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Design of an Arduino-Based Boat Roll Stabilizer System Prototype Using MPU6050 Sensor

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Abstract

In the midst of lakes or oceans, boats used for recreational fishing that are left immobile are more vulnerable to rolling waves or wind. This study was conducted to develop a prototype of the boat's stabilization system and control scheme in order to address the stability issue with the craft. Based on the prototype concept, a small boat was constructed with a control loop that included two DC motors, a motor driver, a gyroscope MPU6050, and an Arduino Uno microcontroller. A prototype stabilizer was used to evaluate two different sets of control parameters, and in both situations the stabilizer was able to provide the boat with critical interference before bringing it back to a vertical position. PWM 1 level change rate (Pulse-Width-Modulation) yields better results than 4 level change rates (PWM), with faster stabilization achievement. (1,12 seconds versus 2,46 second). In the development of the prototype, it is necessary to test the implementation of the system on the boat to the actual size.

Keywords*: Boat Stabilizer, Digital Control, MPU6050, Roll Angle*

Abstrak

Perahu yang dipakai untuk rekreasi memancing saat berada dalam kondisi stasioner di tengah danau atau laut, lebih rentan mengalami gulingan akibat angin atau ombak. Untuk memecahkan masalah kestabilan perahu ini, peneltiian ini dilakukan untuk menciptakan suatu prototipe sistem stabilisator perahu beserta skema kendalinya. Pada rancangan prototipe, dibuat sebuah perahu miniatur yang dilengkapi dengan lup kendali yang terdiri dari mikrokontroler Arduino Uno, giroskop MPU6050, dua motor DC, dan driver motor. Kontrol digital berdasarkan tanda kesalahan (*Error-Sign-based Controller)* dengan pembatas laju perubahan digunakan untuk mengontrol stabilisator. Dua set parameter kontrol diuji pada prototipe stabilisator dan dalam kedua kasus tersebut stabilisator berhasil membawa perahu kembali ke posisi tegak setelah diberi gangguan kritis. Laju perubahan 1 level PWM (*Pulse-Width-Modulation*) memberikan hasil lebih baik dibandingkan laju perubahan 4 level PWM, dengan pencapaian stabilisasi yang lebih cepat (1,12 detik berbanding 2,46 detik). Pada pengembangan prototipe, perlu dilakukan uji implementasi sistem pada perahu dengan ukuran sebenarnya.

Kata kunci: Stabilisator Perahu, Kontrol Digital, MPU6050, Sudut Guling

Introduction

Moving people or products from one location to another is known as transportation, and it has become essential to economic expansion. Transportation that is safe and secure is a necessary component of industry and commerce-related activities. The National Transportation Safety Committee (KNKT) was established by the government of the Republic of Indonesia in 1999 [1] with the goal of achieving transportation safety and enhancing transportation services. One example of how the government recognizes the value of safety in all forms of transportation, including land, sea, and air, is this committee. Water transportation is of strategic significance for Indonesia as an archipelagic state. This mode of transportation is instrumental in order to reach and connect the frontier, outermost, and least developed regions and to unify Indonesia [2]. Furthermore, water transportation using boats and small ships is also the most economical and efficient means for short-distance occasional trips (for recreational purposes) or regular commutes (between work and home) across shallow water such as rivers and lakes. However, water transportation through rivers and lakes is still accident-prone and requires more safety precautions. There have been several incidents of capsized boats due to waves and wind [3][4]. In such incidents the turbulence caused water to enter the boat, causing panic among the passengers, worsening the stability of the boat before capsizing it, and inflicting fatalities. In another situation, a traditional riverboat used by recreational fishers rolled and collapsed after being unable to maintain its stability due to the wash of a passing vessel [5].

A boat stabilizer is a system that is necessary to lessen the rolling motion of a boat. A stabilizer, such a bilge keel or anti-roll water ballast, can be passive, meaning that no external power is needed. By raising the hydrodynamic resistance, the bilge keel lessens the roll of the boat but also impedes its forward propulsion [6][7]. However, the mass of the water ballast can be changed to accommodate the boat's present load. However, compared to other types of ballast, water has a low density, hence the tank needs more room. Fins and gyroscopes are examples of active stabilizers that require additional power and a unique control mechanism. They are favored because they are more efficient. Fins can be made to function at zero speed when the boat is at anchor or when it is moving forward [8][9]. Underway fins are designed to stabilize the boat while it moves, utilizing the movement of the water over the fins underwater to create the stabilizing force [10][11]. Fins at zero speed constantly move to adapt to the waves, current, and wind. A gyroscope is probably the most compact and effective type of stabilizer, not only for boats but also for robots [12][13]. Its disadvantages include being the priciest kind of stabilizer, hefty, and needing intricate maintenance.

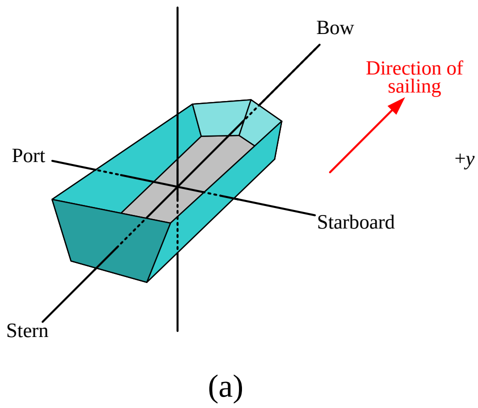
The aforementioned facts motivated the authors to design an active stabilizer with a suitable control scheme for a boat at anchor. Boat stabilizer systems have been investigated previously [14][15]. Santoso proposed the use of a flywheel and stepper motor to provide a counterweight to a boat [14]. The rotational speed of the flywheel is regulated by a controller module while its orientation is adjusted based on the angle read by an MPU6050 gyroscope. A stabilization attempt using servo motors and fins was proposed in [15]. An Arduino Uno microcontroller was used to regulate the fins' locations, which were installed on both sides of the boat. It was demonstrated that the roll angle had stabilized back to zero after the miniature boat was subjected to the disturbance.

Although it has never been studied before, the stabilizer design put forth by the authors of this research is tenable. The suggested stabilizer is made up of motor-driven propellers mounted on either side of a boat. The Arduino Uno controller, two sets of DC motors, propellers serving as actuators, and an MPU6050 gyroscope serving as a sensor make up the control loop. The control scheme was expected to regulate the propellers' rotation so that the generated forces could counter the boat's roll movement [16]. Additionally, a prototype boat that was scaled down was created, with dimensions that provided sufficient susceptibility to roll disturbance. Aerodynamics was not taken into account in the boat's design, which was a restriction. Furthermore, because the propeller position was always set, topics related to propeller tilt were not covered. Here, the authors' earlier proposal for an error-sign-based controller with a change rate limiter is implemented with various changes. After that, the boat is equipped with the prototype of the active stabilizer system. Ultimately, a number of tests are conducted to determine how well the complete system works to stop the boat from capsizing and lessen roll movements.

Method

a. Some Nautical Terms and Boat Stability

Some essential terms related to the position around a boat and its rotational motion are introduced here. Figure 1(a) shows the position around a boat, where *starboard* means the right-hand side of the vessel and *port* refers to the left-hand side. A boat moves in 3 degrees of rotational motion as shown in Figure 1(b). *Roll* is a rotation around the longitudinal *x*-axis, *pitch* is a rotation around the transverse *y*-axis, and *yaw* is a rotation around the vertical *z*-axis. The sign of a rotational motion is taken as positive when it is clockwise (as indicated by the grey circles), and negative otherwise.



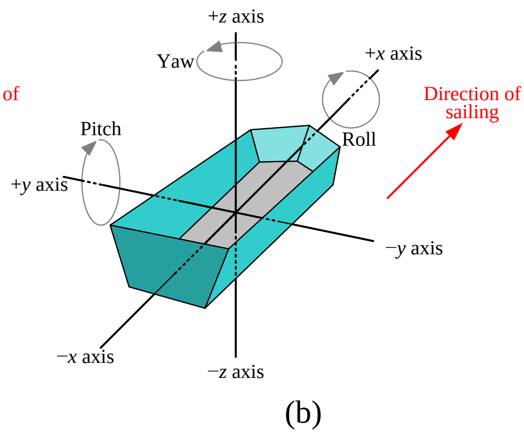
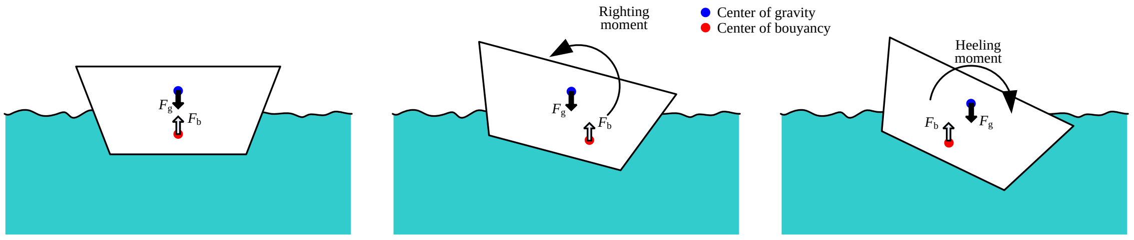


Figure 1. Some Nautical Terminologies of a Boat
(a) Directions; (b) Rotations

The stability of a boat is defined as its ability to return to an upright position after being tilted by external forces such as waves, wind, or change in weight distribution [17]. Examining 0(a), two forces act on a boat as it emerges on water: the downward gravitational force (F_g) acting on the boat's center of gravity (blue dot), and the upright buoyance force (F_b) acting on the center of buoyancy (red dot), which is the centroid of the displaced volume of water.



(a) (b) (c)

Figure 2. A Boat at Different Orientations due to Rotation:
(a) Upright Position, (b) Righting Moment; (c) Heeling Moment

If the boat is rolled to one side, the center of gravity remains in the same position but the center of buoyancy moves at the low side of the boat because the displaced volume of water is larger on the low side [18]. This situation is shown in 0(b). Both forces F_g and F_b now create a *righting moment* that will bring back the boat to an upright position. If the boat is further rolled over a critical angle, the center of buoyancy moves to a position where the so-called *heeling moment* will increase the roll angle of the boat, as depicted in 02 (c). Such a critical role angle is technically termed the *angle of vanishing stability*. When the boat's roll angle reaches this value, it cannot go back to its upright stable position anymore. On the other hand, it continues moving in the direction of increasing roll angle magnitude and capsizes.

b. Boat Roll Stabilizer and Control Scheme

In this paper, a roll stabilizer to create a counter moment and prevent a boat from capsizing. Two propellers are installed on the starboard and the port side of the boat. The motors that rotate the propellers are activated based on the measured roll angle. As illustrated in Figure 3, the boat is rolled in a positive direction (clockwise rotation). Then, to avoid capsizing due to the heeling moment, the stabilizer creates a counter moment F_m through the starboard unit by turning on the starboard motor and rotating the starboard propeller. On the contrary, the port unit is activated if the boat's roll is negative (counterclockwise rotation).

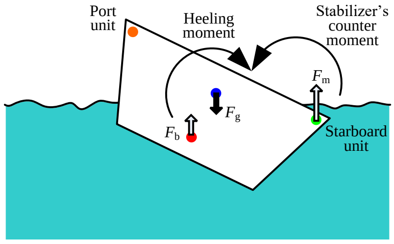


Figure 3. The Proposed Boat Roll Stabilizer Viewed from The Stern of the Boat

In this paper, an Error-Sign-based Controller (ESC) with a change rate limiter is employed as the controller of the boat roll stabilizer. This controller was first proposed in [19] and was proven to be able to avoid undesirable sudden changes in the control output that may lead to oscillations of system output or even hardware malfunction [20]. A modification was made to the controller, by integrating θ, in order to give a threshold angle for the controller. The control law of ESC is given in Eqs. (1) and (2):

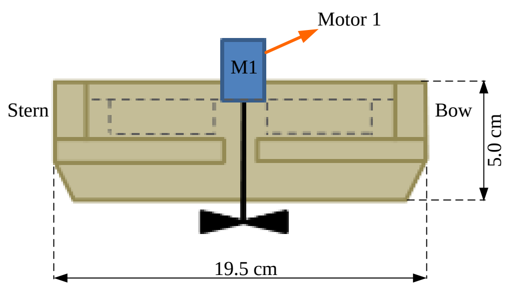
$$u_1(k+1) = \begin{cases} u_1(k) + c, & \text{sign}(e(k)) > 0 \text{ and } e(k) > \theta \\ 0, & \text{otherwise} \end{cases} \quad \text{.........................} \quad (1)$$

$$u_2(k+1) = \begin{cases} u_2(k)+c, & \text{sign}(e(k)) < 0 \text{ and } e(k) < -\theta \\ 0, & \text{otherwise} \end{cases} \quad \text{.........................} \quad (2)$$

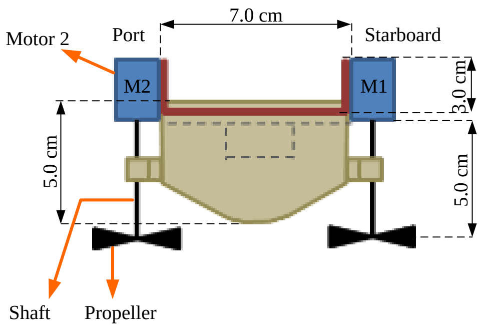
Where u_1 is the controller output for the starboard motor, u_2 is the controller output for the port motor, e is the control error, c is the change rate, and k is the discrete time instant. The control error e is the deviation between the 0° roll angle as a set point and the measured roll angle. In the beginning, u_1 and u_2 are set to zero. Based on the reading of the roll angle, the value of u_1 or u_2 is increased whether with a small change rate $c = \Delta a$ or a large change rate $c = \Delta b$. If the roll angle returns to a safe range of the threshold angle, the outputs of both motors are reset to zero. The control scheme will be further explained using a flow chart in the following subsection.

c. Miniaturized Boat Prototype

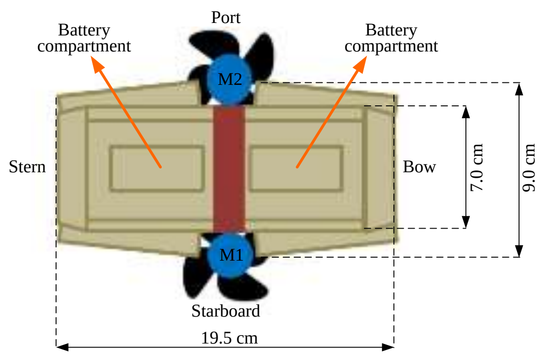
For the purpose of testing the proposed boat roll stabilizer system prototype, a miniaturized boat prototype was built. The schematic design of the boat can be seen in 04. The boat was made of lightweight extruded polystyrene foam. The dimensions of the boat are set to allow the boat to roll easily, while adequately stable in pitch and yaw. The stabilizer consists of two 6 V DC motors with 5 W power and a maximum rpm of 10,000. Plastic propellers are connected to the motors using 5-cm metal shafts, as indicated in Figure 4(b). Two battery compartments were prepared, as indicated in 04(c).



(a)



(b)



(c)

Figure 4. Boat Prototype Design:
(a) side view, (b) rear view, and (c) top view

d. Block diagram, flowchart and wiring diagram

The block diagram of the proposed boat roll stabilizer system prototype is shown in 05. The red arrows signify a high-current power flow, while the blue arrows represent a low-current power flow or an information flow. Although they are not shown, the diagram includes the sensor, the processor, the actuators, and the power source.

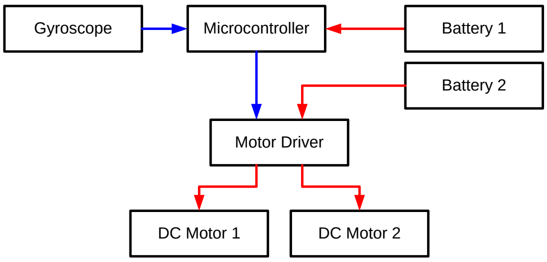


Figure 5. The Block Diagram of the Proposed System

The roll angle of the boat is measured by the MPU6050, as depicted in 06, which is a three-axis accelerometer and three-axis gyroscope with a Micro-Electro-Mechanical System (MEM). An MPU6050 IMU chip makes up the MPU6050 module. Its dimensions are 4 mm × 4 mm × 0.9 mm. It is packaged in a 24-pin QFN format. I2C pull-up resistors, bypass capacitors, and an AP2112K 3.3V regulator are among the components in the module. In addition, a power LED that shows the module's power status is included.

Subsequently, the roll angle is processed by the Arduino Uno microcontroller, where the control scheme program is uploaded. An Arduino Uno is an ATmega328P-based microcontroller board. It features a 16 MHz ceramic resonator, 6 analog inputs, 14 digital input/output pins (six of which can be used as PWM outputs), a USB port, a power jack, an ICSP header, and a reset button.

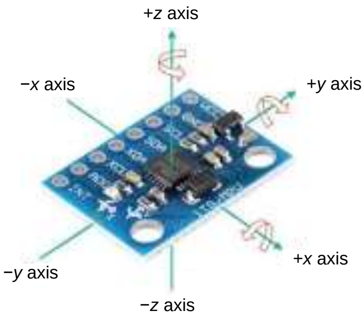


Figure 6. The MPU6050

The microcontroller calculates the voltage to be inputted to the DC motors and transmits it to the L298N motor driver in the form of a Pulse-Width-Modulation (PWM) signal. The 8-bit PWM values from 0 to 255 are the mapping of 0% to 100% of the motor voltage. The motor driver L298N is a DC motor driver module used to control the speed and direction of the motor. This module finds a wide range of applications in electronics and is frequently connected to an Arduino microcontroller. The IC L298N is an H-bridge type integrated circuit that can control inductive loads in devices such as solenoids, relays, DC motors, and stepper motors. The IC L298N utilizes a transistor-transistor logic (TTL) with NAND gates that serves to change the direction of a motor, either a DC motor or a stepper motor.

Furthermore, the L298N driver ensures adequate voltage and current for the DC motors, since the microcontroller operates at 5V with a maximum continuous current of

20 mA, whereas the DC motors operate with a maximum of 6V and 40 mA. The DC motors used by the prototype generated a torque of 0.40 mN·m. Its shaft diameter is 2 mm while the rotor diameter is 8 mm, with a maximum rotational speed of 10,000 rpm at the power rate of 5 W. The whole system is powered by two 9 V, 280 mAh batteries. The flowchart of the proposed system is presented in 07. Once the program starts, the gyroscope of the MPU6050 is to be initialized. The roll angle is measured when the connection between the sensor and the microcontroller is established. The Error-Sign-based Controller (ESC) was implemented with 2 values of change rate, small increment $c = \Delta a$ and large increment $c = \Delta b$. One of the values is applied to a certain motor based on the sign and the range of the roll angle, as shown in the flowchart. Afterward, the change rate value is added to the respective motor voltage. The designated motor voltage is applied to the motor by the motor driver. If the roll angle is back to the threshold region $-10° \leq x \leq 10°$, then the voltages of both motors is reset to zero. The discrete-time instant of the controller is represented by an integer k.

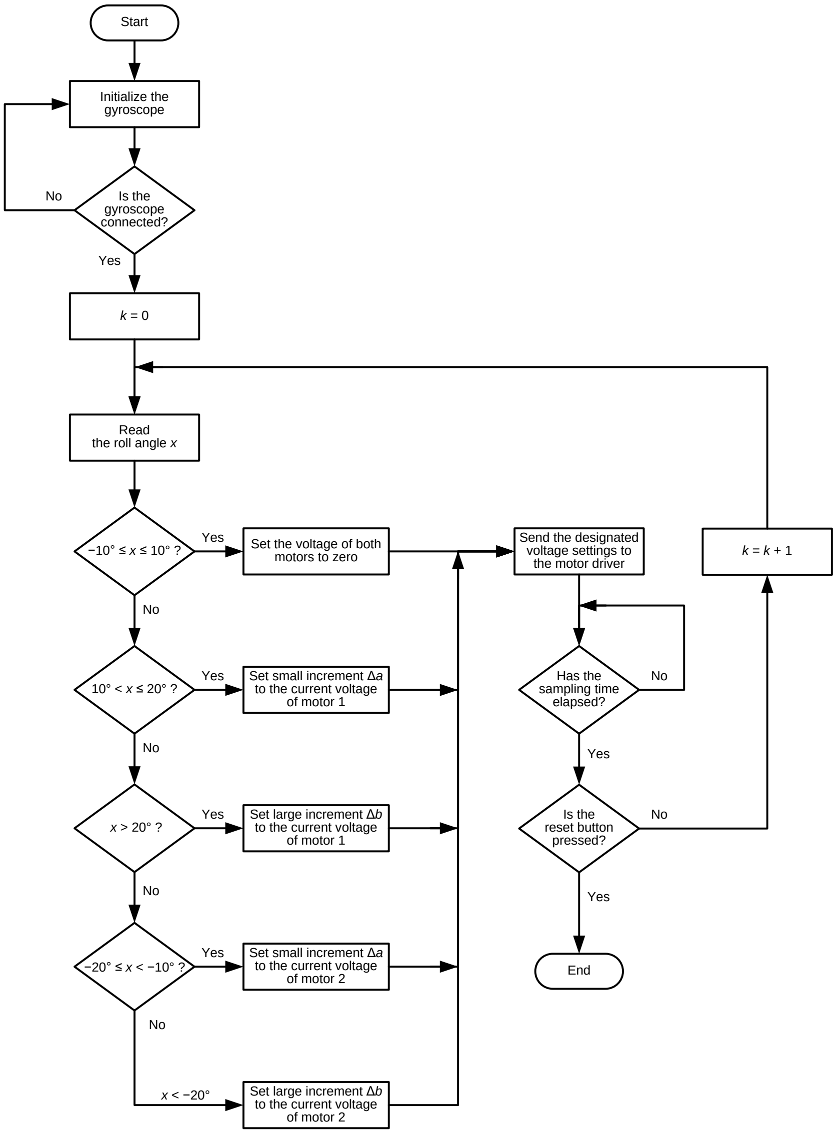


Figure 7. A flow Chart of the Proposed System

The interconnection among the parts of the boat roll stabilizer system prototype is shown in 08 in the form of a wiring diagram.

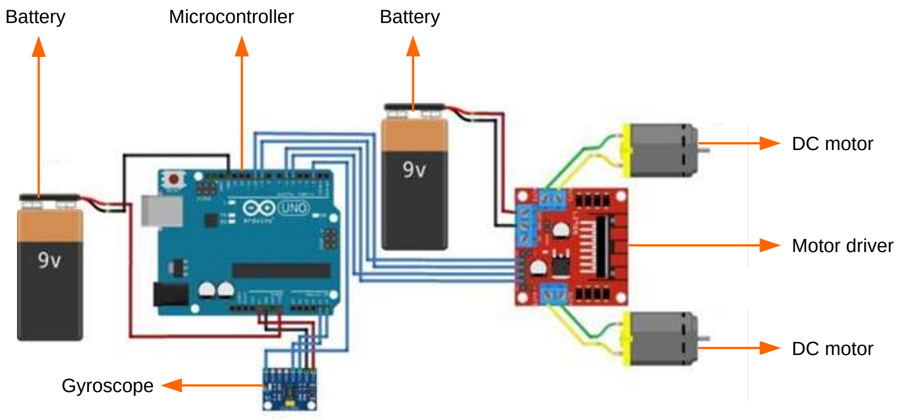


Figure 8. A Wiring Diagram of the Proposed System

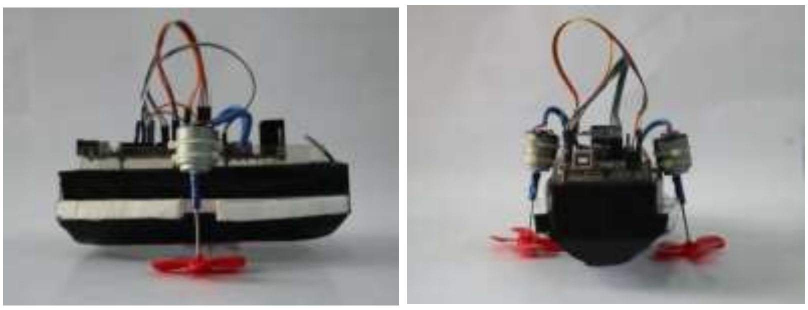
e. Gyroscope calibration

Before the implementation, the gyroscope was calibrated in two steps: zero offset adjustment and sample roll angle measurements. In zero offset adjustment, the gyroscope is placed on a flat and non-rotating surface. Ideally, the respective angles of rotation for the roll, pitch, and yaw are zero on such a surface. It turns out that when the gyroscope is turned on and is placed on the same surface the roll, pitch and yaw angles of rotation are different from zero. The sensor was initialized and the angles were read for 5 seconds with a sampling time of 8 ms. Afterward, the average angle of rotation measurements representing roll, pitch and yaw were calculated giving the zero offset constants. Subsequently, the three constants were integrated into the control program of the system. In a sample roll angle measurement, the gyroscope was tested to measure the angles between 0° and 90° with an increment of 15°.

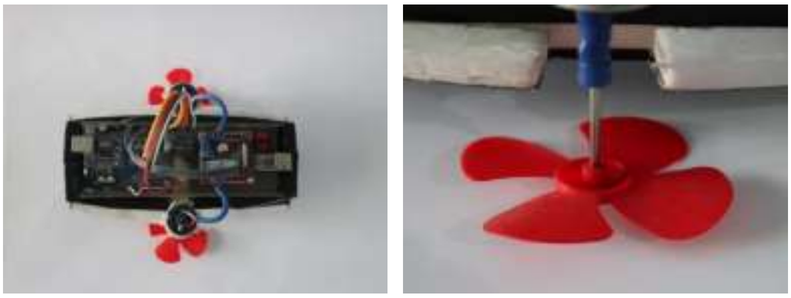
Results and Discussion

a. Construction of the miniaturized boat prototype

The components that are described in the previous section were assembled to build a miniaturized boat prototype as depicted in 09. The Arduino microcontroller was placed in the stern area, while the motor driver was located in the bow area. The motor driver was mounted close to the port motor.



(a) (b)



(c) (d)

Figure 9. The Miniaturized Boat Prototype: (a) Side View, (b) Rear View, (c) Top View, and (d) the Shaft and the Propeller

b. Gyroscope calibration

As was mentioned previously, ideally a flat and non-rotating surface must have a zero angle of rotation associated with each of: roll *x*-axis, pitch *y*-axis and yaw *z*-axis. A zero offset adjustment was conducted successfully by initiating the gyroscope and allowing it to measure the angles associated with the three coordinate axes, respectively, on a flat and non-rotating surface. The average of the respective angles corresponding to measurement duration of 5 s with a sampling time of 8 ms were 5.60° (roll *x*-axis), 0.11° (pitch *y*-axis), and 1.12° (yaw *z*-axis). Thus, the rotation angle equaling 5.60° was an offset value, which was subtracted from all sample roll angle measurements.

The sample roll angle measurements were conducted from 0° to 90° at an increment of 15° with 5 trials for each angle. In order to achieve the objective of this sample roll calibration, the gyroscope was oriented to a certain angle of tilt. Such an angle of tilt was measured with the help of a protractor, as can be seen in 010. In this case, the protractor was glued to a wall to make the calibration process easy. The roll angles representing the protractor- and gyroscope-based angle of tilt measurements; and percent difference can be seen in Table 1. The overall average angle error is 0.534°. This corresponds to the average of the percent differences for roll angles between 15° and 90° was 1.21%.

Figure 10. Gyroscope Sample Roll Angle Calibration Utilizing a Protractor

Table 1. The Results for Seven Sample Angle Measurement

Measurement		Error	Measurement		Error
Protractor (°)	**Gyroscope (°)**	**(°)**	**Protractor (°)**	**Gyroscope (°)**	**(°)**
0	0.10	0.10	0	0.25	0.25
0	0.57	0.57	15	15.03	0.03
0	0.42	0.42	15	15.21	0.21
0	−0.23	0.23	15	15.54	0.54

Measurement		Error (°)
Protractor (°)	Gyroscope (°)	
15	14.57	0.43
15	15.17	0.17
30	30.62	0.62
30	30.55	0.55
30	30.41	0.41
30	30.24	0.24
30	29.87	0.13
45	44.22	0.78
45	45.05	0.05
45	45.70	0.70
45	45.81	0.81
45	45.24	0.24
60	60.12	0.12
60	60.84	0.84
60	60.41	0.41
60	61.65	1.65

Measurement		Error (°)
Protractor (°)	Gyroscope (°)	
60	60.54	0.54
75	74.34	0.66
75	75.05	0.05
75	75.24	0.24
75	75.78	0.78
75	76.72	1.72
90	90.54	0.54
90	90.65	0.65
90	90.52	0.52
90	91.60	1.60
90	89.12	0.88
Average error		0.534

c. Prototype testing

The capability of the boat roll stabilizer system prototype was evaluated. It was tested if it could prevent a miniaturized boat prototype from capsizing if a roll angle exceeds the critical angle. The dimension of the miniaturized boat itself already leads to low roll stability, making it easy to capsize at a small roll angle. 0 shows the small prototype boat while floating undisturbed on water. To find the critical roll angle, an experiment was conducted. With both motors turned off, the roll angle of the boat was recorded via the serial monitor with a sampling time of 8 ms. Then the boat was manually given a roll angle by tilting it to the side and then released. If the boat returned to the upright position, the experiment was repeated with a greater role angle. If the boat rolled further and was on the verge of capsizing, the boat's further rotation was halted and the respective roll angle was taken as the critical roll angle.

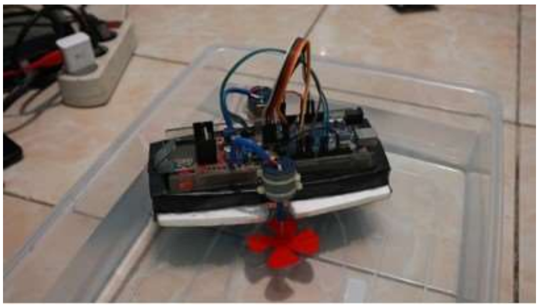
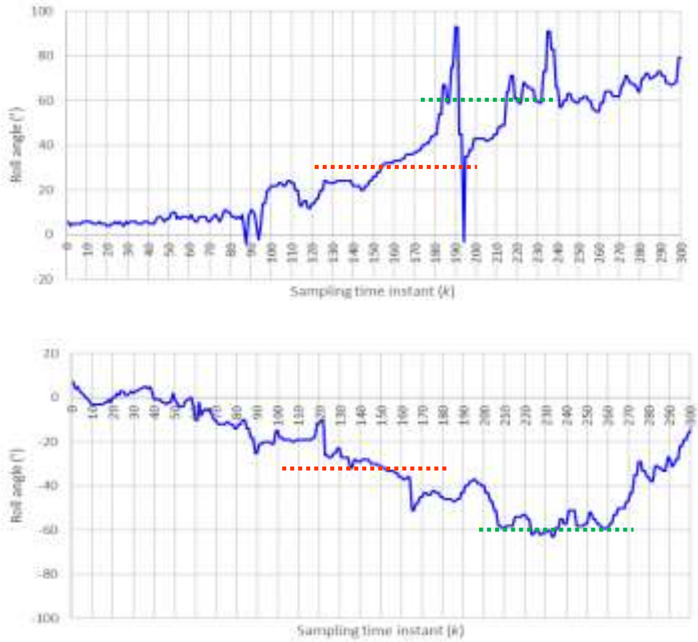


Figure 10. A Prototype Boat is Floating on Water

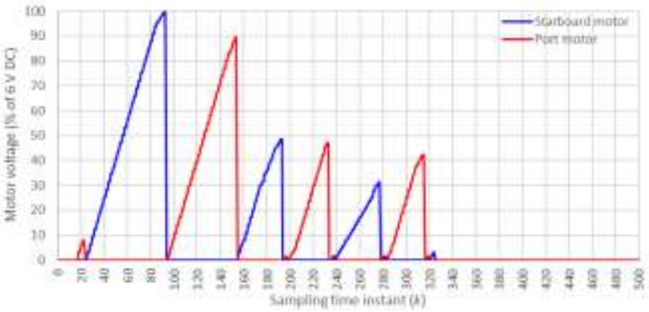
The results of the critical roll angle experiment are shown in 0. 0(a) represents the case where the initial roll was given to the starboard direction, while in 0(b) to the port direction. This experiment shows that the critical roll angle was approximately 30°, as indicated by the red dashed lines. When the boat was given a 30° initial angle of role and released, the angle continued to increase to ≥ 60° (as marked by the green dashed lines) or higher and had to be promptly halted by hand to prevent the boat and the whole hardware from sinking.



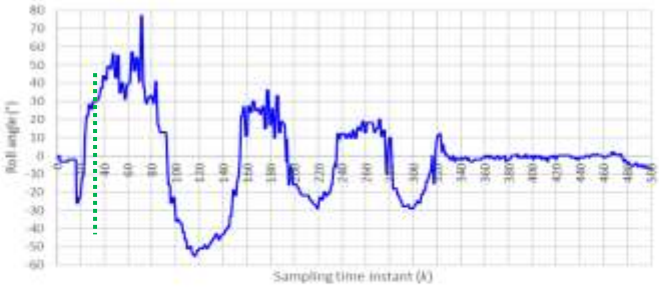
(a)
(b)

Figure 11. The Experiment to Find the Critical Roll Angle:
(a) Roll to Starboard Direction and (b) Roll to Port Direction

At this stage, the functionality of the proposed boat roll stabilizer system prototype was tested. The setting for the first experiment was Δa = 4 PWM levels and Δb = 8 PWM levels. The mapping of the PWM levels from 0-255 to 0-100% of motor voltage implies that an increase of 4 PWM corresponds to an increase of 0.094 V and 8 PWM to 0.188 V. In the experiment, the boat was given a tilt to the starboard direction, and the work of the stabilizer was observed. The result of the stabilizer system prototype with the first setting is shown in 0. The voltage fed to the motors is depicted in 0(a) while the roll angle is presented in 0(b). The vertical green dashed line in 0(b) indicates the time when the roll angle leaves the critical value of 30°. As can be inferred from 0(a), each of the starboard and port motors was turned on alternately four times between k = 18 and k = 325. There are four peaks for each color. This took approximately 307 time-instants or 2.46 s. Afterward, the roll angle could be fully maintained between −10° and 10° and both motors were never activated again.



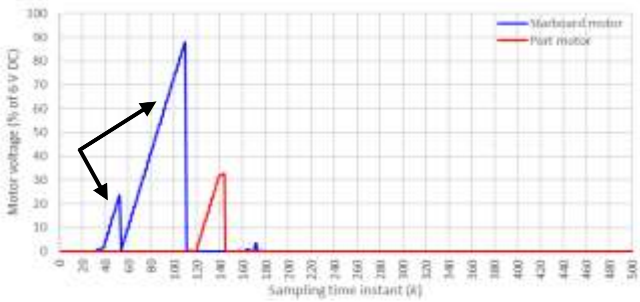
(a)



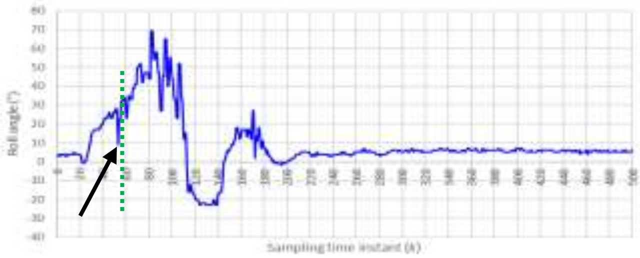
(b)

Figure 12. Test of the Roll Stabilizer System Prototype with the First Control Setting: (a) Voltage of DC Motors and (b) Roll Angle

The second experiment was conducted with Δa = 1 PWM level and Δb = 8 PWM levels. The result of the stabilizer system prototype with the second setting is shown in 0.



(a)



(b)

Figure 13. Test of the Roll Stabilizer System Prototype with the Second Control Setting; (a) Voltage of DC Motors and (b) Roll Angle

The voltage fed to the motors is depicted in 0(a) while the roll angle is presented in 0(b). The vertical green dashed line in 0(b) indicates the time when the roll angle leaves the critical value of 30°. The small value of Δa means that the change of motor voltage was made more gradually when the roll angle was within the range of $10° < |x| \leq 20°$. In total, there are only three sizable actions of the motors, compared to six in the previous test which used Δa = 4 PWM levels. The starboard and port motor were active between k = 30 and k = 170, which corresponds to 1.12 s.

The calibration process of zero offset adjustment was conducted smoothly. The correction constant of 5.60° for the roll angle helped significantly in improving the accuracy of the gyroscope. The obtained average angle error is 0.534°. The percent difference between the protractor-based roll angle measurement and that of the gyroscope for roll angles between 15° and 90° was 1.21%. With such a small percent difference between the two set of measurements, the gyroscope was found to be accurate to measure the roll angle in the boat roll stabilizer system prototype. In the subsequent test, the critical roll angle was found to be approximately 30°. After the initial roll angle of 30° was determined, the roll angle was increased further to 60°. The roll angle jumped up to around 90° at k = 190 before going down to a small negative value at k = 194 (0(a)). This jumping can be considered as an error due to incidental measurement outliers. This test thus confirmed that a boat roll stabilizer is required to avoid the capsizing of the boat.

During the stabilizer test with the first control setting, after giving the initial critical disturbance to the starboard direction, the proposed system needed 4 control actions from the starboard motor and 3 control actions from the port motors, as can be seen in 0(a). In 0(a), while the stabilizer worked with the second control setting, two consecutive actions of the starboard motors occurred, as indicated by the arrows. The reason for this is the bottom spike as pointed by the arrow in 0(b). The roll angle was measured to be within $-10° \leq x \leq 10°$ at this point and the controller instantly reset the starboard motor voltage to zero before afterward increasing the voltage again as the roll angle reentered the region of > 10°.

Based on the test results, it can be concluded that the stabilizer system prototype worked well in both settings. After the boat was given a tilt of which the tilt angle exceeded the critical angle, the controller was able to bring back the boat to the upright position. The second setting with a smaller change rate Δa = 1 PWM took 1.12 s to bring the boat back to the stable region. This duration (1.12s) is less compared to 2.46 s corresponding to Δa = 4 PWM in the first setting. Indeed, the contribution of the change rate Δb remains to be investigated. Its value was set to 8 PWM in both cases.

Conclusion

This study presented the design of a boat roll stabilizer with a change rate limiter and an Error-Sign-based Controller (ESC). Propellers situated on the boat's port and starboard sides make up the stabilizer design. The goal is twofold: to bring the boat back to an upright position and to apply additional force to counter any potential heeling moment. The suggested stabilizer system prototype was tested using a scaled-down boat prototype. The boat is powered by two 6V DC motors, two propellers, an Arduino microprocessor, an MPU6050 gyroscope, a motor driver, and polystyrene foam. The critical roll angle of the boat prototype was found to be approximately 30°, confirming that the boat needs a stabilizer to prevent it from capsizing. Subsequently, the stabilizer system prototype was implemented in two different control settings. The control setting with a smaller change rate (1 PWM level per sampling time) performed better than the one with a larger change rate (4 PWM levels per sampling time). The time interval between the start and the end of motor activity was reduced from 2.46 s to 1.12 s. Nevertheless, the stabilizer system prototype was successful in performing its task to maintain the boat's stability in the two cases of control settings.

The proposed stabilizer system prototype is especially well-suited for protecting boats at anchor from wind and waves when a stationary boat position is necessary, like recreational diving, snorkeling, or fishing. In the future, the stabilizer may be more suited for these kinds of uses, in which the propellers can be retractable to submerge them only when necessary. It is necessary to carry out additional tests to verify that the suggested design method and control strategy can be implemented in practice. A scaled-down boat and actuators with an accurate model-to-real-life ratio for the boat's dimensions, mass, motor torque, and motor mass will be needed for this. Finally, the implementation of the proposed system in a real-life boat will be the ultimate goal of the research. For this accomplishment, motors with adequate torque and testing in the real environment are necessary.

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