MARCo: Solar Powered Autonomous Robotic Unmanned Surface Vehicle

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Abstract

Autonomous sailboats have demonstrated that a robot could potentially perform long-term ocean monitoring and traveling. However, self-operating sailboats in the past had sails, which could lead to issues caused by tipping and heeling too much, and were not fully solar powered, which leads to short power endurance issues. Energy efficient and low cost autonomous robotic unmanned surface vehicle, named MARCo (Marine Autonomous Robotic Communicator), was programmed, developed and tested throughout the year 2018 in a public, co-educational university in Morehead, Kentucky. An off-grid solar system, comprised of 3x 20-Watt 12-Volt panels and a 12-Volt charge controller, was designed, constructed, and installed on a 6ft surfboard to make it solar powered and increase power-endurance with the help of a power management algorithm written in Python. The boat is based on Raspberry Pi, a set of navigation sensors, and a ROCKBlock Iridium Modem. The project has been successful in building a solar-powered, sail-less, autonomous unmanned surface vehicle. The boat was tested in diverse marine environments (Eagle Lake, KY and an indoor pool) and the results showing the overall performance of our boat durability and energy consumption is presented.

Introduction

Unmanned Surface Vehicles (USVs) are fast, highly maneuverable, stable, and resistant vehicles that operate on the surface of water without a crew. USVs play important roles in performing tasks limited to manned vehicles, such as bathymetry, tracking large sea mammals for research studies, meteorological monitoring, maritime search and rescue, and depth measurements of oceans, seas, and lakes.[3] USVs are crucial because they are a cheaper but effective alternative to weather buoys, and research vessels; USVs reduce labor costs and increase productivity by reducing direct and indirect operating costs from humans.[14] Early USVs were developed at the MIT Sea Grant College Program in 1993, and these USVs were capable of testing the autonomous navigation and control systems.[15] Since the early 2000s, robotic USVs have been built with the aim of performing long-term autonomous ocean monitoring. However, none appear to be sail-less or solar powered.[11]

Although having a sail on a boat stabilizes it and uses wind power to propel it, there are disadvantages to using sails on USVs. These disadvantages include challenges in storing the boat, maintenance costs breakdowns, and stress during bad weather.[2] We were thus motivated to build a sail-less solar charged autonomous USV boat. The main advantages of building a boat on a paddleboat or a surfboard include, affordable price of $746, a small size of 72”x26”x17”, and low weight of 24.13kg. This designed boat presents 97.23% less danger in terms on length and a complete reduction of the likelihood for accidents caused by force of wind/wake and hull failure. This USV is intended to be a low-cost alternative to other robotic sailboats like the Autonomous Robot for Rapid Transit and Ocean Observation (ARRTOO).[8,13]

In this paper, we describe the construction of the boat, the electrical components of the boat, hardware and software developments, and its design decisions. While building the boat, the goal was to design a small-sized, lightweight, and a low budget sail-less autonomous boat that as an USV could manage its power and perform long term testing under strong ocean waves, storms, and turbulences.

Methodology

In this section, we introduce the design and implementation details of MARCo and highlight key characteristics of the autonomous navigation system. Figure 1 shows the outlook of MARCo. The three main components of the vehicle include: solar power system, autonomous navigation, and sensor package implementation.

A. Hardware and components

Raspberry Pi 2011.12 is used as the main computer of the system.[12] It runs the main program, which is written in Python programming language. The Raspberry Pi communicates with other boards to work autonomously. Other significant hardware includes USB GPS, ROCKBlock ROCK7 Iridium Satellite Communication Modem, and Arduino Micro as shown in Table I.

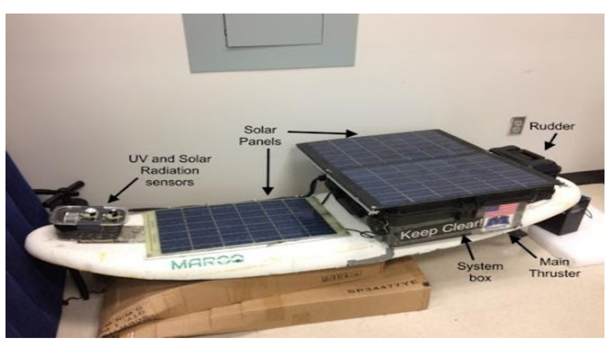

Figure 1. MARCo autonomous unmanned surface vehicle.

Hardware Components	
Development Board	Raspberry Pi 2011.12
Rudder Servo	Waterproof Servo Driver DS3218
Main Battery	Renogy 12V 18AH Battery
Charge Controller	Genasun 5 Amp 12 Volt MPPT Solar Charge Controller
Panels	3x 20W 12V Panel
GPS	GlobalSat BU-353-S4 USB GPS Receiver
Electronic Speed Control	EZRUN 18a ESC
Main Thruster	Bluerobotics T200
Board	6ft Surfboard
Main box/case	Pelican Case 1500
Second Board	Arduino Micro ATMega32u4
Voltage Converter	KNACRO DC 12V to 5V 3A Convert
Camera	ELP 2.1mm Wide Angle Mjpeg 5megapixel Hd Camera USB

Table 1. Hardware Components.

B. Software

At the beginning of the project, the software was developed in the C programming language and tested on an autonomous remote control (RC) car powered by Arduino. Once the software was successfully tested on the autonomous RC car, it was transferred to the boat.

An RC car was chosen for two main reasons. Firstly, the ground speed of the RC is similar to the surface speed of the boat when it is powered by two brushless DC motors. Speed plays an important role in the software development because the software must be able to accurately change the velocity of the vehicle and turn it at a particular angle. Therefore, robust software capable of rapid and accurate changes is needed. Secondly, software changes such as debugging and error handling may be easier with the RC car than the boat due to better accessibility. Furthermore, it is simpler to keep the electronics of the RC car safe from water.

Software for the boat has a main Python program that runs at boot up. The main program interacts with the USB GPS module, ROCKBlock Rock7, the sensors, rudder, and the thruster. A flow chart for the main program is shown below in Figure 1. The definition "multiplePoint()" plays an important role in the program: specifically, it manages all pinpoints and directs the boat to its next destination.

C. Design approach

3D design of MARCO is shown below in Figure 3. To make the boat as light and as small as possible, a 6ft foam surfboard was used. The boat has one 20" x 16" x 8" box for electronics, controllers, and the power system. This box was installed on top of the boat's back half to balance the total mass, which ensures a more optimal location of the mass' center. Inside this box, L shaped enclosures were installed to protect the lead acid battery. The battery is laid on its back, thus allowing it to remain undamaged if the boat flips or tilts.

The second box was for the camera, UV (ultraviolet) radiation sensor, and the solar radiation sensor. This box was placed far from the main box and at the the very front of the boat to allow the camera to have a better view and the sensors to access better sunlight.

The thruster and the rudder were installed in the back beneath the surfboard to maximize the turning force and the thruster power. The rudder was designed proportionally to the length and the weight of the boat.

Two fins were placed near the rudder and the thruster, to minimize the sideways motion.[4] The solar panels were placed on the box and the boat, which allowed them to intercept the most sunlight.

In Figure 3, "A" points to three 12V, 20W solar panels. "B" points to the 6ft surfboard which was used as the main body. "C" points to the main system box which stores the lead acid battery, Raspberry Pi, GPS module, charge controller, and Iridium Satellite Communication Module. "D" points to the rudder box which stores the waterproof servomotor. "E" points to the rudder system which is shown in Figure 4.

D. Power System

1) Components

As shown in Table I, the boat has three 12 volts 20-watt solar panels for its main power systems. A lead acid battery was chosen because of its low cost per kilowatt-hour of $131/kWh,[9] ability to charge at extreme temperatures from -20°C to 50°C,[6] and its low self-discharge of 5% per month.[5]

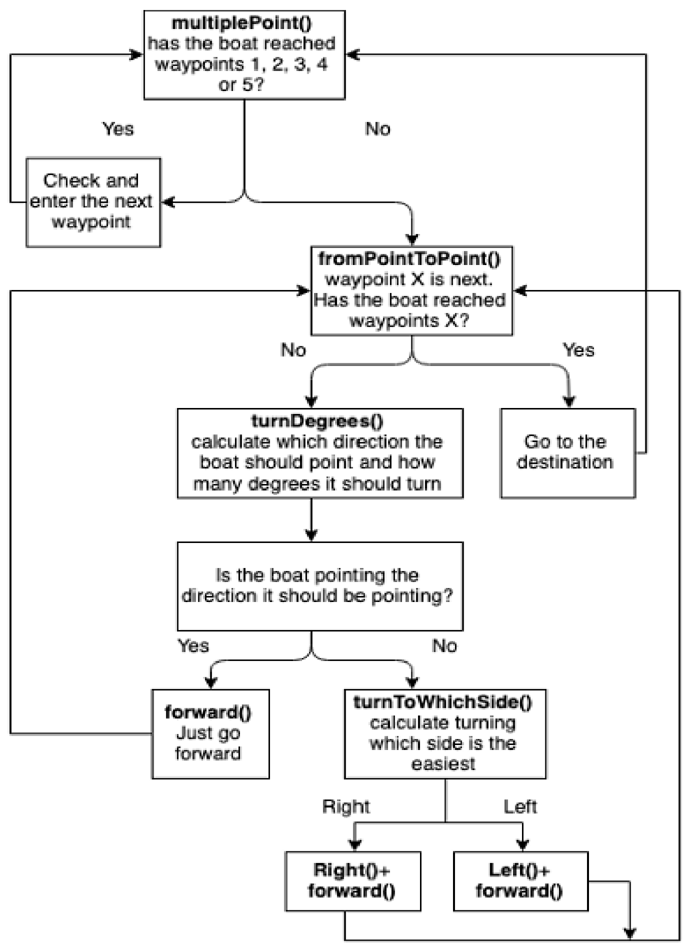

Figure 2. Flow chart for the autonomous Python program of MARCo.

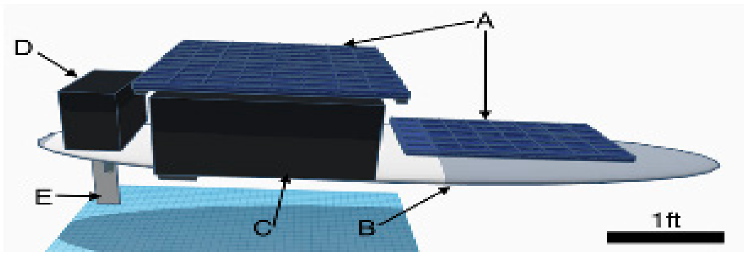

Figure 3. 3D design of MARCO.

Sensors	Info
DS18B20 x3	Temperature Sensor Probes
MPU6050 3 Axis Gyroscope Module	Accelerometer
UV Sensor Davis 7841	UV Sensor
Solar Radiation Sensor Davis 7821	Solar Radiation Sensor
INA219 Current Sensor x2	Current and Voltage Sensor

Table 4. Sensors installed in the boat.

For example, compared to a Lithium-Ion battery's cost per capacity, and charge temperature, the lead acid battery's cost per capacity ($/kWh) is 75.28% cheaper, and the lead acid battery's charge temperature is 20°C lower and 5°C higher, respectively. The battery was chosen for the system's overall power consumption of 36W minimum per day and average cumulative energy of 214.57Wh from the solar panels.

2) Consumption

At night, the system consumes about 0.7 amps with the thruster off. During the day, depending on the voltage of the battery and the power generated by the current, the thruster can spin at different speeds and power consumption varies as shown in Table III. Total current consumption of the whole system varies as the speed and current consumption of the thruster varies depending on the given Pulse Width Modulation (PWM) signal as shown in Table II. Pulse Width Modulation is highly efficient with low power loss to use electricity to control analog devices such as motors and lamps. The pulse-width modulation technique controls the average value of voltage delivered to the motor by switching between power-on and power-off at a fast rate. The main thruster Bluerobotics T200 takes only PWM signal to spin. Moreover, everything except the thruster runs at 5V, while the thruster runs on 12V.

Pulse Width(PWM) Signal Input to ESC(μs)	Current consumption of the thruster (A)
1500	0.07
1550	0.07
1600	0.37
1650	0.64
1700	0.92
1750	1.15
1800	1.37
1850	1.565
1900	1.76

Table 2. PWM Signal Input to ESC(μS) and corresponding current consumption.

3) Management

A specific power management system was developed: a voltage-based and sunlight power-based management system as shown in Table IV. MARCo's power endurance is 48 hours in the dark with the thruster off and unlimited in the sun.

4) Sensors

Table 4 lists the sensors of the boat, most of which are installed on the outside of the box. Although the majority of the sensors do not interfere with the performance of the boat, they give us data which could be used in the future. Because the Raspberry Pi does not have analog pins [10], Arduino Micro was used to control the UV (ultraviolet) radiation and the solar radiation sensors.

5) Rudder System

Given the unique properties of the boat, a unique rudder system needed to be developed. The whole rudder system was installed inside a waterproof box. The "skeg-hung rudder" is programmed to turn about 45° to the left and right. A waterproof DS3218 servo motor was chosen for the rudder system. The servo motor is attached to a gear which is connected to a rod as shown in Figure 4. "Straight leading edge" design was chosen because it is known to be mechanically stronger.[7]

6) Navigation algorithms and tracking

The boat uses five waypoints to navigate autonomously to any given location. The boat will follow a user defined path which consists of five waypoints. Relative to the current latitude and longitude coordinates, the algorithm, specifically the turnDegrees() function, keeps calculating the exact direction in degrees the boat is supposed to travel to reach the next waypoint in the shortest amount of time. As soon as the boat reaches its desired waypoint, the next waypoint will be entered as its new destination. For example, researchers, professors, and students can define a path that goes through areas where the research needs to be conducted. The boat will closely follow this path and collect needed data. The Global Positioning System (GPS) plays a crucial main role in the autonomous navigation system developed from first principles, which include complicated autonomous navigation tasks. These concepts and the accompanying problems were broken down into basic elements of reasoning and navigation and then the algorithm was built ground up. Figure 2 shows the autonomous navigation algorithm as a flowchart. The navigation system was tested thoroughly on an autonomous RC car before installation. The testing was performed on an RC car prior to installation due to its ground speed and debug accessibility as per discussed above in Section II.

Overnight in 12 hours	During a day
0.6 Amps * 5 Volts * 12 Hours = 36 Watt-hours	Depends on the generated solar power

Table 3. MARCO's power consumption.

Five combinations of latitude and longitude [(38.190703, -83.430098), (38.190819, -83.430197), (38.190821, -83.430376), (38.190679, -83.430466), (38.190554, -83.430340)] were entered and the RC car was expected to reach five waypoints one. The RC car did not have to be near or at one of five waypoints. Once the system turned on, it immediately navigated to the first waypoint. On average, it took the car two to three turns to point to the direction of the next waypoint. As soon as the system was within a two foot range from the latitude and longitude location, it counted the waypoint as reached. After reaching the fifth waypoint, the RC car started navigating to the first waypoint.

Tracking can be done using the Iridium satellite modem. Every two hours, the boat sends a message that includes its latitude, longitude, temperature, information from

The voltage of the battery(V) VS generated solar current (mA)		<100mA	100mA - 300mA	300mA - 500mA	500mA+
Battery Voltage (V)	Battery Percentage				
5.1V - 12.1V	System OFF	Thruster OFF	Thruster OFF	Thruster OFF	Thruster OFF
12.1V - 12.5V	0-50%	Charging State	Charging State	Charging State	Charging State
12.5V - 12.6V	50%-60%	Charging State	Charging State	Charging State	1550 PWM
12.6V - 12.7V	60%-70%	Charging State	Charging State	1550 PWM	1600 PWM
12.7V - 12.8V	70%-80%	Charging State	1550 PWM	1600 PWM	1650 PWM
12.8V - 12.9V	80%-90%	1550 PWM	1600 PWM	1650 PWM	1700 PWM
12.9V +	90%+	1600 PWM	1650 PWM	1700 PWM	1700 PWM

Table 5. MARCO's power management system.

the sensors, tilt, and information about its power. By the same token, messages can be sent to the boat. From anywhere on Earth with a clear view of the sky, MARCo sends short messages which consist of bytes.[1]

Results

In this section, we present experimental results based on 24 hours of testing. Overall, the system weighted 24.13 kg, and dimensions were 72”x26”x17”. The system had the weight capacity of 66.59 kg. To evaluate our algorithms and systems, several experiments were conducted with real robot systems. Performance was evaluated by plotting and graphing on Google Maps and Google Sheets, respectively. Real robot tests, including autonomous and sensors testing, were conducted at a marine environment; meanwhile, the solar panel tests were conducted on land. Performance of the boat’s power management was evaluated by observing whether the boat charges enough using the solar panels and how efficiently it manages its energy.

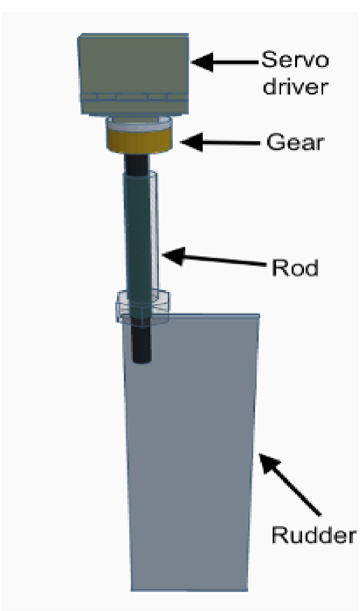

Figure 4. Rudder System as designed in 3D ThinkedCAD.

A. Solar panels testing

The solar panel testing was performed by placing the panels outdoors in direct sunlight. Panels were connected to the battery the whole time. Raspberry Pi, with the help of the INA219 sensor, recorded the current the panels are generating. Figure 5 shows power generated by the off-grid solar system on an average sunny day. The average power generated was 2.86 Watts and the average voltage was 10.84V throughout the day.

B. Autonomous testing

MARCo was tested at Eagle Lake (38.193491, -83.434520) in Morehead, KY. Four to five waypoints were given and MARCo was expected to go to each destination and return to the starting point.

As a result, the autonomous program worked well as intended. It completed 4-5 laps in an hour, traveling at about 1.5m/s. The boat’s autonomous system is considered to be ready to perform long-term autonomous travel as long as solar energy is available. As discussed in II. Methodology, the boat can survive 48 hours with no sunlight and the thruster off. However, the distance the boat can travel depends on the solar power it gets as well as the current battery voltage. Other than the amount of sunlight it receives, there is no limit on how long or far the travel can occur. As long as there is sufficient solar power generated and enough battery voltage, the boat will keep traveling at different speeds as shown in Table IV.

C.Sensors testing

Sensors were tested with the whole system. Sensors took accurate readings according to sunset and sunrise. Readings changed as the environment temperature changed. Results, which are plotted, can be seen in Figures 6, 7, 8 and 9 below. The testing was done between 6 PM on the first day and 6 PM on the second day.

A correlation between battery voltage and solar charging was recorded. For instance, around 12 PM, the solar panels generated about 150mA current as shown in Figure 8. As a result, the voltage of the battery stopped dropping and stayed at 11.8V or above.

Another correlation was recorded, specifically the external temperature and MARCo’s Raspberry Pi’s CPU temperature (°C). As shown in Figure 9, the temperature at the lake started dropping below 0°C around 4 AM. This resulted in a temperature drop in the internal temperature of the box and temperature of MARCo’s Raspberry Pi’s CPU (central processing unit) as shown in Figure 9 and Figure 10.

Conclusions

The low-cost, lightweight, and a small sized sail-less unmanned surface vehicle MARCo was designed, constructed and thoroughly tested.his solar-powered MARCo boat shown in Figure 1 was built based on three main components: solar power, autonomous navigation, and sensor package implementation. This solar-powered MARCo boat shown in Figure 1 was built based on three main components: solar powering, autonomous navigating, and sensor package implementation. Powered by a 12V 18Ah battery and three 20W 12V panels, MARCo autonomously navigates and records data through a path given in latitude

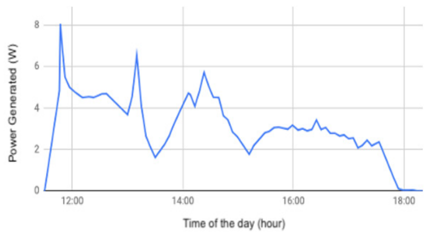

Figure 5. Power generated by three 20W 12V panels. Tested on 9/21/2018.

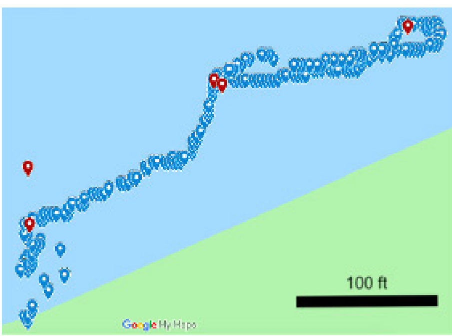

Figure 6. Path MARCo took during 5-waypoint testing at Eagle Lake. A waypoint is a specific location on Earth given in latitude and longitude. A longer path can be broken down into multiple waypoints. Between waypoints, the algorithm finds the shortest path between two points (current location and next waypoint) and tries to stay on that path. Waypoints play a crucial role in breaking the total path into smaller, shorter paths for the algorithm.

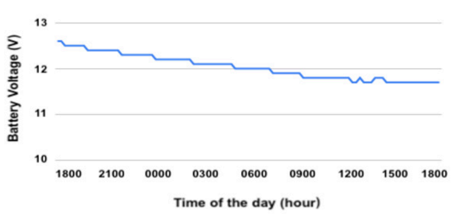

Figure 7. MARCo's battery voltage as it survives a 24-hour test on a cloudy day. At 9 AM, the battery voltage ceases to drop as the solar panels start generating energy as shown in Figure 5 and 7. This shows the battery voltage drops the most when the solar panels are not generating any energy due to absence of sunlight or at night.

and longitude coordinates. With its small size, light weight and lack of a sail, MARCo may be viewed as an alternative to other solar-powered USVs – such as Autonomous Robot for Rapid Transit and Ocean Observation (ARRTOO) – which operate autonomously on the surface of the water. This work has outlined the construction of the solar-powered USV MARCo and proposed the testing involving it. Our future work is aimed at adding Machine Learning to the software and developing an obstacle detection and avoidance system based on LIDAR sensors and cameras with the help of Deep Learning algorithms.

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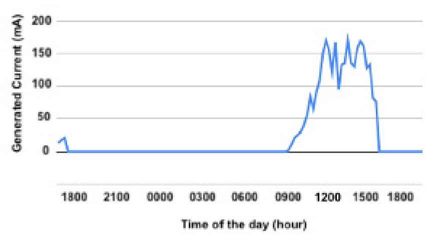

Figure 8. Generated current by the panels as it survives a 24-hour test on a cloudy day. The graph shows the most solar energy productive hours are between 9AM and 5PM. The average generated current was 29.78mA throughout 24 hours and 103mA between 9AM and 5PM.

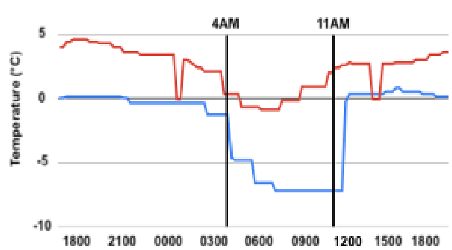

Figure 9. Air temperature (blue) and the temperature inside the box (red) as MARCo survives a 24-hour test on a cloudy day. Monitoring the box or the battery temperature is crucial as all battery capacities drop drastically at low temperatures. The graph shows the battery environment reaches its lowest temperature between 4 AM and 11 AM. Based on this, it is best for the system to perform minimal tasks between 4 AM and 11 AM.

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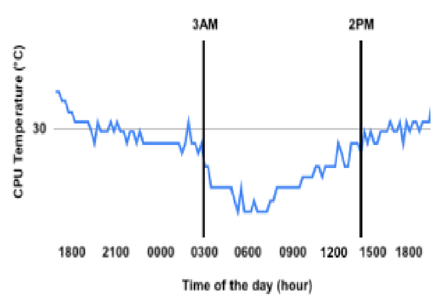

Figure 10. MARCo's Raspberry Pi's CPU temperature(°C) as it survives a 24-hour test on a cloudy day. This shows the direct effect of the environment temperature on the CPU. The CPU temperature drops drastically past 3 AM and rises back to an average of 30°C at 2 PM. It is crucial to measure the CPU temperature as the board can behave differently at extreme temperatures.

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