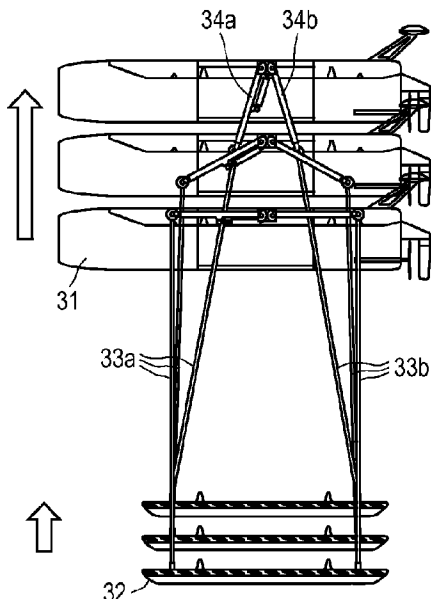




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 MOTION



(57) Abrégé/Abstract:

A wave-powered vessel has a buoyant vessel body, mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust, a mechanical means including an electrical generator for converting movement of the vessel body caused by wave motion to electrical power and a separate mechanical means including an electrical generator for converting horizontal movement of the vessel body through water to electrical power.

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## **Abstract**

A wave-powered vessel has a buoyant vessel body, mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust, a mechanical means including an electrical generator for converting movement of the vessel body caused  
5 by wave motion to electrical power and a separate mechanical means including an electrical generator for converting horizontal movement of the vessel body through water to electrical power.

# WATERCRAFT THAT HARVEST BOTH LOCOMOTIVE THRUST AND ELECTRICAL POWER FROM WAVE MOTION

## FIELD

5           The information disclosed and claimed below relates generally to the fields of vessel motility and power generation. More specifically, it provides watercraft configured for autonomous operation, harvesting both locomotive thrust and electrical power from wave motion.

## BACKGROUND

10           Wave-powered vessels have been described in U.S. Patent **7,371,136**; U.S. Patent **8,043,133**; and published applications US **2008/188150 A1**; US **2008/299843 A1**; and WO/**2008/109022**. Exemplary vessels are manufactured and sold by Liquid Robotics, Inc., Sunnyvale CA, USA under the brand Wave Glider<sup>®</sup>.

15           A previously unrelated field of development covers large stationary systems near shore that use wave motion to generate electrical power for communities on land. U.S. Patent No. **4,134,023** discusses an apparatus for extracting energy from waves on water. U.S. Patent No. **6,194,815** provides a piezoelectric rotary electrical energy generator. Published application US **2004/0217597 A1** discusses wave energy converters that use pressure differences. U.S. Patent **3,928,967** is the so-called “Salter’s Duck” patent, an  
20           apparatus and method of extracting wave energy. The status and perspectives of wave energy technology is generally reviewed by Clément et al. in *Renewable and Sustainable Energy Reviews* **6 (5): 405–431, 2002**.

## SUMMARY

This disclosure provides improved technology for manufacturing and deploying nautical craft that can travel and navigate on their own. A hybrid vessel is described that converts wave motion to locomotive thrust by mechanical means, and also converts wave motion to electrical power for storage in a battery. The electrical power can then be tapped to provide locomotive power during periods where wave motion is inadequate and during deployment. The electrical power can also be tapped to even out the undulating thrust that is created when locomotion of the vessel is powered by wave motion alone.

An exemplary wave-powered vessel may have a buoyant vessel body, a mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust; and an electrical generator for converting movement of the vessel body caused by wave motion to electrical power. Converting wave motion to horizontal thrust may be done in a configuration where an underwater component or swimmer is attached below the vessel body by one or more tethers. In this configuration, the swimmer is weighted to travel in water below the vessel body, and is configured to pull the vessel body by way of the tether. The swimmer has fin surfaces that mechanically provide forward thrust when actuated by rising and falling of the swimmer in the water.

The on-board electrical generator may comprise a means for converting vertical movement of the vessel body caused by wave motion to electrical power, a means for converting horizontal movement of the vessel body through water to electrical power, or both. Shown in the figures is a wave-powered vessel where the electrical generator comprises a piston powered by a swing arm that moves from a horizontal to a vertical position in accordance with the vertical movement of the vessel body. The swing arm is mechanically connected to a swimmer weighted to travel in water below the vessel body. Optionally, the swimmer may be adapted so that motion of the fin surfaces may be dampened to increase electrical power generated by the electrical generator.

Another type of electrical generator comprises a rotatory fin or turbine powered by horizontal movement of the vessel body through the water. In this case, the rotatory fin or

turbine is adapted to generate electrical power when rotated in one direction, and to act as a motor providing horizontal thrust to the vessel through the water when rotated in the opposite direction. Further types of electrical generators for harnessing swave powers are detailed later in this disclosure.

5 Wave-powered vessels described herein typically have an electrically powered motor to provide horizontal thrust that powers the vessel through the water. There is also a battery configured to store electrical power generated by the electrical generator and to feed electrical power to the motor to provide propulsion. Optionally, the vessel may have one or more solar panels that also supply electrical power to the battery.

10 The battery may be used to power an inboard or outboard electrical motor at any time there is reserve electrical power and it is desirable to increase the sped of the vessel. For example, the battery can power the motor during periods where the motion in each full wave cycle is inadequate to provide sufficient horizontal thrust to the vessel.

In another embodiment, there may be provided a wave-powered vessel with  
15 locomotive thrust powered alternately by wave motion and by electrical power so as to buffer the trust powered by the wave motion. The electrical power is supplied by a battery, which in turn is charged up by a system that converts wave motion to electrical power, as already outlined.

In another embodiment, there may be provided a wave-powered vessel configured  
20 for deployment from shore. The vessel is kept in compact form, and launched by way of the electric motor to deeper water, whereopn the other components of the vessel are deployed outward and downward. A vessel of this nature typically has a buoyant vessel body, a swimmer configured to retract and be secured against the vessel body, one or more tethers connecting the float to the swimmer, an electrically powered motor configured to  
25 propel the vessel through the water; and a battery supplying power to the motor, having sufficient capacity to power the vessel from shore to a location where the swimmer can be deployed. Again, the swimmer is weighted to travel in the water below the vessel body,

and is configured with fins to pull the vessel by way of the tether when actuated by vertical movement.

Such a vessel may also have a releasable tow buoy. The vessel body and the tow buoy are configured so that the tow buoy may be releasably housed within the vessel body while on shore, and pulled behind the vessel body after the vessel is deployed.

The vessels described herein may be suitable for use in autonomous operation (without a human attendant on board). The vessel has electronics configured to sense the geographical location of the vessel. There is also a microprocessor programmed to determine the vessels current location, and steer the vessel from its current location towards a target location.

In one embodiment, there is provided a wave-powered vessel, including: (a) a buoyant vessel body; (b) a mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust; and (c) a mechanical means including an electrical generator for converting movement of the vessel body caused by wave motion to electrical power, and including a piston powered by a swing arm that moves from a horizontal to a vertical position in accordance with the vertical movement of the vessel body.

In another embodiment, there is provided a wave-powered vessel, including: (a) a buoyant vessel body; (b) a mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust; (c) a mechanical means including an electrical generator for converting movement of the vessel body caused by wave motion to electrical power, and (d) a separate mechanical means including an electrical generator for converting horizontal movement of the vessel body through water to electrical power.

In another embodiment, there is provided a vessel with locomotive thrust powered alternately by wave motion and by electrical power so as to buffer the thrust powered by the wave motion. The vessel includes: (a) a buoyant vessel body; (b) a mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust; (c) an electrically powered motor to provide horizontal thrust to the vessel through the

water; and (d) an on board microprocessor programmed to detect the wave cycles, predict the undulations in mechanically derived locomotive thrust, and synchronize the electric motor out of phase to compensate.

In another embodiment, there is provided a wave-powered vessel configured for deployment from shore. The wave-powered vessel includes: (a) a buoyant vessel body; (b) a swimmer configured to retract and be secured against the vessel body; (c) one or more tethers connecting the buoyant vessel body to the swimmer; (d) an electrically powered motor configured to propel the vessel through the water; and (e) a battery supplying power to the motor, having sufficient capacity to power the vessel from shore to a location where the swimmer can be deployed. The swimmer is weighted to travel in the water below the vessel body, and is configured to pull the vessel by way of the tether. The swimmer includes fin surfaces that mechanically provide forward thrust when actuated by rising and falling of the swimmer in the water. A mechanical means for converting movement of the buoyant vessel body caused by wave motion to electrical power includes the swimmer and the one or more tethers. An electrical generator for converting movement of the buoyant vessel body caused by wave motion to electrical power includes the motor, the battery and a rotary fin or turbine powered by the horizontal movement of the vessel body through the water.

In another embodiment, there is provided a wave-powered vessel including: (a) a buoyant vessel body; (b) a propulsion system that is structured to mechanically convert movement of the vessel body caused by wave motion to locomotive thrust; (c) a first generating system that is structured to convert vertical movement of the vessel body caused by wave motion to electrical power; and (d) a second generating system that is structured to convert horizontal movement of the vessel body through water to electrical power.

In another embodiment, there is provided a wave-powered vessel, including: (a) a buoyant vessel body; (b) a propulsion system that is structured to mechanically convert movement of the vessel body caused by wave motion to locomotive thrust; (c) a generating system that is structured to convert movement of the vessel body caused by wave motion to



electrical power; (d) a battery wired to receive electrical power generated by the generating system; (e) an electrically powered motor wired to receive electrical power from the battery and positioned to provide locomotive thrust of the vessel through the water; and (f) one or more solar panels configured to supply electrical power to the battery.

5           In another embodiment, there is provided a dual power method for propelling a vessel smoothly along the surface of a body of water. The method involves: (a) harvesting motion of the vessel caused by and oscillating in accordance with waves on the body of water; (b) mechanically converting at least some of the harvested motion so as to propel the vessel horizontally with oscillating thrust in a particular direction; (c) generating electrical  
10 power; (d) storing the electrical power; and (e) retrieving electrical power from storage to drive an electrically powered motor in an oscillating fashion, thereby propelling the vessel in substantially the same direction in an alternating pattern with the oscillating thrust provided in step (b) and thereby smoothing the oscillating thrust.

          In another embodiment, there is provided an apparatus configured for deployment  
15 on a body of water. The apparatus includes: (a) a surface component that is buoyant; (b) a separate underwater component configured and weighted to be suspended underwater; (c) one or more tethers connecting the surface component to the underwater component each through a corresponding swing arm mounted to the surface component or the underwater component; (d) a generating system operably connected to the swing arm(s); and (e) a  
20 battery electrically connected to the generating system. The apparatus is structured such that when it is deployed on a body of water, the underwater component is suspended underwater from the surface component by way of the tethers, and wave motion on the body of water causes the surface component to rise and fall relative to the underwater component, thereby moving the swing arms in a manner that oscillates with the wave  
25 motion. The moving of the swim arms drives the generating system to produce electrical power, which is then conveyed to the battery.

          In another embodiment, there is provided a wave-powered vessel, including: (a) a buoyant vessel body; (b) a propulsion system that is structured to mechanically convert

movement of the vessel body caused by wave motion to locomotive thrust; and (c) a generating system that is structured to convert movement of the vessel body caused by wave motion to electrical power. The generating system includes a surface component connected to an underwater component through one or more swing arms such that when the vessel is deployed on a body of water, wave motion on the body of water causes the surface component to rise and fall relative to the underwater component, thereby moving the swing arms in a manner that oscillates with the wave motion.

In another embodiment, there is provided a wave-powered vessel, including: (a) a buoyant vessel body; (b) a propulsion system that is structured to mechanically convert movement of the vessel body caused by wave motion to locomotive thrust; and (c) a generating system that is structured to convert movement of the vessel body caused by wave motion to electrical power. The propulsion system includes an underwater component that includes fins or wings that mechanically provide locomotive thrust when actuated by rising and falling of the swimmer in the water. The propulsion system includes a fin control system configured to variably dampen movement of the fins or wings, whereby the proportion of vessel movement used for locomotive thrust can be reduced in favor of electrical power generation.

In another embodiment, there is provided a wave powered vessel, including: a buoyant vessel body; a swimmer body, mechanically coupled to the vessel body; a propulsion system that is structured to mechanically convert at least a first portion of a movement of the vessel body relative to the swimmer body caused by wave motion into locomotive thrust; and a generating system structured to convert at least a second portion of the movement of the vessel body relative to the swimmer body caused by wave motion into electrical power.

In another embodiment, there is provided a method of powering a vessel including buoyant vessel body mechanically coupled to a swimmer body. The method involves: mechanically converting, with a propulsion system, at least a first portion a movement of the vessel body relative to the swimmer body caused by wave motion into locomotive

thrust; and mechanically converting, with a generating system, at least a second portion of the movement of the vessel body relative to the swimmer body caused by wave motion into electrical power.

In another embodiment, there is provided a wave powered vessel, including: a  
5 buoyant vessel body; a swimmer body, mechanically coupled to the vessel body; a  
propulsion system that is structured to mechanically convert at least a first portion of a  
movement of the vessel body relative to the swimmer body caused by wave motion into  
locomotive thrust; a generating system structured to convert at least a second portion of the  
movement of the vessel body relative to the swimmer body caused by wave motion into  
10 electrical power; and a microprocessor. The microprocessor is programmed to control a  
proportion of the at least the first portion movement of the vessel body relative to the  
swimmer body converted to the locomotive thrust to the at least the second portion of the  
movement of the vessel body relative to the swimmer body converted to electrical power.

## BRIEF DESCRIPTION OF THE DRAWINGS

**FIG. 1A** shows how water moves in roughly circular orbits in waves;

**FIG. 1B** is a side view of a wave-powered vehicle showing the overall operation;

**FIG. 2** shows an example of an algorithm for directing a vessel towards or  
5 maintaining it at a target position (a geographical location);

**FIG. 3** shows the availability of solar power as a function of the annual cycle;

**FIG. 4** is a block diagram summarizing how the interaction of power sources can  
occur;

**FIG. 5A, FIG. 5B, FIG. 6A, and FIG. 6B** are side views of a vessel that illustrates  
10 how wave motion can be converted to electrical power;

**FIG. 7, FIG. 8A, and FIG. 8B** show an example of a vessel that uses wave motion  
to generate both locomotive thrust and electrical power from vessel motion;

**FIG. 9** is a graph of hypothetical data that illustrates how stored electrical power in  
the battery can be used to power the electric motor and provide propulsion whenever  
15 desired; and

**FIG. 10** is a perspective view showing how a vessel body and a tow buoy may be  
configured so that the tow buoy may be releasably housed within the vessel body while on  
shore, and pulled behind the vessel body after the vessel is deployed.

## DETAILED DESCRIPTION

This disclosure provides watercraft that derive both locomotive thrust and electrical energy by wave motion. Detailed illustrations of the watercraft include a vessel that harvests the power of vertical movement using tethers attached to a spring-loaded suspension device. Wave energy is converted to potential energy in the springs, which is then used to drive an electricity generator. In another example, the vessel has a propeller that can be driven backwards as a generator when in motion so as produce electrical power. Electrical energy obtained by either of these means may be used to power electronics or stored in a battery for later use. The stored energy can be used to provide propulsion on calm days when wave action does not in itself provide enough power for the vessel to travel at the desired speed.

### Converting Vertical Wave Power to Locomotive Thrust

One feature of the watercraft described herein is the ability to use wave motion to drive the vessel from place to place across a body of water.

Wave motion can be approximated for many purposes as a linear superposition of roughly sinusoidal waves of varying wavelength, period and direction. As a wave moves horizontally along the surface, the water itself moves in roughly circular orbits of logarithmically decreasing diameter with depth. This is shown in **FIG. 1A**. The orbit at the surface has a diameter equal to the height of the wave. The orbital diameter at depth is a function of wave length:

$$H_y = H_s e^{-2\pi y/L}$$

where  $L$  is the wave length,  $H_s$  is the surface wave height and  $H_y$  is the orbital diameter at depth  $y$  below the surface.

Vessels can be configured to exploit the difference in motion between  $H_s$  and  $H_y$ , for example, in the following way. A vessel body is positioned at or near the surface, and a submerged swimmer or glider component is positioned at depth  $y$ , and connected to the vessel body by one or more tethers. As waves lift and lower the float portion, wings or fins on the submerged portion passively rotate so as to convert the relative motion of the surrounding water into forward thrust. The azimuth of the thrust vector can be directed completely independently of the direction of the waves by a rudder at the back of the glider. The vessel has multiple wings each with a short chord dimension. This minimizes lost motion between the up stroke and the down stroke and enables successful conversion of even very small waves into forward thrust.

**FIG. 1B** is a side view of a wave-powered vehicle that illustrates this principle. The vehicle comprises a float or vessel body **10** resting on the water surface, and a swimmer **20** hanging below, suspended by one or more tethers **30**. The float **10** comprises a displacement hull **11** and a fixed keel fin **12**. The swimmer comprises a rudder **21** for steering and wings or fins **22** connected to a central beam of the rack **23** so as to permit rotation of the wings around a transverse axis within a constrained range, and provide propulsion.

In still water (shown in the leftmost panel), the submerged swimmer **20** hangs level by way of the tether **30** directly below the float **10**. As a wave lifts the float **10** (middle panel), an upwards force is generated on the tether **30**, pulling the swimmer **20** upwards through the water. This causes the wings **22** of the swimmer to rotate about a transverse axis were the wings are connected to the rack **23**, and assume a downwards sloping position. As the water is forced downward through the swimmer, the downwards sloping wings generate forward thrust, and the swimmer pulls the float forward. After the wave crests (rightmost panel), the float descends into a trough. The swimmer also sinks, since it is heavier than water, keeping tension on the tether. The wings rotate about the transverse axis the other way, assuming an upwards sloping position. As the water is forced upwards through the swimmer, the upwards sloping wings generate forward thrust, and the swimmer again pulls the float forwards.

Thus, the swimmer generates thrust when both ascending and descending, resulting in forward motion of the entire craft.

### **Autonomous Navigation**

5           A wave-powered vessel may be configured to navigate across a body of water autonomously (without human attendance), and to perform its own power management.

Self-directed navigation is possible when the vessel is equipped with a means of determining the geographical location of the vessel, a means for determining direction, a means for steering the vessel, and a means for operating the steering so that the vessel  
10 travels or stays at a target location. The steering means is typically a rudder that turns sideways against the water so as to cause the vessel to spin towards a new heading. Alternatively or in addition, it may be a mechanical arrangement that presses upwards and downwards on opposite sides of the vessel in the manner of an aileron, thereby causing the  
15 swimmer connected by a single tether, it is usual to put the steering means on the swimmer providing the locomotive power. In configurations having two or more tethers, a rudder may be placed on the float, the swimmer, or on the float and the swimmer together.

Electronics to sense the geographical location of a vessel can triangulate off a series of reference points. Particularly effective is the global positioning system (GPS), or a  
20 similar network of positional transmitting sources. The vessel will also usually have an electronic compass or gyroscope to determine the vessel heading. Positional data about the geographical location and the vessel heading is processed in a decision algorithm or programmed microprocessor, which may then provide navigation instructions. Consequently, the steering means adjusts to head the vessel in accordance with the  
25 instructions.

**FIG. 2** shows an example of an algorithm for directing a vessel towards or maintaining it at a target position (a geographical location). Once the target position is inputted, it is compared with the current location of the vessel inputted from a GPS

receiver. The processor calculates the proper heading, and compares it with the heading inputted from the compass. The processor then outputs instructions to the rudder servo to adjust the vessel onto the correct heading. For vessels that are capable of regulating transit speed or locomotive force, the processor may also output instructions to adjust the speed (not shown). Measurement and correction by comparison with GPS and compass data is performed iteratively as the journey continues.

Electrical power is typically needed for the electronics used for self-navigation. This can be supplied by photovoltaic cells located on the deck of the vessel. For low wind resistance, for low visibility, and to reduce the sensitivity to the direction of the sun, it is best if this surface is horizontal. For example, the top deck can be installed with SunPower™ E20 panels each containing 96 Maxeon™ cells. Under standard conditions (irradiance of 1000 Watts/m<sup>2</sup>, AM 1.5, and cell temperature of 25° C) six panels produce a total of 1962 Watts.

### 15 **Converting Wave Movement to Electrical Power**

The field of wave-powered watercraft is advanced by providing two sources of locomotive power. One is a highly efficient mechanical conversion of wave motion directly to locomotive thrust, as described earlier in this disclosure. The second is conversion of wave motion to electrical power, which can be stored and used at a later time. Having the two systems on board may provide a number of advantages.

**FIG. 3** shows the availability of solar power as a function of the annual cycle, and as a function of time (adapted from MD Ageev, *Advanced Robotics* 16(1):43-55, 2002). Depending on the size and efficiency of the photovoltaic cells, there may be periods when solar power is inadequate to power the electronics on board. A battery system can be used to buffer and sustain the electronics through diurnal variation, but if the vessel spends long periods in the far north, for example, solar power may be inadequate. On the other hand, using wave motion for locomotive thrust may be insufficiently reliable at or near the equator or in summer months.



When wave motion is high, enough power can be harvested not only to propel the vessel through the water, but also to provide ample electrical power. In fact, enough electrical power can be harvested from the waves not only to power the electronics, but also to create an energy supply that can later be used for locomotion. An electrical generator  
5 can be driven by vertical and/or horizontal movement of the vessel caused by the waves. The vessel is configured so that the vertical undulations of the vessel are mechanically coupled to a means of providing horizontal locomotive power to the vessel (such as a fin or wing rack), and are also mechanically coupled to a generator of electrical power.

In vessels equipped in this way, other sources of electrical power (like photovoltaic  
10 cells for solar power) are entirely optional — the wave motion mechanically provides power to drive the vessel through the water, and also provides electricity to run electronics and microprocessors aboard.

When electrical power generated from wave motion and/or from solar panels is in excess of immediate needs, it can be stored in an on-board rechargeable battery. The stored  
15 electrical power can be used at a later time to power on-board electronics and microprocessors. It can also be used to power an electrically driven propulsion system, such as an electric motor coupled to a propeller or turbine. Thus, on calm days when there is insufficient wave motion to drive the vessel at the desired speed, the battery (optionally in combination with photovoltaic cells) can power the propulsion system. Conversely, the  
20 wave generated electrical power can be stored for use during periods that are too dark to rely entirely on solar power — for example, at night — and/or to supplement locomotive thrust.

**FIG. 4** is a block diagram summarizing how the interaction of power sources can occur. Sources of power are indicated on the top line; results at the bottom. Wave motion  
25 can provide locomotive thrust by mechanical interconnection, such as in a two-part vessel where a floating portion is tethered to a submarine portion. Wave motion can also power a generator adapted for implementation on a vessel, which generates electricity delivered to a rechargeable battery. Vessel motion through the water (a result of propulsion mechanically

generated from the wave action) can power an electrical generator of its own, which also feeds the battery. Solar panels (if present) also provide electrical power to a battery. Although they may be separate, typically the battery for any two or three of these power sources are shared by the sources that are present.

5           Electrical power from the battery supplies on-board electronics, such as navigation equipment, a microprocessor that manages power allocation, and sensors or detectors of various kinds. Electrical power can also be tapped at any time it's available to provide vessel propulsion: either to supplement thrust obtained from the wave motion mechanically, or to substitute for mechanical thrust at times when wave motion is  
10 insufficient. As explained below, the electric motor may be the same apparatus as the electrical generator powered by vessel motion, run in reverse to provide vessel propulsion.

**FIG. 5A, FIG. 5B, FIG. 6A, and FIG. 6B** are side views of a vessel that illustrates how wave motion can be converted to electrical power. The vessel has been equipped to harvest wave motion for both locomotive and electrical power. There are two tethers **33a**  
15 and **33b** connecting the vessel body **31** to the swimmer **32**, fastened to opposite arms **34a** and **34b** of a suspension device **37** by way of rotating hinges **35**. The arms of the suspension are spring loaded to return to a neutral horizontal configuration in opposite directions along an axis parallel to the vessel's length, pivoting around a central suspension point **36**.

20           Also shown on the vessel body **31** are a propeller **41** powered by an electric motor **42**, a rudder **43**, and an assembly **44** for receiving and transmitting data and operating instructions that is mounted on the top deck **45**. The configuration can be adapted with more tethers attached to more link arms that fold forwards and/or backwards, and are mounted on the vessel body **31** beside, in front, or behind the suspension device **37** shown  
25 here.

**FIG. 5A** superimposes three images showing what happens when the vessel body **31** is lifted by a wave. At the starting position, the suspension device **37** is configured in the neutral position with arms **34a** and **34b** horizontally positioned in opposite directions.

As the wave lifts the vessel body **31**, it pulls the swimmer **32** upwards. However, the density of water slows the upward movement of the swimmer **32**, thereby pulling the arms **34a** and **34b** of the suspension device **37** downwards. This loads the spring on each arm with potential energy.

5           **FIG. 5B** superimposes three images showing what happens as the vessel approaches the crest of the wave. The upwards motion of the vessel body **31** slows, but the swimmer **32** still travels upwards due to the tension in the arms when they were being pulled downward. As the swimmer **32** continues upwards to a point where the arms **34a** and **34b** resume the neutral horizontal position, the potential energy in the suspension device **37** is released, and can be captured by a generator means that converts the potential energy in the  
10           spring into electrical power.

**FIG. 6A** superimposes three images of the configuration of the suspension device **37** as the potential energy is released. In this example, the two tether winches **33a** and **33b** pivotally mounted **35** to the ends of link-arms **34a** and **34b** drive a piston: specifically, a  
15           linear hydraulic cylinder **38**, which in turn creates pressure to drive a hydraulic turbine generator (not shown). For simplicity the hydraulic cylinder **38** is shown here attached to only one of the link arms **34a**, although more typically there is another hydraulic cylinder attached to the other link arm **34b**. The link arms **34a** and **34b** could package nicely in the center span structure without protruding above the deck **45** of the vessel body **31**.  
20           Optionally, the link arms **44a** and **44b** can be configured to lock in the neutral horizontal position during times where all of the wave energy is needed for thrust, or when electric generation is not necessary.

**FIG. 6B** provides a detail of the action of the hydraulic cylinder **38** during a cycle of movement of the link arm **34a** from the neutral horizontal position to the vertical tending  
25           spring loaded position as the swimmer is pulled upwards by the vessel body **31** as the wave peaks. When the link arms are in the neutral position, the hydraulic cylinder is extended **39a**, and is pushed together **39b** into a compressed position **39c** as the link arm **34a** descends towards the vertical. When the link arm **34a** returns to the horizontal position as

the wave troughs, the hydraulic cylinder returns to the extended position **39a**, completing the cycle.

The arrangement shown in these figures may be adjusted to the user's liking to fit a particular installation. The swing arm system shown in **FIG. 5A, FIG 5B, FIG. 6A,** and  
5 **FIG. 6B** may be placed on the swimmer rather than on the float. The link arms are pivotally mounted at the proximal end towards the upper surface of the swimmer, and are spring loaded to assume a horizontal neutral position. The tether is attached to the distal end of the arm, and connects to the float above. Wave motion again stretches the distance between the float and the tether, but in this case the link arms are pulled into an upwards  
10 orientation, creating potential energy in the spring that can be converted to electrical power.

Whether mounted on the float or the swimmer, the electrical power generation system may harvest the up and down motion of the link arms by a suitable arrangement that ultimately results in a mechanical force turning conductive wire or bar within a magnetic field, or turning a magnet through a conductor. Included are mechanical arrangements that  
15 result directly in rotatory motion (such as a rotating axle), or a back-and-forth action (such as a liquid or gas filled piston) that can be converted mechanically into rotatory motion.

The electrical power generation system shown in **FIG. 5A, FIG.5B, FIG. 6A,** and **FIG. 6B** are provided by way of an example of how such a system may be implemented with high conversion efficiency. The example is not meant to be limiting except where  
20 explicitly indicated. Other systems for harnessing electricity from wave power on a moving vessel may be adapted from stationary on-shore technology now deployed or under development.

Electrical power generating systems may be configured to harness vertical oscillation of the water surface in a wave cycle, or horizontal movement of the wave peaks,  
25 or a combination of the two. By way of illustration, a system that harvests electrical power from vertical movement can comprise a tube that floats vertically in the water and tethered to the vessel. The tube's up-and-down bobbing motion is used to pressurize water stored in the tube below the surface. Once the pressure reaches a certain level, the water is released,

spinning a turbine and generating electricity. In another illustration, an oscillating water column drives air in and out of a pressure chamber through a Wells turbine. In a third illustration, the power generating system comprises a piston pump secured below the water surface with a float tethered to the piston. Waves cause the float to rise and fall, generating  
5 pressurized water, which is then used to drive hydraulic generators.

To harvest horizontal wave movement, the electrical power generating system may comprise one or more large oscillating flaps positioned to catch waves as they go by. The flap flexes backwards and forwards in response to wave motion, which in turn drives pistons that pump seawater at high pressure through a pipe to a hydroelectric generator.  
10 Another implementation comprises a series of semi-submerged cylindrical sections linked by hinged joints. As waves pass along the length of the apparatus, the sections move relative to one another. The wave-induced motion of the sections is resisted by hydraulic cylinders, which pump high pressure water or oil through hydraulic motors via smoothing hydraulic accumulators. The hydraulic motors drive electrical generators to produce  
15 electrical power.

### **Converting Horizontal Movement of the Vessel to Electrical Power**

Another way of converting wave motion to electrical power is a two-step process. The first step is to use the wave motion to create locomotive thrust, thereby causing the  
20 vessel to move through the water. The second step is to harvest the movement of the water about the vessel resulting from the locomotion, and convert it to electrical power.

**FIG. 7, FIG. 8A, and FIG. 8B** show an example of a vessel that uses wave motion to generate both locomotive thrust and electrical power from vessel motion. In this example, the swimmer or wing-rack is tethered to the buoy or vessel body by a foreward and aft tether with a winch for adjusting the length of tether that is deployed. As the buoy  
25 moves up and down with the waves, the swimmer rack has wings that translate the vertical movement into transverse locomotive movement. The wing-rack then pulls the vessel body as directed by the rudder under control of the microprocessor.

The electrical system shown here comprises upward facing solar panels, providing an auxiliary source of electrical power. The power module for generating electricity is shown in detail in **FIG. 8B**. The module comprises rechargeable batteries, a rotating magnet conductor arrangement that plays the role of both motor and generator, and a third component that plays the role of both propeller and turbine. As shown in **FIG. 7**, when there is an abundance of wave power, the wings on the swimmer generate thrust or locomotive power to move the vessel forward. As the waves power the vessel through the water, the propeller is turned backwards, applying torque to the motor so as to generate electrical power for storage in the battery. When there is an absence of wind power, or when the wing rack is retracted into the vessel body, the batteries or solar panel powers the motor, which turns the propeller so as to provide locomotive power.

The power module is shown in **FIG. 8A** secured to one side of a catamaran type float. This can be varied to secure the power module for example to the other side, to the middle of a float with a central keel, or to the side rails or middle spine of the swimmer. Two or more power modules can be used, secured for example to both sides of a catamaran type float, or to a float and swimmer together in any combination.

In the example shown, the hull type is a displacement catamaran, which has the advantage of being very efficient below the hull speed, and can be powered up to 3 times faster than the hull speed with minimal wake. It has six 325 watt SunPower panels for almost 2000 watts peak solar power collection. It also has two Tesla-sized lithium ion battery packs housed in cylindrical power modules that are pressure tolerant to 200 m. These packs each have roughly 7000 cells totally 25 kWh of energy. The power modules are 12.75 inches in diameter — the same as a Remus 600 or a BlueFin 12D AUV.

## **Balancing Between Locomotive Thrust and Electrical Power Generation**

In some implementations, the various power harvesting systems on a vessel may be configured to be regulated so as to prioritize delivery of power from wave motion to locomotive thrust or electricity generation in the desired proportion.

The electrical power generating system may be configured to lock out or variably dampen movement of the components that convert the wave motion to rotatory motion, and hence to electricity. For example, the link arm system shown in **FIG. 5A**, **FIG. 5B**, **FIG. 6A**, and **FIG. 6B** may be designed so that the link arms may be secured by a clamp or other means in the horizontal neutral position. This effectively locks out the power generating system in favor of the wave-powered propulsion system, which may be desirable when the wave motion is not in excess of what is required to propel the vessel at the intended speed, and/or when electrical power is not needed (for example, when the battery is charged to full capacity). In a variation of this system, the damping is variable, so that the proportion of wave motion used for electrical power generation may be precisely adjusted.

Conversely, the wave-powered propulsion system may be configured to lock out or variably dampen movement of the components that convert the wave motion to thrust. For example, the wings or fins shown in **FIG. 1B** may be designed so that they may be secured in a neutral position. This effectively locks out the propulsion system in favor of the electrical power generating system, which may be desirable when the wave motion is well in excess of what is required to propel the vessel at the intended speed, and/or when electrical power is needed in greater abundance to power on-board electronics and/or recharge the battery. In a variation of this system, the damping is variable, so that the proportion of wave motion used for locomotive thrust may be precisely adjusted.

Besides adjusting use of the wave motion between thrust and electricity generation, a variable damping system on the propulsion system may have a further benefit: namely, to regulate speed of the vessel depending on the amount of wave motion currently available, and the desired target location. For example, when it is desired that the vessel stay in position at its current location, the propulsion regular and rudder may be caused assume a direction and speed that exactly compensates for the net effect of underlying current, wind, and horizontal wave force affecting the vessel's position. This effectively secures the vessel at its current GPS location, and saves the vessel from having to travel in circles to maintain its position.

Thus, either the propulsion system, or the electrical power generating system, or both may be configured with a lock out or variable damping arrangement to adjust the priority between the two systems.

Where such regulation systems are installed, they may be controlled by an on-board  
5 microprocessor programmed to determine the appropriate priority between locomotion and electrical power generation, and then to regulate the damping or lockout devices on each system accordingly. The microprocessor may be programmed to take into account such factors as vertical wave motion, latitude (determined by GPS), temperature, other weather factors, battery level, distance from the intended target location, amount of available solar  
10 power, time of day, payload, sensor data, and operating parameters programmed into or transmitted to the microprocessor.

### **Alternating Locomotive Thrust from Wave Motion and an Electrical Motor to Buffer Vessel Speed**

15 Stored electrical power in the battery can be used to power the electric motor and provide propulsion whenever desired. Besides powering the motor during periods when wave motion is quiescent, it can be used on an ongoing basis to buffer the thrust powered by the wave motion.

**FIG. 9** is a graph of hypothetical data that illustrates how this might work.  
20 Mechanisms that convert wave motion into locomotive power by gradually pressurizing a gas or a liquid may provide fairly uniform thrust. However, other mechanisms result in undulations in thrust that occur once or twice per wave cycle. For example, in a configuration where a wing rack is tethered beneath a float (as in **FIG. 1B**), the mechanism provides forward thrust while the rack is travelling upwards or downwards in the wave  
25 cycle. When the wave is peaking or at its nadir, tension on the tethers is fairly constant, and forward thrust is minimal. Thus, in a single wave cycle (as shown in **FIG. 9**), forward thrust peaks twice.



In many uses of a wave-powered vessel, the undulations are of little consequence. However, there are instances in which a constant speed (and thus relatively constant thrust) is desirable: for example, when using sensors that comprise streamers flowing backwards from the vessel. The undulations in thrust obtained by mechanical conversion can be buffered by powering the electrical motor in an undulating pattern of the same frequency but essentially out of phase. In this manner, thrust from mechanical conversion and thrust from the electric motor alternate, so that the combined locomotive thrust is buffered to a more consistent level. The pattern of power to the electric motor may be controlled by an on board microprocessor programmed to detect the wave cycle, predict the undulations in mechanically derived locomotive thrust, and synchronize the electric motor out of phase to compensate.

### **Watercraft Configured for Self-Deployment**

Another advantage of the hybrid powered vehicles described herein may be that in many instances they may be deployed directly from shore. This saves the trouble and expense of hiring a special vessel and crew to do the deployment in deep water. Instead, the components of the vessel are kept bound together, and the electric motor powers the vessel to deep water for full deployment.

For example, a wave-powered vessel configured for deployment from shore may comprise a buoyant vessel body, a swimmer configured to retract and be secured against the vessel body, one or more tethers connecting the float to the swimmer, an electrically powered motor configured to propel the vessel through the water, and a battery supplying power to the motor, having sufficient capacity to power the vessel from shore to a location where the swimmer can be deployed. The battery is charged up before launch, and the swimmer is kept secured to the float. The electric motor takes the vessel to deep water, and then the tethers are let out to deploy the swimmer to its operative position below the float — either automatically, or by remote control. After deployment, the battery can be

recharged on an ongoing basis using the electrical power generating systems aboard the vessel.

5 **FIG. 10** provides a further illustration. Some projects with wave powered vessels require the vessels to take a substantially massive payload. If kept aboard the float or the swimmer, the payload could impair vertical movement, and thus reduce efficiency of the vessel for converting wave motion to thrust and electrical power. Typically, the payload is towed in a container or platform referred to as a “tow buoy” behind the float or the swimmer, either on or below the water surface. However, deploying the vessel and the tow buoy separately from shore is difficult.

10 The figure shows how the vessel body and the tow buoy may be configured so that the tow buoy may be releasably housed within the vessel body while on shore, and pulled behind the vessel body after the vessel is deployed. The refinements shown include rollers to guide the tow buoy up one or more complementary ramps inside the float. To transport the vessel to the launch site, the tow buoy is positioned securely inside the float, and the  
15 tethers connecting the wing racks to the float are retracted so that the wing racks nest securely to the bottom of the float. Following launch, the precharged battery powers the vessel to deep water, whereupon the wing racks are deployed downward, and the tow buoy is deployed out the back of the float so as to be towed by the float without impairing the float’s vertical movement due to wave motion.

20

#### **Use of Wave-Powered Watercraft**

The hybrid wave-powered vessels described herein can be manufactured, sold, and deployed for any worthwhile purpose desired by the user. For example, the vessels can be used to survey and monitor regions of the ocean or other bodies of water, including the  
25 chemistry of water and air, weather, and marine life. The vessels can be used to relay signals from sensors under the water or on other vessels to a data processing center. They can be used to monitor activities on shore, and the behavior of other watercraft. They can

also be used to distribute substances into the ocean from the vessel body or from a tow buoy.

Sensors and related equipment that may be used include one or more of the following in any suitable combination:

- 5       • Sensors for gas concentrations in air or water
- Heat flux sensors
- Meteorological sensors: wind speed & direction, air temperature, solar intensity, rain fall, humidity, pressure
- Physical oceanography sensors; wave spectrum & direction, current sensors, CTD  
10       profiles
- Micro-organism counts and classification through water sampling and vision systems
- Fish and wildlife tracking by acoustic tag detection, such as those manufactured by Vemco
- 15       • FAD structures to provide shade and attract marine life
- Acoustic sensors for active or passive detection and classification of marine wildlife. For example, hydrophone for listening to whales, or active sonar for fish counts
- Chemical sensors to detect the concentration of a substance being released by the  
20       vessel

Equipment installed on a vessel of the type described herein to facilitate data collection may include a means for obtaining sensor data at variable depths. This can be achieved using a winch system to lower and raise sensors mounted on a heavier-than-water platform. Another option is a tow buoy mounted with sensors, with servo-controlled  
25       elevator fins to alter the pitch of the tow body, thereby controlling its depth while being pulled. The vessel may also have data storage systems and a microprocessor programmed to process and interpret data from the sensors, either integrated into the location and

navigation processing and control system on the vessel, or as a stand-alone microprocessor system.

Watercraft described herein equipped with sensors and/or payloads have a variety of sociological and commercially important uses. Such uses include fertilizing plankton, feeding fish, sequestering carbon from the atmosphere (PCT/US2012/029718), conducting seismic surveys (US 2012/0069702 A1) or prospecting for new sources of minerals or fuel oil.

### **Glossary**

10 The terms “vessel”, “watercraft”, and sea going “vehicle” are used interchangeably in this disclosure and previous disclosures to refer to a nautical craft that can travel across and about any body of water at or near the surface.

A “wave-powered” vessel is a vessel that derives at least a majority of its power for locomotion from motion of the water in relation to the surface. Optionally, the vessel may also derive power from solar energy and other natural sources, and/or man-made sources such as batteries and liquid fuel powered engines. In this context, a “wave” is any upward and downward motion of the surface of a body of water at a point of reference (such as the center of floatation of a vessel).

20 A “vessel body” or “float” is a component of a vessel that travels on or near the surface of the water. It may have its own source of locomotive power and/or rely on being pulled by a submarine component. It is made buoyant by having a density (including enclosed air pockets and upward opening cavities) that is

25 A “swimmer”, “pod”, “submarine component”, “sub”, “glider” or “wing rack” is a component of a vessel that travels below the surface of the water and below the vessel body, to which it provides locomotive power or propulsion. The swimmer is heavier than water, so as to travel downwards through the water to the extent allowed by the tethers and the vessel body and suspension systems to which the tethers are attached above. It is

typically equipped with a plurality of “fins” or “wings” that rotate upwards or downwards around an axle transverse to the direction of travel. This disclosure generally refers to vessels having single swimmers or wing racks. However, vessels may be configured with multiple swimmers, typically joined to the same two or more tethers at different depths, each providing locomotive thrust in response to wave action, and optionally configured for nesting when retracted (PCT/US2012/029696). Thus, deriving wave power from a swimmer includes or can be adapted *mutatis mutandis* to include two, three, or more than three swimmers or wing racks.

10 An “autonomous” vessel is a vessel that is designed and configured to travel across a body of water without needing a human on board or in constant active control at a remote location. It has a self-contained source of locomotive power. Navigation is controlled, either by a combination of sensors, electronics, and microprocessors aboard or at a remote location and in wireless communication with the vessel. The vessel may also be programmed to manage the ratio of locomotive power derived mechanically from wave action, and from an electric motor. It may also be programmed to control dampening of the action of fins on the swimmer.

20 A “tow buoy” is a storage container or equipment platform that is towed behind a vessel, attached either the float or the swimmer, and traveling on or below the water surface. The term does not necessarily indicate that the container or platform has a degree of buoyancy.

25 A “microprocessor” or “computer processor” on a vessel or control unit inputs data, processes it, and then provides output such as data interpretation or instructions to direct the activity of another apparatus or component. For vessels or units that have different data sets for processing in different ways, the microprocessor for each algorithm may be separate, but more commonly they are a single microprocessor configured and programmed to process each the different data sets with the corresponding algorithms when it is appropriate.

The wave-powered vessels described herein may be organized in fleets of two or more that interact with each other and/or with a central control unit. The terms “control unit”, “central control unit” and “control center” are used interchangeably to refer to an electronic assembly or combination of devices that receives information about one or more conditions of the water, the weather, or other aspects of the environment at one or more locations, makes decisions about where it is appropriate to distribute fertilizer or another substance from one or more distribution vessels, and sends instructions to the vessels in the fleet accordingly. The control unit may be placed anywhere on shore within range to receive and transmit data and instructions, or it may be aboard one of the vessels in the fleet, optionally integrated with the microcircuitry of that vessel.

While specific embodiments have been described and illustrated, such embodiments should be considered illustrative of the subject matter described herein and not as limiting the claims as construed in accordance with the relevant jurisprudence.

**EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:**

1. A wave-powered vessel, comprising:

(a) a buoyant vessel body;

5 (b) a mechanical means for converting movement of the vessel body caused by wave motion to horizontal thrust;

(c) a mechanical means comprising an electrical generator for converting movement of the vessel body caused by wave motion to electrical power; and

10 (d) a separate mechanical means comprising an electrical generator for converting horizontal movement of the vessel body through water to electrical power.

2. The wave-powered vessel of claim 1, wherein the mechanical means (c) comprises a piston powered by a swing arm that moves from a horizontal to a vertical position in accordance with the vertical movement of the vessel body.

15 3. The wave-powered vessel of claim 1, wherein the separate mechanical means (d) further comprises a rotatory fin or turbine powered by horizontal movement of the vessel body through the water.

4. The wave-powered vessel of any one of claims 1 to 3, wherein mechanical means (b) comprises:

(i) a swimmer; and

20 (ii) one or more tethers connecting a vessel body to the swimmer;

wherein the swimmer is weighted to travel in water below the vessel body, and is configured to pull the vessel body by way of the tether, the swimmer comprising a plurality of fin surfaces that mechanically provide forward thrust when actuated by rising and falling of the swimmer in the water.

5. The wave-powered vessel of claim 4, the swimmer is adapted so that motion of the fin surfaces may be dampened to increase electrical power generated by the electrical generator.
6. The wave-powered vessel of any one of claims 1 to 5, further comprising an electrically powered motor to provide horizontal thrust to the vessel through the water.
7. The wave-powered vessel of any one of claims 1 to 6, comprising a rotatory fin or turbine adapted to generate electrical power when rotated in one direction, and to act as a motor providing horizontal thrust to the vessel through the water when rotated in the opposite direction.
8. The wave-powered vessel of claim 6 or claim 7, comprising a battery configured to store electrical power generated by the electrical generator and feed electrical power to the motor to provide horizontal thrust to the vessel through the water.
9. The wave-powered vessel of claim 8, further comprising one or more solar panels supplying electrical power to the battery.
10. The wave-powered vessel of claim 8 or claim 9, wherein the battery powers the motor and provides horizontal thrust to the vessel alternately with thrust powered by the wave motion so as to buffer the thrust powered by the wave motion.
11. A wave-powered vessel, comprising:
  - (a) a buoyant vessel body;
  - (b) a propulsion system that is structured to mechanically convert movement of the vessel body caused by wave motion to locomotive thrust;
  - (c) a first generating system that is structured to convert vertical movement of the vessel body caused by wave motion to electrical power; and
  - (d) a second generating system that is structured to convert horizontal movement of the vessel body through water to electrical power.



- 5
12. The wave-powered vessel of claim 11, wherein the first generating system comprises an underwater component that is tethered to and weighted to be suspended below the surface component such that wave motion on the body of water causes the surface component to rise and fall relative to the underwater component, said motion being harvested by the first generating system to produce electrical power.
  13. The wave-powered vessel of claim 11, wherein the second generating system comprises a rotatory fin or turbine that rotates in response to horizontal movement of the vessel body through the water, said rotation being harvested by the second generating system to produce electrical power.

10

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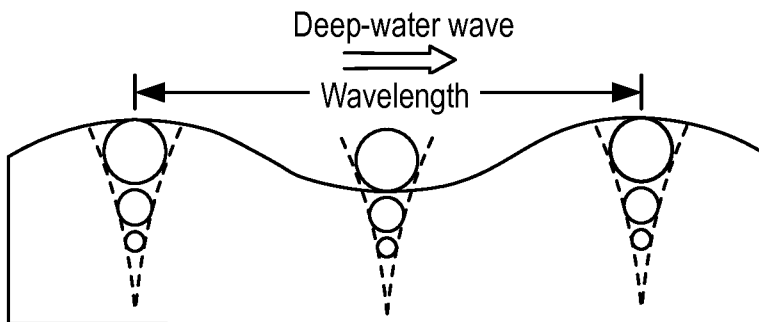


FIG. 1A (Prior Art)

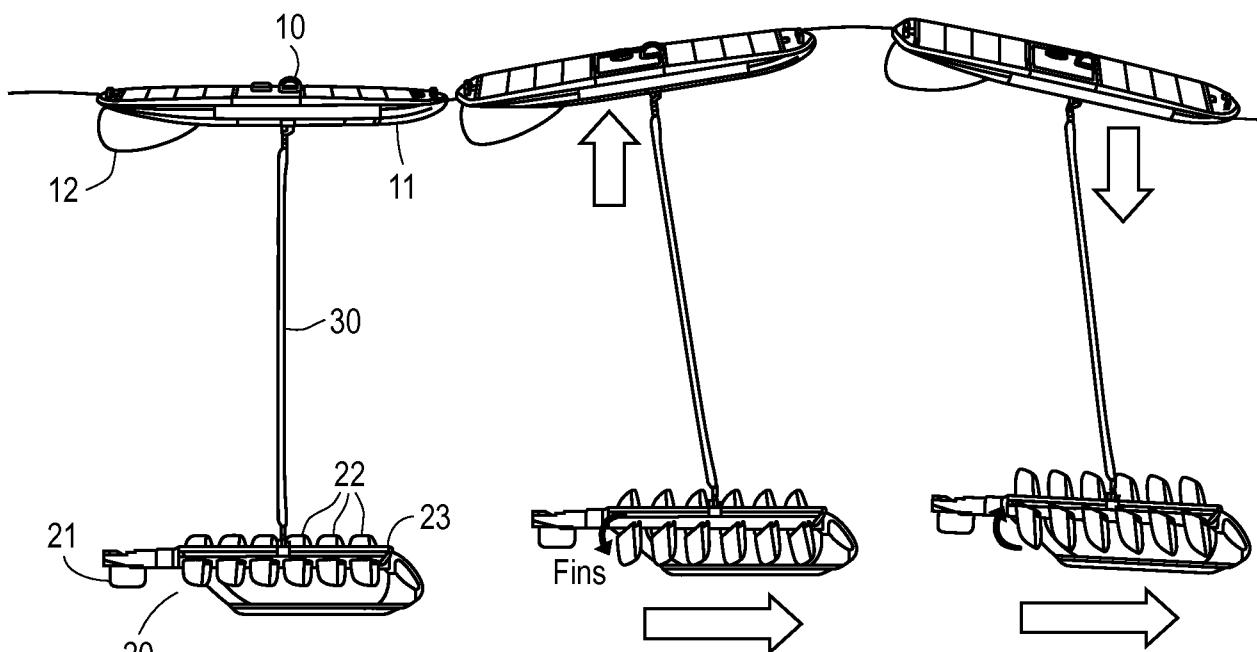


FIG. 1B (Prior Art)

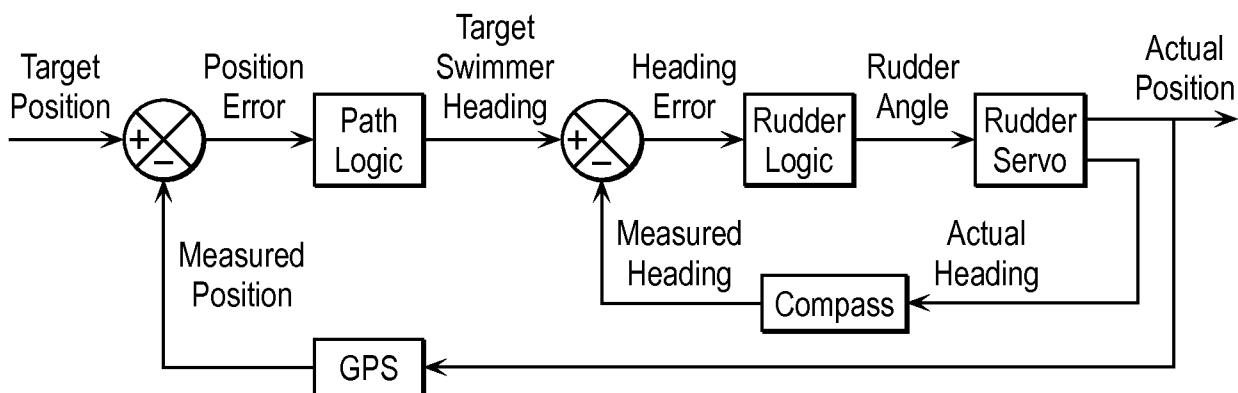


FIG. 2 (Prior Art)

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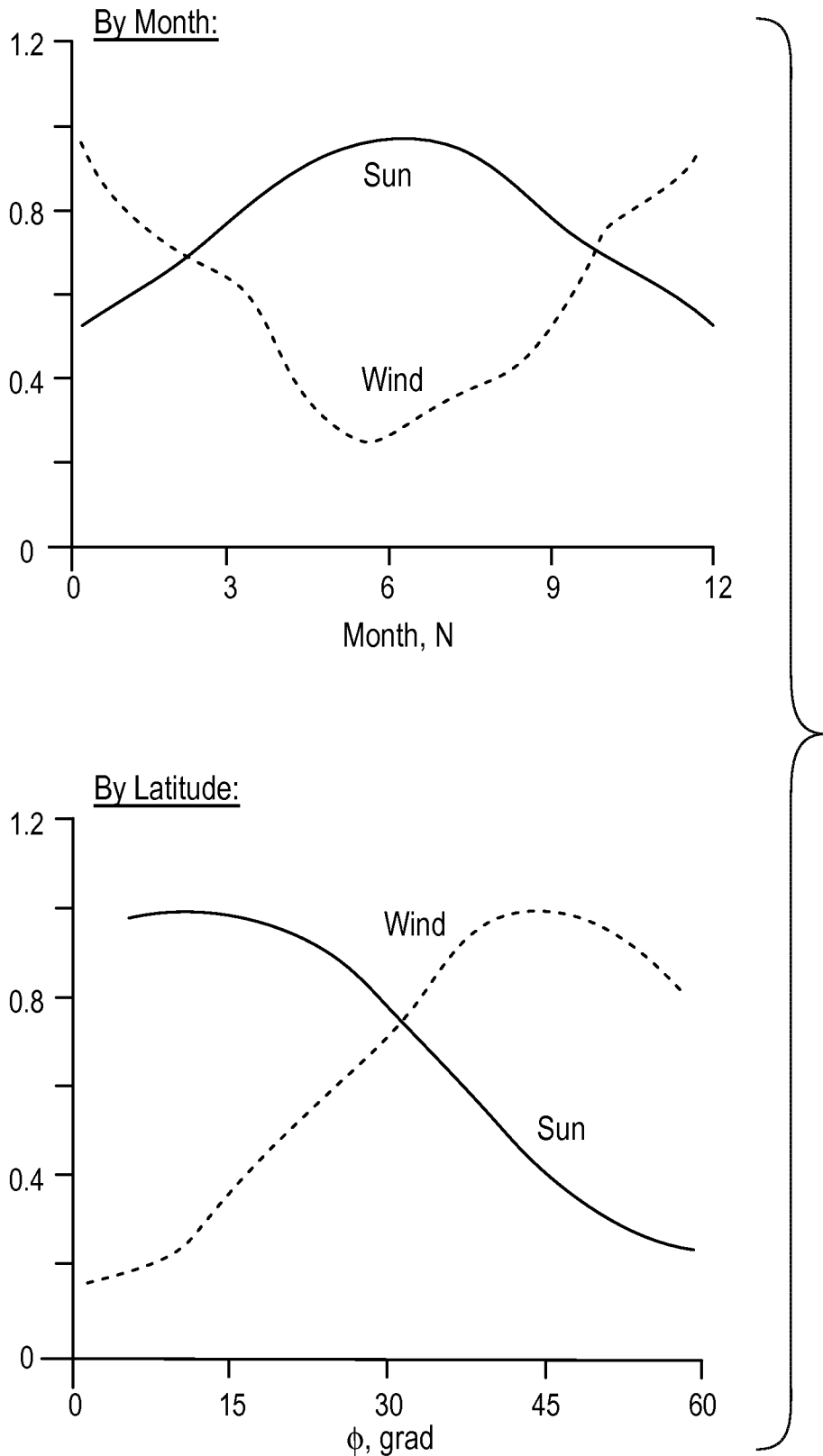


FIG. 3

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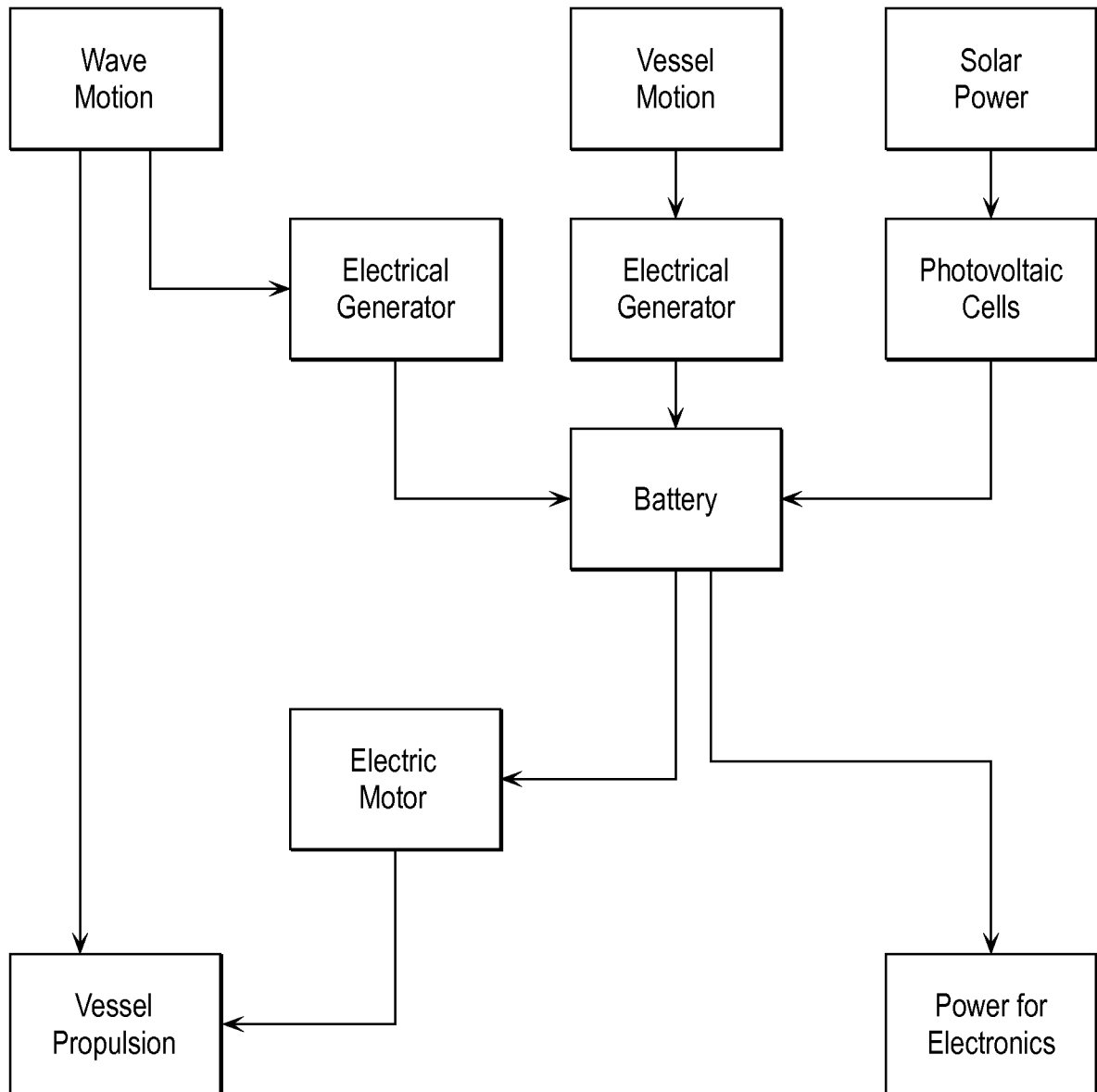


FIG. 4

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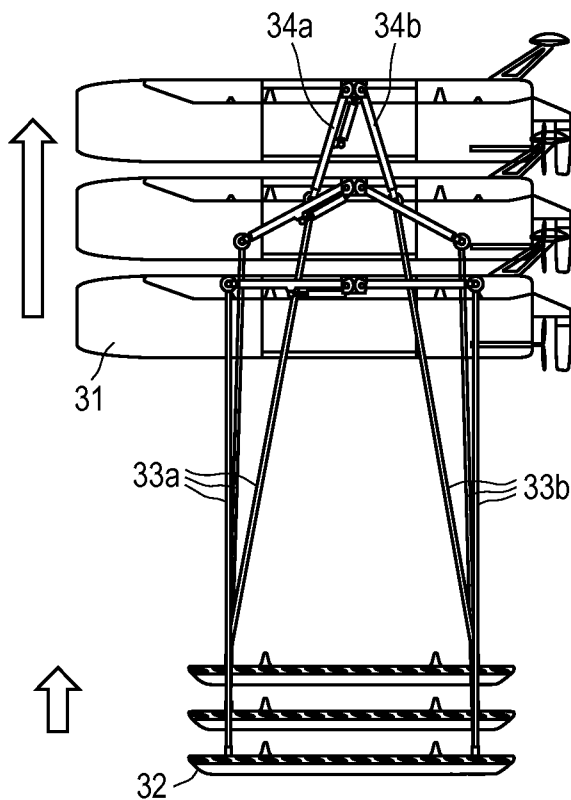


FIG. 5A

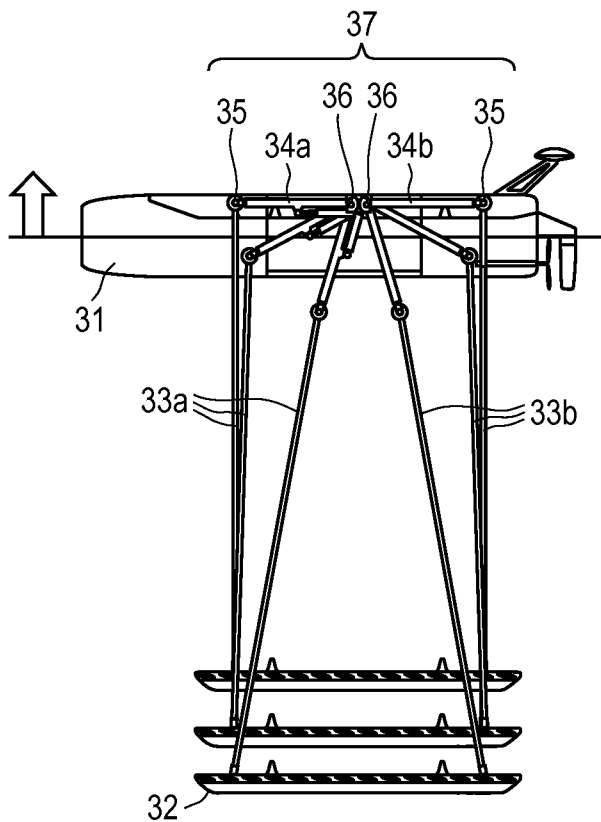


FIG. 5B

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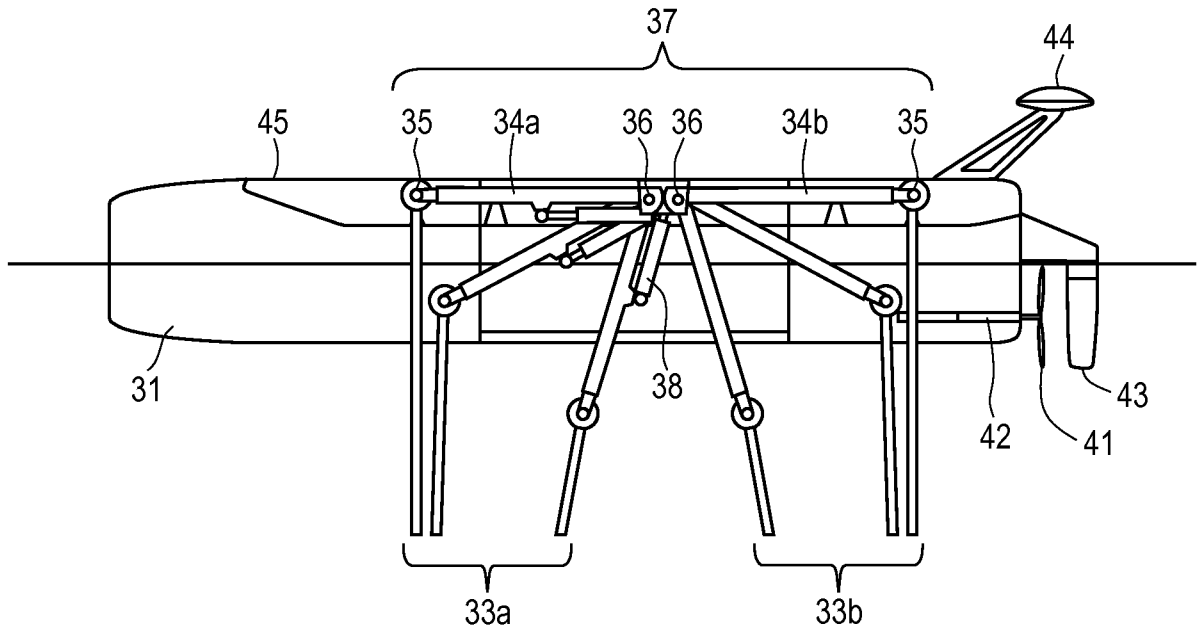


FIG. 6A

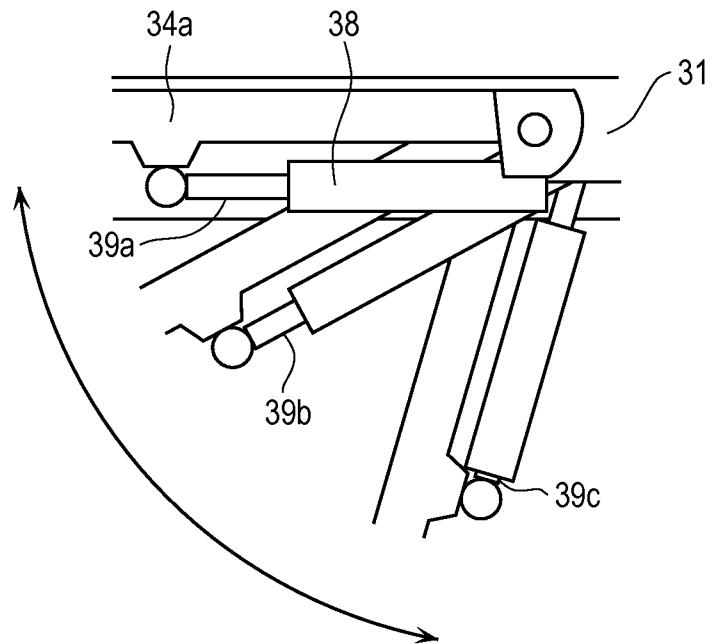


FIG. 6B

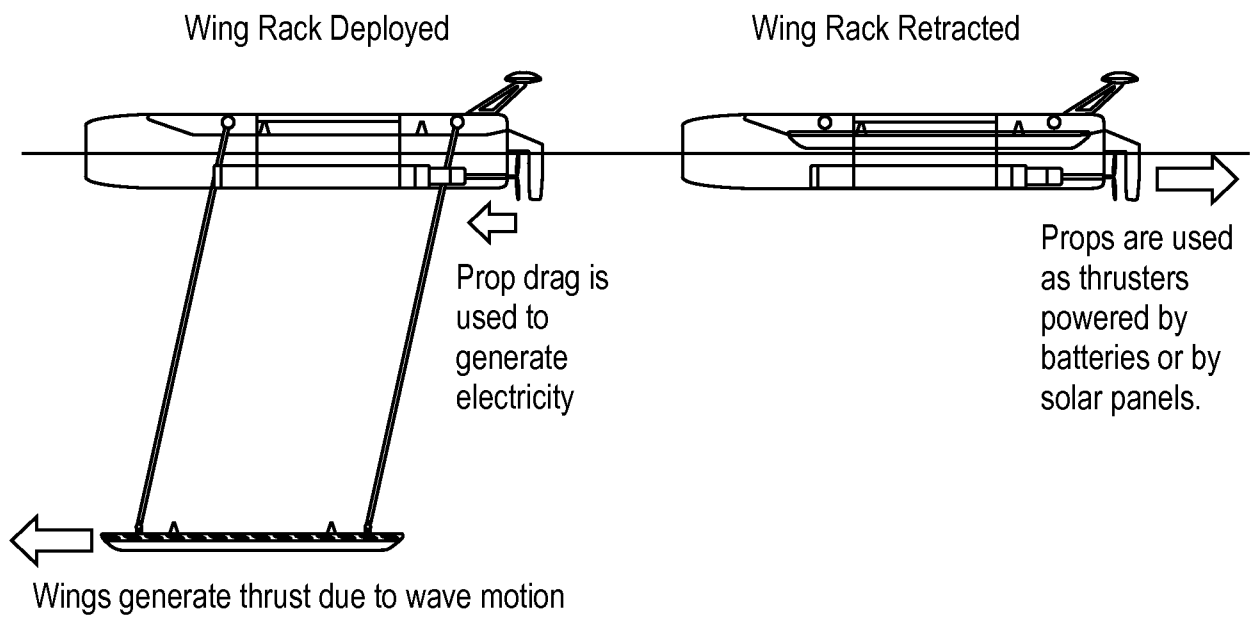


FIG. 7

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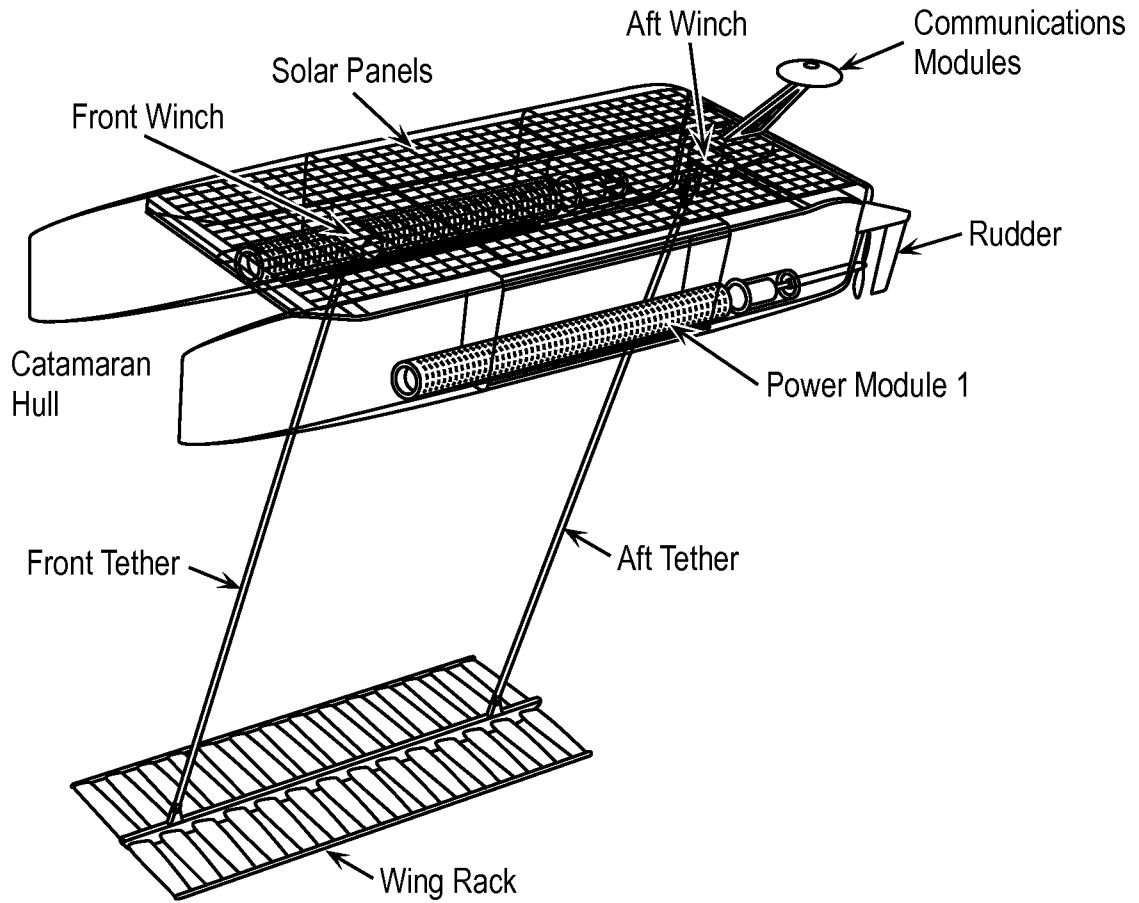


FIG. 8A

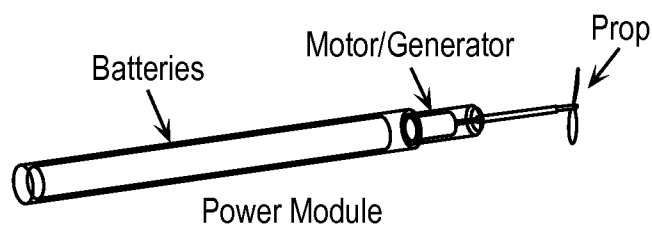


FIG. 8B



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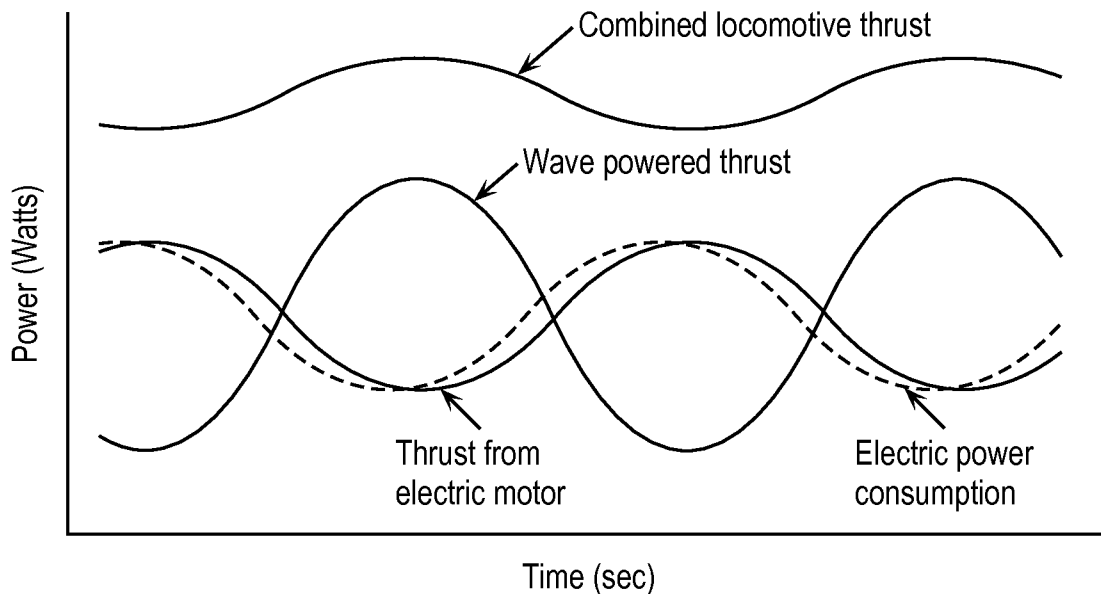


FIG. 9

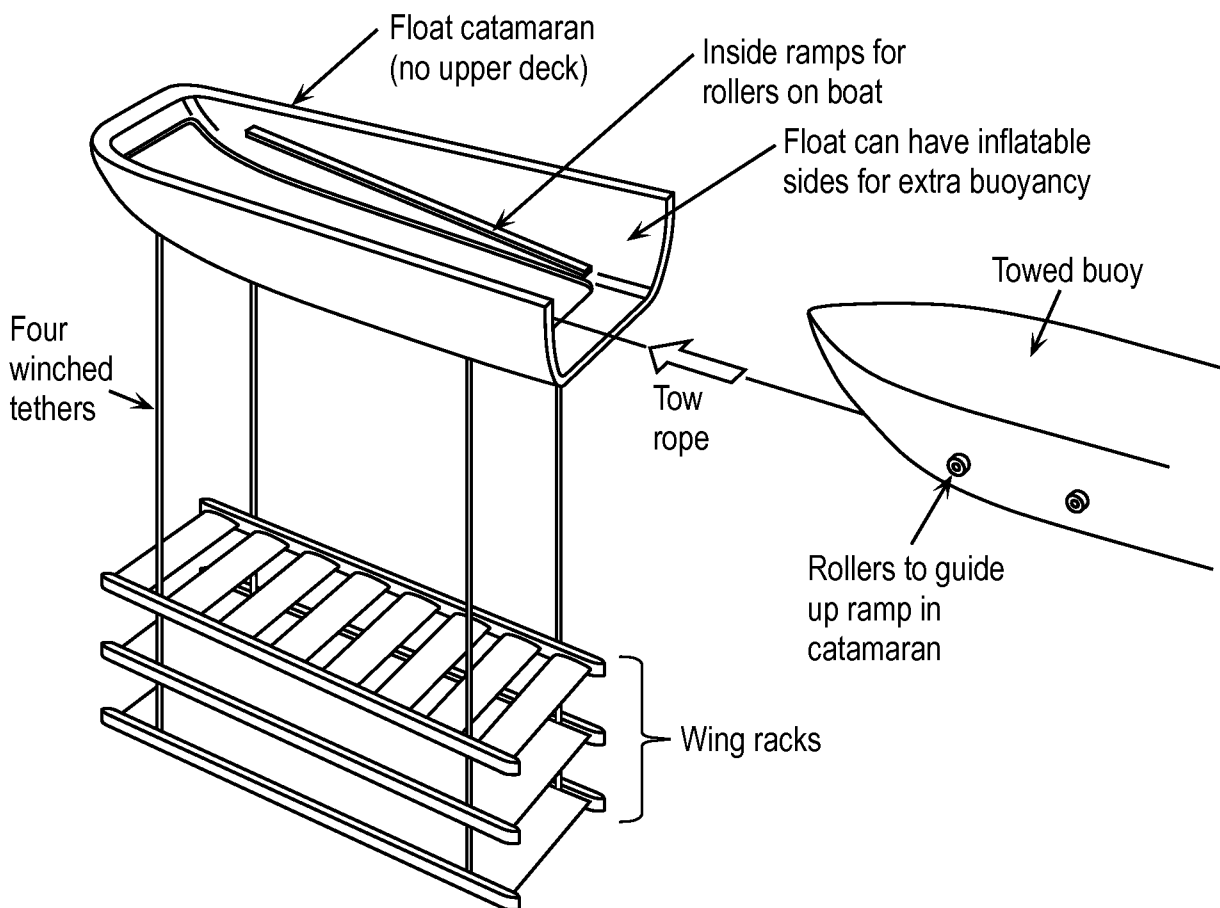


FIG. 10

