVT allows for an increased range of flow speeds for power generation, which is achieved via a servo motor. Speed sensors are strategically placed on both the input and output shafts of the B-CVT to monitor and regulate performance. The energy from the B-CVT is transmitted to a Marsrock permanent magnet synchronous generator, which is rated at 100 W when operating at 600 rpm. The generator features a cut-in speed of 0.42 - 0.46 m/s, which is the minimum flow speed required for the PTO to begin generating electrical power, although the FSWW initiates rotation at approximately 0.4 m/s. The generated electrical energy is used to charge an onboard 12V lead-acid battery bank, managed by a charge controller. The PTO device also includes a mechanism for controlling the speed of the FSWW by modulating the torque load applied by the generator on the rotor. This system ensures optimal energy conversion efficiency across varying flow conditions, making it a robust solution for marine energy harnessing applications.

11. Flight Deck for Drone Operations

    Title: Multi-Function Flight Deck for Aerial Drone Operations from Marine Platforms

    Description: This invention is a purpose-built flight deck designed for the landing, charging, and takeoff of aerial drones from an unmanned marine platform. The deck features automated guidance systems to assist drones in landing under various sea conditions. It includes a direct-contact charging pad capable of recharging drone batteries autonomously without a need for a cable, as well as restraints that secure the drone during recharging and rough seas. The flight deck is integrated with the platform's control systems, allowing for synchronized drone operations, ensuring continuous power supply for extended drone missions. The concept of operation is that when the drone lands, its presence is sensed by laser light beams on the flight deck and a drone restraint mechanism is activated that guides the drone over the charging plates and secures it during charging. Once the drone is fully charged, the restraint system can retract as commanded and allow the drone to take off the platform.

11. Benchtop Turbine Testing Capability

    Title: Advanced Benchtop Simulator for Predictive Testing and Validation of PTO Systems for Marine Hydrokinetic Turbines

    Description: This invention describes a benchtop testing system designed for the prototyping and validation of marine hydrokinetic turbines. The system simulates marine current conditions in a controlled laboratory environment, allowing for the assessment of turbine performance under various flow scenarios. It includes adjustable flow speeds, real-time data acquisition, and monitoring systems to evaluate parameters such as power output, efficiency, and structural integrity. The benchtop system features a 400W brushless direct current (BLDC) motor, a motor controller, a 1200W power supply, a desktop computer, and a Teensy electronic board. The BLDC motor is coupled to a 50 Nm torque sensor and fixed to a C-channel through L-shaped support plates. A secondary 10 Nm torque sensor is available to be connected to the generator shaft. The C-channel has fixture provisions to hold individual components of the PTO, as well as the complete PTO, in support of laboratory testing and characterization of generators, gearboxes, and the full PTO assembly. The benchtop system also emulates the behavior of the FSWW in support of development of torque load control algorithms for the turbine. The benchtop system is essential for optimizing turbine designs before full-scale deployment, reducing the time and cost associated with iterative field testing.

Market Transformation Plan

The Marine Hydrokinetic (MHK) turbine platform developed at Florida Atlantic University (FAU) showcases advancements in automation in harnessing marine currents for energy generation using unmanned mobile platforms. Two approaches are being considered for market transformation of the prototype MHK Platform and its major components. First, to transition the complete MHK Platform to a developer of USVS or small MHK device developer. Ocean Power Technologies have been contacted in this regard; they have acquired the company that made the USV that formed the basis of the MHK Platform at FAU so that there is potential synergy and interest in advancing the system. Second, to consider transitioning of the subcomponent technologies, including the automated anchoring system, the flight deck and the automated device deployment system. The flight deck is already being transitioned to an active ONR project at FAU entitled “Small Modular-Payload Machine Learning -Enabled USV Platforms in Support of Collaborative USV Operations”, which involves cooperative behavior between the USV and the aerial drone. The automated device deployment system is being considered for utilization in monitoring for harmful algal blooms in South Florida. MHK energy developers’ and TEAMER interest is sought in the PTO, the benchtop turbine testing system and the lab scaled-model lab testing system that have been developed. In general, to transition this innovative technology from academic research to industrial application, various stages of commercialization, from prototyping to market entry, need to be addressed.

1. Intellectual Property Protection

Patent Applications: Secure patents for the unique elements of the MHK platform, including the FSWW turbine design, the automated deployment and anchoring systems, and the flight deck for aerial drones. This is in progress.

2. Prototype Testing and Validation

Extended Field Trials: While the system has been field-tested in tidal waters, extended field trials would need to be conducted in various marine environments to validate the performance, reliability, and durability of the MHK platform under different conditions.

Third-Party Validation: Partner with independent marine engineering firms to validate the performance metrics and safety of the platform, providing credibility to potential industrial partners and investors. Potential partners are being sought, including ORPC and OPT.

3. Refinement and Optimization

Design Iteration: Incorporate feedback from field trials, and computational and laboratory studies to refine and optimize the turbine design, deployment mechanisms, and power-takeoff systems.

4. Partnership, Competitors and Collaboration

Industry Partnerships: Establish partnerships with established marine energy companies and USV manufacturers to leverage their expertise in large-scale production and market access.

Competitors: Notable competitors include Orbital Marine Power's O2 platform in Orkney waters, UK, ORPC's pontoon-based Rivgen platform, and *Sustainable Marine's* mono-hull ship-based platform in the Bay of Fundy.. Collaboration with these efforts could be beneficial, particularly in making some of their platforms' functions autonomous, which would enhance their operational efficiency.

Collaboration: Seek opportunities for collaboration with existing MHK developers, particularly those focusing on in-stream floating platforms, to complement their technologies with the MHK Platform's autonomous features

5. Manufacturing and Infrastructure Requirements

Scalability Assessment: Evaluate the scalability of the current design for mass production. Identify potential bottlenecks and areas for cost reduction. This includes exploring larger-scale systems with higher capacities and considering extensions such as increasing the waterwheel's length or diameter.

Infrastructure Requirements: Assess the infrastructure needs for mass production, including manufacturing facilities, supply chain logistics, and assembly processes. Establish partnerships with manufacturers to ensure a reliable supply chain for large-scale production

6. Regulatory Compliance and Certification

Compliance with Marine Standards: Ensure that the MHK platform complies with national and international marine safety and energy generation standards.

Certification: Obtain necessary certifications from relevant authorities (e.g., U.S. Coast Guard) to facilitate market acceptance and ensure that all necessary legal and safety requirements are met. Based on a Biological Evaluation, the Platform has already been certified for in-water operations under certain mitigating safety requirements.

7. Market Strategy and Commercialization

Market Analysis: Conduct a market analysis to identify potential customers, such as coastal communities, offshore industries, and renewable energy providers. Potential customers include MHK technology developers; USV manufactures; DOD; surveyors of coastline and coastal areas who use aerial drones. The MHK Platform can The platform can serve applications like long-term water quality monitoring, environmental surveillance, and shallow water surveying, with the MHK turbine providing power for instrumentation and drone recharging.

Commercialization Timeline: Target initial pilot projects within 2-3 years, with full market entry planned within 5 years, depending on the outcomes of extended field trials and regulatory approvals.

Product Marketing: Develop a marketing strategy that emphasizes the unique benefits of the MHK platform, including its autonomous operation, stability, ease of deployment, and environmental safety. Leverage digital marketing, industry conferences, and trade shows to increase visibility.

Pilot Projects: Initiate pilot projects with selected partners to demonstrate the platform's capabilities and build a portfolio of successful case studies.

Marketing and Outreach: Develop a marketing strategy that highlights the unique benefits of the MHK platform, including its stability, ease of deployment, and environmental safety.

8. Training and Support

User Training: Develop comprehensive training programs for operators and maintenance personnel to ensure efficient and safe operation of the MHK platform.

Technical Support: Establish a technical support infrastructure to assist customers with installation, operation, and troubleshooting.

9. Financial Planning

Cost Analysis: Perform a detailed cost analysis to determine the financial viability of large-scale production and deployment. This analysis would consider capital expenditure (Capex) and operational expenditure (Opex) costs for different production scales

Investment and Funding: Secure investment from venture capital firms, government funding, and strategic partners to finance the commercialization process. Explore grants, subsidies, and partnerships that could offset initial capital costs.

10. Continuous Improvement and Innovation

R&D Continuation: Maintain ongoing research and development efforts to enhance the efficiency, functionality and competitiveness of the MHK platform, keeping it competitive in the evolving renewable energy market.

Feedback Loop: Create a continuous feedback loop with industry partners and end-users to continuously gather insights and improve the platform.

11. Competitors and Market Positioning

Barriers to Market Penetration: Key challenges include (a) ensuring reliability in diverse marine environments, (b) gaining market acceptance for the MHK technology, (c) establishing a reliable supply chain for large-scale production, (d) competing with established energy technologies, and (e) addressing uncertainty in the economic viability and ROI of MHK projects.

Mitigation Plan Overcome these challenges through (a) ongoing field testing and optimization, (b) engaging with industry stakeholders via trade shows, conferences, and case studies, (c) partnering with suppliers and manufacturers, considering local manufacturing capabilities, (d) highlighting the MHK platform's unique advantages, such as reliability and consistency compared to wind and solar, and (e) conducting detailed cost analyses and case studies to build investor confidence.

Future Research

The development of the MHK platform can be advanced significantly through future research, addressing both technical and market challenges and facilitating the transition from a prototype to a widely adopted, commercially viable renewable energy solution. The following potential areas of future research are identified:

1. Optimization of the Turbine Design for increased power output: Enhance the efficiency and performance of the Freestream Waterwheel (FSWW) turbine through conducting advanced 3-D computational fluid dynamics (CFD) simulations and laboratory studies to refine blade design and optimize hydrodynamic efficiency and acceleration of in-flow to the turbine. A CFD study already underway in conjunction with NREL and TEAMER support. Laboratory work underway in exploring devices for flow acceleration.
2. Integration with Hybrid Renewable Energy Systems: Design and develop and test integrated systems combining the MHK Platform technology with other renewable energy sources such as solar and wind, including developing control algorithms to optimize energy production and storage across multiple energy sources.
3. Enhanced Data Acquisition and Analysis: Improve the accuracy and utility of data collected by the MHK platform using upgraded sensor systems to include advanced LIDAR, sonar, torque and other marine-specific sensors; develop machine learning techniques to predict maintenance of optimal performance.
4. Advanced Power-Takeoff (PTO) Systems: Increase the efficiency and reliability of the power conversion process through exploring alternative PTO mechanisms and configurations to improve energy conversion efficiency; and through integrating real-time monitoring and adaptive control systems to optimize PTO operation under varying conditions.
5. Scalability and Customization: Develop scalable and customizable versions of the MHK platform to cater to different market needs through designing modular components that can be easily scaled up or down to match specific energy requirements.
6. Automation and Autonomous Operation: Enhance the automation and autonomous capabilities of the MHK platform through developing advanced control algorithms for fully

autonomous deployment, operation, and retrieval of the FSWW turbine, including machine learning techniques.

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Appendix. Techno-Economic Potential of the MHK Platform

Introduction

A 2018 DOE EERE Report suggested unmanned marine and aerial vehicles as an emerging market for MHK energy. In particular, the report saw significant potential market within the DOD sector (Navy and Air Force) involving use of unmanned aerial vehicles or drones in ocean areas. Such unmanned aerial vehicles can benefit from capabilities to recharge stealthily at sea, rather than returning to a land-based recharging station, thereby enhancing mission success, range, and cost. The report is boosted by a May 2021 DOD Operational Energy Capability Improvement Fund (OECIF) and the Operational Energy Prototyping Fund (OEPF) solicitation for proposals (https://www.oecif.org/) in support of the deployment of more mobile and distributed operations with decreased and more agile logistics. These include developing potential game-changing technologies that drastically reduce energy resupply risks, costs, and signatures to enable persistent unmanned system and unattended sensors. The current project, involving development of a MHK device that provides power to potentially persistent unmanned systems in the coastal zone, is consistent with the solicitation.

Power Production and LCOE

In assessing the techno-economic potential of the MHK device, we allow for the fact that unmanned systems in support of persistence surveillance would be operating in the coastal zone. Such operations involve capital, operational and maintenance costs. If we assume that the small scale MHK device being developed will be used to support the energy requirements for such operations and could be placed on one or more of the existing USV platforms, then the cost of harnessing the renewable resource may be considered additional to the cost of unmanned operations. The latter are covered by the unmanned vehicle mission support. We assume that the incorporation of the MHK device will result in additional capital costs (CapEx), but that the operational and maintenance (OpEx) costs will be shared with the O&M costs for the unmanned assets. Based on expected values of CapEx for the prototype device, we explore various possible scenarios, involving one, or more units of different capacities. Although LCOE consideration for the system may not be entirely suited to assess the techno-economic potential of the system, it provides a good estimate of cost vs. benefit for different system capacities. The potential benefits are measured in terms of annualized power production (AEP), total weight of the system and levelized cost of electricity (LCOE) given by the formula [14]

$$\mathrm{LCOE} = \frac{(\mathrm{FCR}\ \times\ \mathrm{CapEx}) + \mathrm{OpEx}}{\mathrm{AEP}} \qquad (1)$$

Here FCR is the fixed charge rate.

The resource is characterized by a probability distribution of the speed of a variable current, such as in a tidal stream (Figure 15). Based on the field data for power production, the expected power output using the designed FSWW with the 9-blade, full-submergence configuration and the PTO system is determined. The resource and converter characteristics (Table 1) and the expected power output are used to determine AEP in SAM. Figure A1 depicts the contribution to AEP associated with the speed of the current for two different system capacities. The base unit is the MHK platform based on the WAM-V unmanned surface vehicle that has been designed. The extended unit represents a consideration of a potential extension of the base unit to a larger system of higher capacity. The particular extension considered is where the length of the waterwheel is increased by three times so that it extends on wither sides of the pontoons of the catamaran MHK platform. The extended system would use the same PTO. As a result, the capacity of the FSWW could be extended three times, while the additional costs would only be related to the extension of the waterwheel, but not the PTO. Alternative extensions could be accomplished through use of a larger wheel diameter or use of a larger unmanned platform. The estimated costs of the subsystems associated with the MHK turbine are listed in Table A1. The costs include cost of parts and estimated cost of labor in fabricating the subsystems USWW, the PTO and the deployment systems. These costs are based on engineering judgement and actual costs incurred in developing the prototype system. On the basis that these subsystems are directly related to power generation, while other unmanned aspects of the surface vehicle would be tied to support for specific USV mission, we regard the costs of these auxiliary subsystems for power generation as representing CapEx in our analysis. As mentioned above, we assume further that vehicle operation and maintenance costs are tied to specific maritime mission and the existing support for the mission can be leveraged to lower the cost of operation and maintenance of the MHK turbine. OpsEx is therefore estimated on this basis, leveraging this support. Thus, OpEx represents the estimated additional costs associated with harnessing MHK system onboard an existing USV. While the actual costs may differ, the method allows analysis of the cost vs. benefit of the designed MHK turbine and enables exploration of the trends associated with unit size and the number of units in operation, in support of understanding the cost drivers and potential measures for cost reduction. With these parameters defined, equation (1) for FCR = 0.108, which is a typical value assumed in SAM, is used to develop Tables A3, based on tidal currents with maximum speed of 1.1 m/s and in Tables A4 based on a constant current of 1.1m/s as in a river or a sustained coastal current. The LCOE for a single extended unit is around 50% lower than the base unit. For application of multiple MHK platforms, we consider economies of scale for both CapEx and OpEx costs. For production of multiple MHK Platforms, costs typically decrease as the quantity produced increases due to factors such as bulk purchasing of materials, more efficient production processes, and spreading fixed costs over a larger number of units, thereby decreasing capital (CapEx) cost per unit. Additionally, when scaling up from one MHK Platform to operating several units, operational costs typically also benefit from economies of scale. This means that while the total operational costs will increase with more units, the average operational (OpEx) cost per unit usually decreases due to shared resources, optimized logistics, and more efficient maintenance processes. The assumed discount factors with scale for CapEX and OpEx are provided in Table A2. LCOE is a function of both the available resource and the attributes of the MHK converter. LCOE is plotted as a function of system capacity in Figure A2 for the case of a tidal current of maximum speed 1.1 m/s and Figure A3 for the case of a constant current of speed 1.1 m/s, such as in a river or along a coast. The figures include data points associated with one and multiple units as well as with base and extended units. Consistent with other analyses (see for example, [15]) the results show a trend of reduction in LCOE with increase in system capacity.

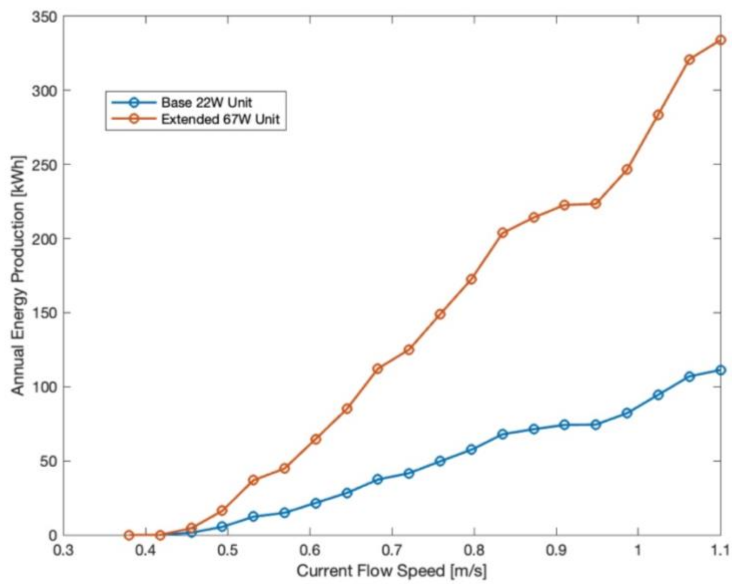

Figure A1: Estimated AEP based on current speeds in the range 0 – 1 m/s for base and extended turbine units. A capacity factor of 0.57 is assumed.

Subsystem	Costs ($)
FSWW	7351.57
PTO	12283.71
Deployment Frame	4263.53
Deployment Driver	2257.75
Total	26156.56

Table A1 Estimated CapEx costs associated with the MHK system based on prototype costs.

No. of Units	CapEx Discount Rate (%)	OpEx Discount Rate (%)
1	0	0
10	15	20
50	30	35
100	45	50

Table A2. Economy of scale. Assumed discount rates for CapEx and OpEx.

No of base units (22W)	CapEx ($)	OpEx ($)	AEP (kWh)	LCOE ($/kWh)	AEP/System weight [kWh/kg]
1	26157	500	112	29.69	0.8
10	222335	4000	1120	25.01	
50	915495	16250	5600	20.56	
100	1438635	25000	11200	16.10	
No of Extended units (67W)	**CapEx ($)**	**OpEx ($)**	**AEP (kWh)**	**LCOE ($/kWh)**	**AEP/System weight [kWh/kg]**
1	40861	750	336	15.37	1.3
10	347319	6000	3360	12.95	
50	1430135	24375	16800	10.64	
100	2247355	37500	33600	8.34	

Table A3: LCOE for single and multiple base units of 22W capacity and extended units of 67W capacity operating in tidal current of maximum speed 1.1 m/s.

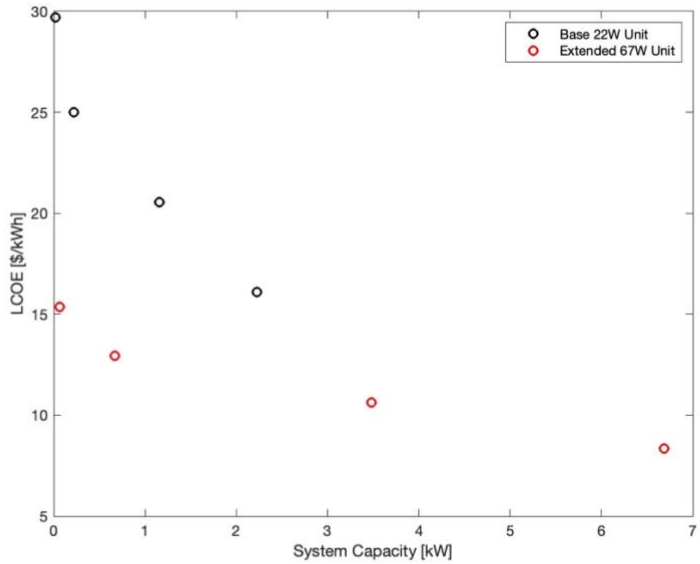

Figure A2: LCOE as a function of System Capacity based on maximum tidal current speed of 1.1m/s, base or extended configuration and number of units.

No of base units (22W)	**CapEx ($)**	**OpEx ($)**	**AEP (kWh)**	**LCOE ($/kWh)**	**AEP/System weight [kWh/kg]**
1	26157	500	181.67	18.30	1.3
10	222335	4000	1816.7	15.42	
50	915495	16250	9083.5	12.67	
100	1438635	25000	18167	9.93	
No of Extended units (67W)	**CapEx ($)**	**OpEx ($)**	**AEP (kWh)**	**LCOE ($/kWh)**	**AEP/System weight [kWh/kg]**
1	40861	750	545.01	9.47	2.1
10	347319	6000	5450.1	7.98	
50	1430135	24375	27250.5	6.56	
100	2247355	37500	54501	5.14	

Table A4: LCOE for single and multiple base units of 22W capacity and extended units of 67W capacity operating in a river at current speed 1.1 m/s.

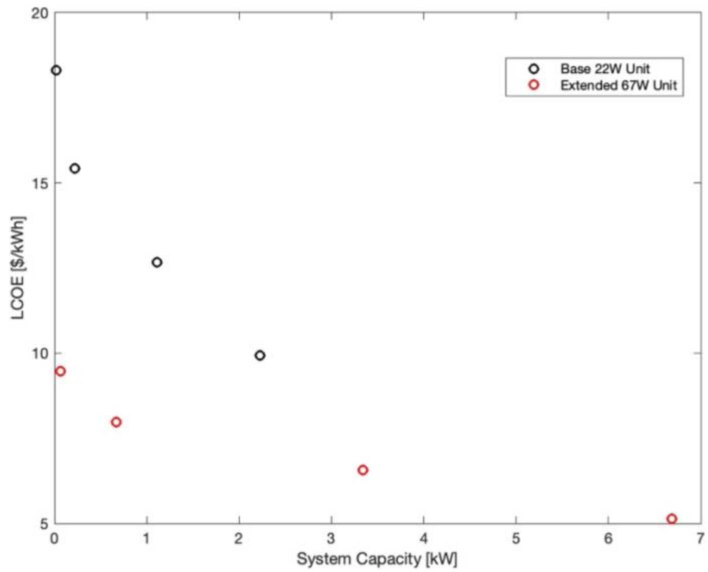

Figure A3: LCOE as a function of System Capacity based on constant river current speed of 1.1m/s, base or extended configuration and number of units.

System Weight Considerations

The weight of all the subsystems is tabulated in Table A5. The total weight of the MHK system, representing the payload on the unmanned surface vehicle is 139kg, well under the 159kg payload capacity of the vehicle platform. The ratio of power production to weight is provided in Tables A3 and A4. The ratio is increased by 62% in going from the base unit to the extended unit while the weight of the extended unit is increased by 88%. AEP is increased by a factor of 3.

Subsystem	**Weight [kg]**
9 Bladed, 2 support, FSWW	51
PTO	23
Swing Arm, Axle Bracket & Concentrator	11
Flight Deck (Structure)	15
Motion Control Rigging	5
Anchor system	29
Charging Pad and Drone Restraint	5
Total Weight	**139**

Table A5: Subsystem breakdown of the weight of the MHK payload

Discussion

The techno-economic potential considered above does not take account of the significant benefits provided to aerial drones operating in the maritime domain through making available recharging capabilities offshore. The savings in not having to utilize energy traveling back and forth to a land recharging station would need to be estimated in order to assess its impact on LCOE of the system. By the same token, operations may be restricted in bad-weather days, resulting in loss in AEP. The prototype MHK turbine system is based on an available unmanned vehicle at Florida Atlantic University. The vehicle serves as a good developmental platform for the MHK turbine system. However, once established, the system could easily be migrated to alternative custom platforms for enhanced capacity.

The MHK system payload of 139kg is well within the vehicle payload limit of 158kg. The base vehicle has a power to weight ratio of 0.8 kWh/kg. This is increased by 62% in moving from the base unit to a possible unit with extended capacity.