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ANALYSIS OF SINGLE-AXIS GYROSTABILIZER ON A SCALED-SIMPLIFIED-HULL MODEL FOR STABILIZATION

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Abstract:

Advancements in technology have led to the development of new mechanisms and systems for stabilizing marine vessels, with a focus on enhancing safety and stability to prevent capsizing incidents. Roll motion has been a critical factor in ship stability, as excessive rolling can lead to crew discomfort, decreased efficiency, and even capsizing. This paper outlines the development of Gyrostabilizer on a 3D-Printed Body of a Simplified Hull-Model based on Ground Testing that focusses on the hull's stabilization in rolling motion only. Gyrostabilizer design in the system is mainly to show how the difference in passive and active control of gyrostabilizer affects the efficiency of rolling reduction of the scaled-hull model as compared to when it is naturally rolled. This experiment's analysis is based on the goal of achieving the stability in static model of rolling motion, and discussions related to it are included in the paper. The method used in this research is force excitation from a side of the mechanism and force-pushing slider on the system. The research results encompass the gyro system with a passive and active control in providing a better roll reduction with the same amount of force excited from a side on the system. Averaging from all three tests for each control, a percentage of roll reduction of 14.81% and 33.93% was achieved when implementing passive and active control respectively.

Keywords:

Anti-rolling Device, Gyroscope, Gyrostabilizer, Rolling Motion, Vessel.

Introduction

Marine environment has a lot to explore especially when the water environment is covered about 70% of Earth surface, distributed exquisitely all around the globe. Amidst the evolving

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technology landscape, ship or vessel that originally maneuvered manually has been explored to be autonomously operated to assist human and carrying out job that is extremely dangerous and unsafe for workers such in an extreme and strenuous wave in mid-sea. A lot of operation in surface and underwater is happening such as berthing (Peter, 2021), bathymetry and surveying (Tomy et al., 2017), oil spill detection (Al Maawali et al., 2019), loading and unloading, transportation or any ship hull services (Nor Azman et al., 2022). In case of military application, a high-risk operation such as underwater mines detection (Tanakitkorn, 2019) and interrogation of suspicious waterborne vehicle are very much helpful in minimizing threat by limiting exposure of squad from encountering directly. Knowing that there are a lot of opportunity areas for ships to operate autonomously, it is important to ensure the safety and stability of the vessels to prevent those assets from being capsized due to unpredictable waves or external factor like strong wind that can lead to a huge loss to the business and agency (Kavallieratos et al., 2020)(Höyhtyä & Martio, 2020).

As marine vessel experiencing 6 Degree of Freedom (DOF) motion (Varela & Soares, 2011); translational (surge, sway, heave) and rotational (roll, pitch, yaw), lots of research had been focusing on rolling motion as it deemed to be the most critical and perilous motion to ship's stabilization as it can lead to crew discomfort and decreased vessel efficiency, potentially resulting in capsizing (Ayob & Yaakob, 2015) (Igbadumhe et al., 2020). In real sea conditions, excessive roll motion is a major factor in ship capsizing (Chai et al., 2022). To address the issues of rolling, a few solutions for roll stabilization for instances bilge keel, active fin, gyroscopic stabilizer and antirolling tank have been introduced. It is important to note that, irrespective of the type of stabilizer utilized, the most effective means of reducing rolling relies on the ability to minimize the duration of the rolling motion, aiming to reach a zero angle and maintain a stable, upright position for the ship (Alaswad, 2020).

Conventional large ships have bilge keel or fin-like protruding on the starboard and port side (Liu et al., 2018). This type of stabilizer is known as external stabilization devices as the mechanism is installed in the ship's outer body. They have a slight disadvantage of an inevitably susceptible to fluid, consequently compromising the performance at lower speed (Moaleji & Alistair, 2007). Gyrostabilizer or anti-rolling gyro (ARG) and anti-rolling tank (ART) are categorized as internal stabilization system as the mechanism installed on-board and has no effect of hydrodynamic drag. However, ART requires more space on the ship's deck and the structure incorporates a time delay to achieve equilibrium between the ship and the wave frequencies generated on the vessel's surface (Marzouk & Nayfeh, 2009). On the other hand, gyroscope is an instant stabilization device, that requires some space depending on the vessel size. Even gyroscope has been a long-existing engineering application, the advancement of contemporary technologies in materials, mechanical criteria, electrical drive enhancements, and control systems has generated a revived enthusiasm for ship gyrostabilizers (Perez & Steinmann, 2009). Hence, this paper focuses on the roll reduction testing of a gyrostabilizer mechanism on a hull model based on ground testing and incorporates the concept and theory behind it.

Utilizing active control in a Gyrostabilizer system has been proven to significantly reduce roll motion compared to passive control, highlighting the critical role of advanced stabilization mechanisms in preventing capsizing incidents (Chai et al., 2015) (Igbadumhe et al., 2020). Thus, by having a stabilization system installed on-board the vehicle, a long-range operating vessel could be set off confidently and securely. Additionally, a stabilized marine vehicle could

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help comfort crew on-board from experiencing seasickness and increase operational performance with a better sensor reading input reading due to less impact of ship rocking and swaying (Zhou et al., 2019).

Literature Review

Gyrostabilizer has been used widely in many applications including ground, marine and space (Townsend & Shenoi, 2011) such as for 2-wheeler vehicle (Gogoi et al., 2017), large vessel (Akpadiaha & Jeremiah, 2019) and space vehicle respectively (Yoon & Tsiotras, 2004). A gyroscopic stabilizer operates based on the principle of angular momentum conservation. It consists of a rapidly spinning disc mounted on an axis, which experiences a phenomenon called gyroscopic precession. When combined with the angular momentum of the flywheel, this precessional motion generates a stabilizing torque that counteracts the rolling motion of the body, allowing it to maintain an upright position. In simpler terms, the gyroscopic stabilizer is a rotating flywheel used to dampen the rolling motion of a body, such as a two-wheeled vehicle or an unmanned surface vehicle (USV).

The design of gyroscopic stabilizer can be classified into two distinct types; number of gyroscope and control. The number of gyroscopes could be uniaxial (one) and biaxial (two) commonly for any gyrostabilizer vehicular technology. When two gyroscopes are attached in parallel with their spinning and precession angles rotating in opposite directions, they could eliminate the gyroscopic moments that occur in other directions, specifically the pitch and yaw motion of the ship. This configuration effectively counteracts these unwanted gyroscopic effects (Sathit. et al., 2021). However, they also emphasized that while multiple uniaxial gyros can be installed, using three perpendicular gyroscopes can only stabilize in one direction. In addition, more gyroscopes orientation and installation mean volumetric place and weights added on the vehicle (Demİr, 2020), along with increase in power consumption on a system (Talha et al., 2017). The emergence of modern technology of control system enables researchers to explore controller various of controller types for increasing the efficiency of gyrostabilizer (Perez & Steinmann, 2009). It is believed that a proper control method on single-axis gyrostabilizer enables vessel stability in rolling reduction without any concern of unwanted gyroscopic effect. Hence, this paper concentrates on implementing single-axis type of gyrostabilizer for roll stabilization.

As for control, gyrostabilizer could be passively controlled or actively controlled. Passive control permits free rotation of precession around the gyro gimbal axis (Kuseyri Sina, 2020), whereas active control utilizes a gimbal motor to counteract the torque generated by wave-induced rolling motion at the gimbal frame. Figure 1 below shows the concept of passive and active control of gyro.

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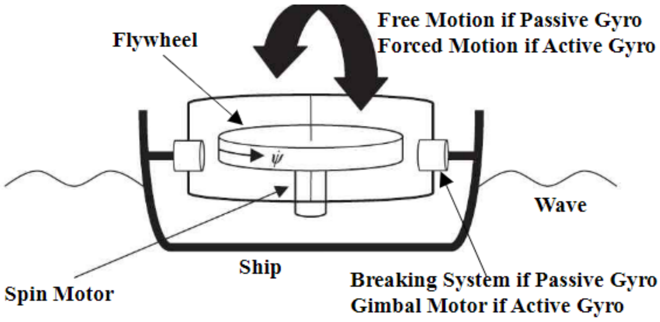

Figure 1:Principle of Operation for Passive and Active Gyrostabilizers in Ship Motion Control.

Source: (Lee, 2015)

Alaswad (2020) presents a passively controller gyrostabilizer on a 10M yacht in his research while Takeuchi et al. (2011) highlighted that commercially Mitsubishi heavy industries Ltd has been already implemented Anti Rolling Gyro (ARG 375T) on Ferreti 731 yacht in the market after conducting bench-testing on performance test. Since it is also passively installed, the angular change of the flywheel axis rotation is controlled by using a damper or energy absorber. Therefore, it eliminates the need for a sensor or gimbal controller to actively detect the hull's orientation. However, passive controlled gyrostabilizer is better use at zero-speed of vessel as it solely relies on the actuator's rotation speed and cannot adjust to the complex wave environment with varying wave-induced amplitudes (Li et al., 2022).

Recent research has been increasingly focusing on active control mechanisms for gyrostabilizers in various vehicular technologies, aiming to enhance stabilization efficiency and address the limitations of passive control systems. Active control systems play a crucial role in adapting to changing sea conditions and providing more responsive stabilization, particularly in scenarios where passive control may be insufficient. Companies such as Veem Marine, Seakeeper, Ship Dynamics, and Halcyon have introduced active type gyrostabilizers in the market, reflecting the growing interest in advancing active stabilization technologies. The development and implementation of active control strategies for gyrostabilizers represent a significant area of research that seeks to optimize the performance of these systems in dynamic environments. One of the key research gaps in the field of active controlled gyrostabilizers or anti-rolling gyros lies in the exploration of advanced control algorithms and strategies to further enhance the effectiveness and adaptability of these systems. Studies such as those by Park & Cho (2018) on the development of self-balancing robots with control moment gyroscopes and Rabah et al. (2018) comparing position control using different controllers for a gyroscopic inverted pendulum provide insights into the application of advanced control techniques in stabilization systems. Additionally, research by Talha et al. (2017) focusing on the design of a fuzzy tuned PID controller for anti-rolling gyros in ships demonstrates the potential of artificial intelligence in improving stabilization mechanisms.

Furthermore, investigations into the optimization of parameters for ship anti-roll gyros, as studied by (Zhu et al., 2020), and the analysis of disturbance torque effects on gimbal systems by (Nguyen et al., 2022) contribute valuable knowledge to the field of gyro stabilization. These studies shed light on the complexities of gyrostabilizer control and the importance of parameter tuning and disturbance mitigation for enhancing system performance. Moreover, research by Kim & Ryou (2020) on sonar image stabilization for unmanned surface vehicles based on

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motion sensors and the study by San et al. (2018) on rolling damping of conventional boats with bilge keels provide insights into specific applications of stabilization technologies in different maritime contexts.

Among research been made focussing on single-axis gyrostabilizer, Akpadiaha & Jeremiah (2019) illustrates a good comparison of implementation actively controlled over passively controlled gyrostabilizer which improve up to 30% of roll reduction. Next, Li et al. (2022) comes with a simulation-based study on a 32 meter-port salvage tug in a various wave height environment. It is observed that with adaptive controlled gyrostabilizer, the roll manages to be reduced disproportionally to a wave height. Same goes for Talha et al. (2017), they conducted simulated-based experiment of passive and active controlled gyrostabilizer comparison and undeniably gain a better performance using active control. Whilst a lot of research on single-axis gyrostabilizer has been remarkably made based on simulation and emphasizing big ship, there is a little on study on gyrostabilizer for small vessel. There is a study done on scaled barge model stabilization using gyro to supports offshore wind turbines due to the concern of high induction in fatigue loads on all turbine structures because of the significant oscillatory motions of the floater (Manmathakrishnan & Pannerselvam, 2019). Thus, before conducting on real barge model, the dry test on the scaled model has been executed.

Thus, this paper concentrates on single-axis anti rolling gyrostabilizer on a 1:5 scaled-simplified hull-model that utilizes fuzzy-logic active control of precessional motion using a servo. The rolling reduction performance is analyzed and compared with passive control performance and without turning on the system. In the next section, the details on the gyroscope concept and its modelling are further illustrated.

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Table 1: Different Types of Gyrostabilizer Types and Classification with Their Specification on Different Vessels.

Reference	Environment	Vehicle	Type/Classification				Commercial	Real-time results	Simulation Results
			No. of gyro	Spin Axis	Orient-ation	Control			
(Gogoi et al., 2017)	Ground	Two-wheeled	Uniaxial/One	Vertical	-	Passive	N	Y	Y
(Karagiannis, 2015)	Amphibious (Ground-Water)	Two-wheeled	Biaxial /Two	Vertical	Parallel	Active	N	Y	Y
(VEEM, 2022)	Water	Yacht	Uniaxial/One	Vertical	-	Active	Y (Veem)	N	N
(Takeuchi et al., 2011)	Water	Yachts (Ferretti 731)	Uniaxial/One	Vertical	-	Passive	Y (Mitsubishi)	Y	Y
(Seakeeper, 2022)	Water	Yacht	Uniaxial/one	Vertical	-	Active	Y (Seakeeper)	N	N
(Townsend & Shenoi, 2011)ater	Ship	Twin - gyro/Two	Horizontal	Parallel	Active	Y (Ship Dynamics)	N	N	
Click or tap here to enter text.(Palraj & Rajamanickam, 2020)	Water (Regular and Irregular wave)	Scaled 1:50 Barge with static Owt	Uniaxial/One	Vertical	-	Active (PD)	N	Y	Y
(Kuseyri Sina, 2020)	Water (Irregular wave)	Vessel	Biaxial	Vertical	Parallel	Active (H ∞)	N	N	Y
(Akpadiaha & Jeremiah, 2019)	Water (Regular and Irregular wave)	MV Ofure (Search and Rescue Boat)	Uniaxial/One	Vertical	-	Active	Y (Veem VG145SD)	Y	N
(Perez & Steinmann, 200(	Water	Naval Patrol Vessel	Biaxial	Vertical	Parallel	-	Y(Halcyon)	N	Y
(Gillmer & Johnson, 1982) (Townsend & Shenoi, 2014)	Water	Iitalian luxury Liner	Three	-	-	Active	-	N	N
(Talha et al., 2017)	Water	Vessel	Uniaxial	Horizontal	-	Active (Fuzzy-tuned PID)	N	N	Y
(Li et al., 2022)	Water	Port salvage tug	Uniaxial	Horizontal	-	Active (Adaptive)	N	N	Y

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Gyrostabilizer Design, Concept and Modelling.

Gyrostabilizer Design

Gyroscopes in general consist of high-speed rotating flywheel, and gimbal frame. A fully developed system of gyrostabilizer on the other hand comprises of DC motor as actuator, flywheel, damper and frame as can be referred in Figure 2 below.

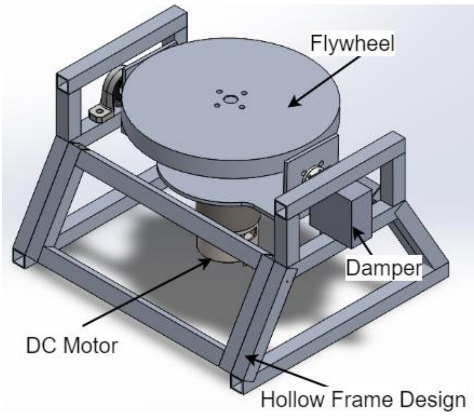

Figure 2: Single-Axis Gyrostabilizer components.

Gyroscope Concept

A spinning gyroscope of a certain velocity, **Ω** creates an angular momentum along the spinning-axis based on Newton's second Law. This concept is given by the equation:

$$L = I\Omega \tag{1}$$

where L is the angular momentum, **Ω** is its velocity and I is the moment of inertia of the flywheel around the z-axis, and it is described by:

$$I = \frac{1}{2}mr^2 \tag{2}$$

where m is the mass of the flywheel and r is the radius of the flywheel. Another important gyroscopic effect is the precessional motion, $\dot{\theta}$ that refers to the occurrence where the axis of a spinning object, such as a gyroscope, moves in a conical pattern in space when subjected to an external torque as shown in equation 3. However, with locked precessional axis based on gyrostabilizer system as per shown in Figure 1, the precessional motion only rotates in the longitudinal axis if subjected to an external force such as wave, causing the original spinning axis of the flywheel change its angular rotation orientation to the other axis. In addition to this, a τ_control present in the gyrostabilizer system acts to oppose the natural precessional motion in opposite direction produce a gyro torque which is represented as:

$$\tau_{gyro} = I\,\Omega\,\dot{\theta} \tag{3}$$

The precession velocity, $\dot{\theta}$ can be expressed another way with the presence of precession angle of gyro, θ, which shows that $\dot{\theta}_{prec} = \frac{d\theta_{prec}}{dt}$ thus, the stabilization torque from the gyroscope can be denoted as:

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$$\tau_{stab} = \frac{1}{2} m r^2 \Omega \frac{d\theta_{prec}}{dt} \cos(\theta_{prec}) \tag{4}$$

From the equation above, it is observed that in order to construct a gyrostabilizer for rolling motion, one should pay attention to the following four factors:

(i) mass of the gyroscopic flywheel, $\boldsymbol{m}$
(ii) radius of the flywheel, $\boldsymbol{r}$
(iii) spinning velocity of the flywheel, $\boldsymbol{\Omega}$
(iv) precession velocity, $\dot{\boldsymbol{\theta}}_{\boldsymbol{prec}}$

The mass of gyroscopic wheel is very much dependent on the size of vessel or ship as bigger mass and radius of the flywheel will affect the center of gravity of the vehicle, leading to an unstable in vehicle mass distribution when installed. So, it is inevitably vital for one to consider the size of the weight based on the size of the vehicle. However, the last two factors depend on the actuator's specifications and capability in which both are power consumption. In this research, DC motor has been used for flywheel rotation while servo motor is being used for precessional motion control.

Methodology

This research is conducted at research lab at Centre for Unmanned Technologies (CUTe) in International Islamic University Malaysia (IIUM) using quantitative method. Figure 3 below shows the illustration of flowchart along the research process starts from CAD modelling of scaled-simplified hull model and analyses of roll's stabilization performances.

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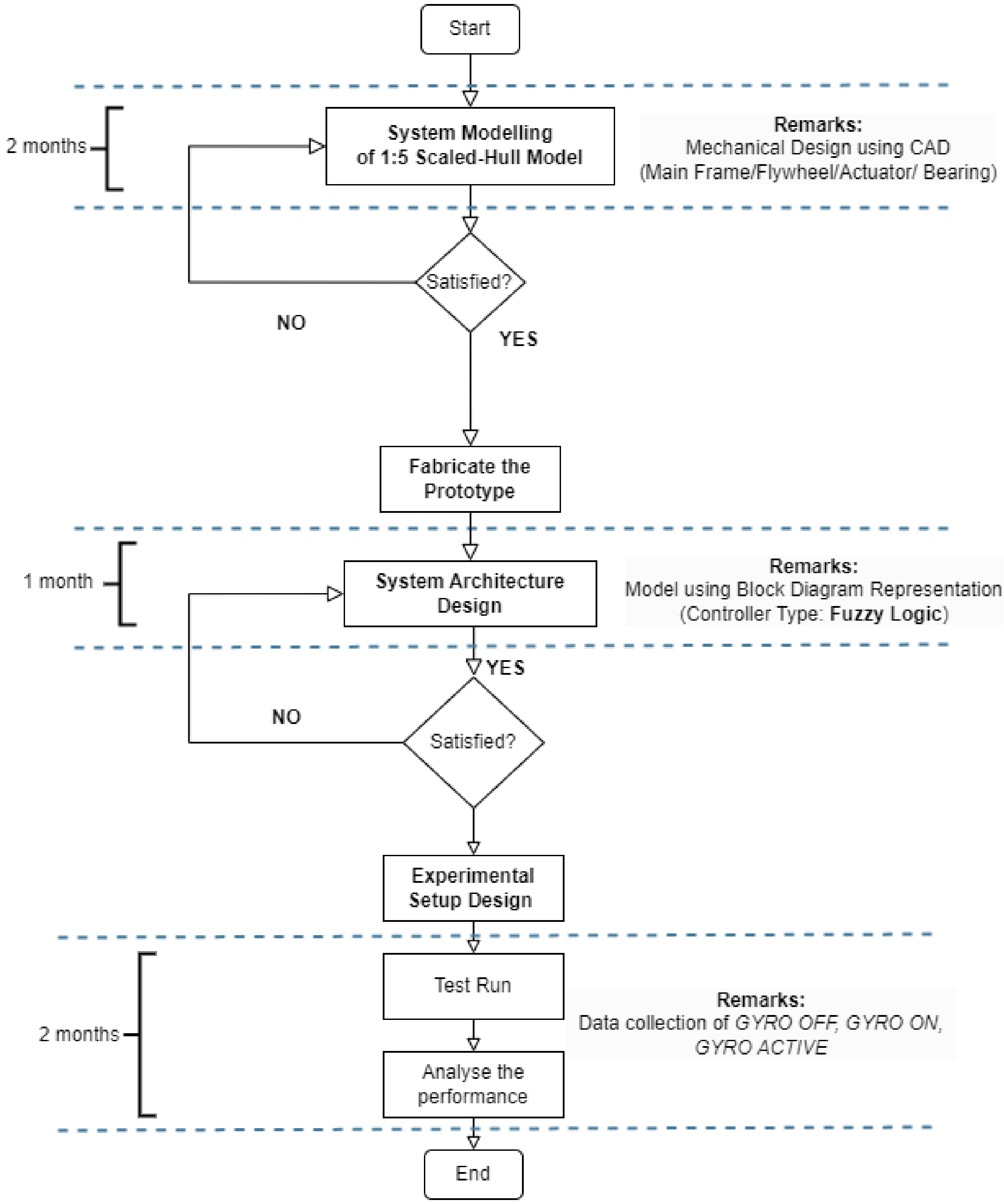

Figure 3: Flowchart of Research Process.

Modelling of scaled-simplified hull model with gyrostabilizer is based on real size of 1m vessel model using SOLIDWORKS 2021 CAD. After the design is deemed to be satisfactory, fabrication of the prototype is made which comprises of components; main frame (body), actuator for active precessional control, bearing and flywheel for momentum generation. Lastly, the design of control and tuning process using fuzzy-logic controller is taken place before analysing the performance of the prototype's rolling. The time taken for this study is illustrated along with research process in Figure 3 above, where the modelling of the system, the architecture design including coding and test run took 2 months, 1 month and 2 months respectively.

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Mechanical Design

The prototype of Scaled-Simplified Hull Model is designed using addictive manufacturing of 3D-Printed Material as it is simple yet effective. The mechanical design of the 3D-Printed prototype is presented in Figure 4 below.

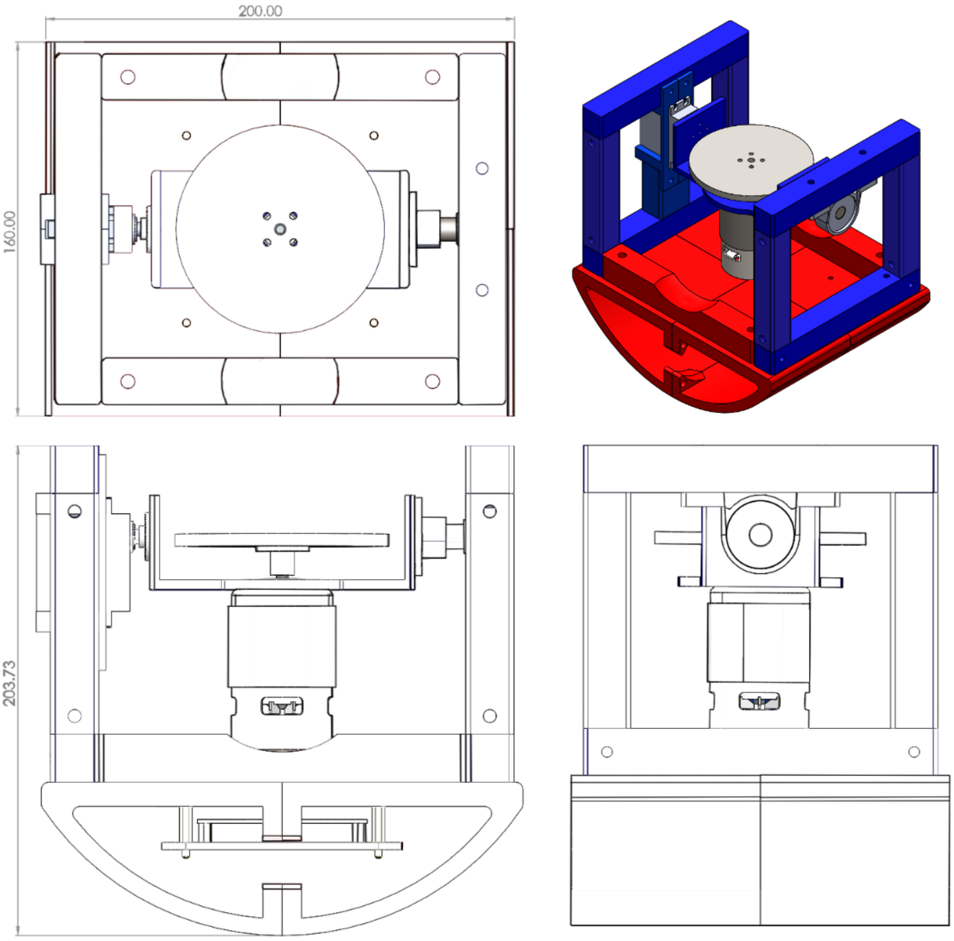

Figure 4: Gyrostabilizer Design Drawing with Top View, Isometric View, Side View and Front

Figure 4 illustrates the gyrostabilizer design for this research, a scaled and simplified- hull model design to be tilted or heeled on roll-axis only. The material used to build the hull body is made of Polylactic acid (PLA) through 3D printing, FDM method using Ender 3 3D-Printer. The base is printed separately into quarters and joined using bolts and nuts. In addition to this, the hollow frame design for gyro-cage on top of the main body is also made of 3D-printed PLA.

As mentioned for gyrostabilizer requirement, it must be made up of flywheel as weight that to provide the counter-torque for rolling stabilization. Since this is a scaled design, the radius is fixed to its maximum allowance based on the body frame size which is 0.0445m and the mass of the gyro has been fixed to 182g, a desired mass for righting moment of the system as calculated in equation (5). Furthermore, it is important to select the best material to provide the lowest possible thickness for the flywheel for the center of gravity of entire system could be

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reduced in order to make it more stable. The designed 3D-printed prototype specifications are given in the Table 2 below.

Table 2: Parameters of 3D-Printed Scaled-Simplified Hull Model.

Parameters	Value
Main body Mass, m_b	1.6 kg
Gravitational Force, g	9.81 m/s2
Size (L x W x H)	160mm x 200mm x 203.67mm
Platform Thickness, r_g	10mm
Gimbal Dimension (L x W x H)	110mm x 70mm x 39mm
Bearing Inner and Outer Radius	10mm and 16.5mm
Bearing type	Pillow Block Bearing

Flywheel For Gyro Weight Selection

The relationship between the total amount of righting moment required to stabilize the tilted body and the gyro torque amount in terms of angular momentum of rotating gyro are represented as following free body diagram in accordance with equation 4 and 5. Equation 5 depict the total righting moment, M to stabilize the rolling condition of gyrostabilizer system and equation (4) portray the gyro stabilization torque. The equation (5) and (6) is related to by the mass of gyro, m represented in equation 6.

$$\circlearrowright M = mg\sin\ \theta \times L \quad (5)$$

where m is mass of whole system, g is gravitational force, θ is angle of roll, and L is length from ground to centre of gravity.

The relation between those two equations can be described as:

$$mg\sin\theta \times L = I\,\Omega\,\dot{\theta} \quad (6)$$

Through equation (5), the mass of the gyro can be determined by separating the mass of whole system, m and mass from flywheel rotational inertia, I, as shown in equation (7) and (8) respectively.

$$m = m_b + m_{gyro} \quad (7)$$

$$I = {}^{1}\!/_{2}\, m_{gyro} r^2 \quad (8)$$

After acquiring mass value for gyro (flywheel) weight, it is possible to ascertain the thickness or height of the disc by considering the density of the material used and its corresponding volume. The volume and thickness can be described as:

$$V = \frac{m}{\rho} \quad (9)$$

$$t = \frac{V}{\pi * r^2} \quad (10)$$

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where, V is Volume, V = Volume, ρ is Density, m is Mass, t = thickness, and r = radius of the flywheel.

Table 3: Disc Volume and Thickness distribution based on Different Material.

Material	Density (kg/m^3)	Mass (kg)	radius (m)	Volume (m3)	Thickness (m)
Mild Steel	7860	0.182	0.0445	0.000031425	0.005051
Aluminium	2710	0.182	0.0445	0.000091144	0.01465
3D Print	1240	0.182	0.0445	0.000199194	0.03202
Iron	7800	0.182	0.0445	0.000031667	0.005092

From Table 2 above, mild steel material type is selected for its weight is observed to be the lowest thickness of 5.05mm (about 0.2 in).

System Control Architecture

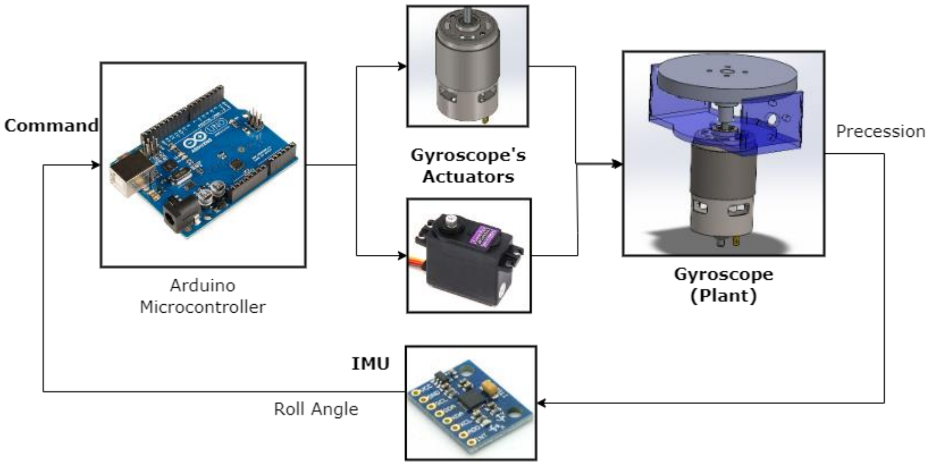

Figure 5: Interconnection of The Gyro and Physical hardware.

The control system architecture is shown in Figure 5. The electronic component comprises of 4 important units, Arduino as microcontroller to give command, DC 775 motor and MG995R servo as actuators to spin the flywheel and control the precession angle respectively, and Inertial Measurement Unit (IMU) sensor to monitor the rolling motion of the system where the desired roll angle is 0 degree. IMU, DC Motor and Servo are the components attached on the system's main body 3D-printed parts while Arduino and other components such as motor driver, buck converter and 12V battery stayed outside of the main body through wiring connection. A USB for serial communication is connected from the Arduino to the computer to obtain and view the results. In Figure 6, shows the fabrication of the entire system.

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Experimental Setup

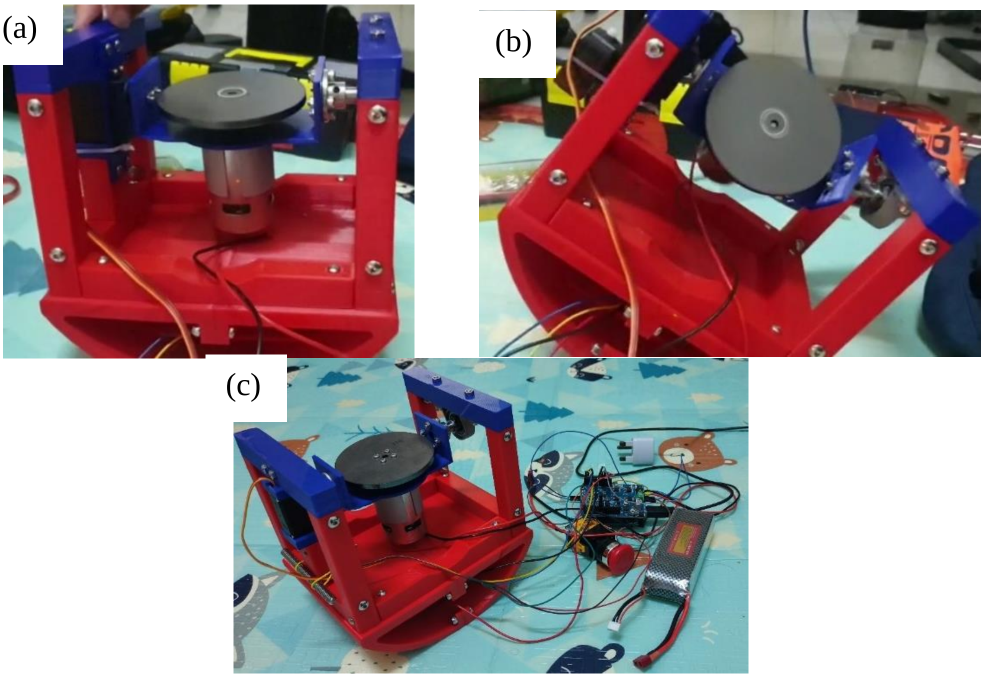

Figure 6: Experimental Setup: (a) Before Force Excitation. (b) After Force Excitation. (c) Fabrication setup.

The experimental setup was proposed by exciting a fixed certain force from the side of the gyrostabilizer and observing the rolling period of the system before it reaches a merely zero-degree angle. As shown in Figure 6 above, a force is excited from initial position of the prototype, and the gyrostabilizer act to damp the roll. There are three types of testing done which are *GYRO TURN OFF*, *GYRO ON* and *GYRO with SERVO ON*. For gyro ON means the flywheel is rotated at its full speed by setting the duty cycle to 255 in the code. This technique is called controlling the Pulse Width Modulation (PWM) where we can achieve our desired analog results (motor speed) by governing it digitally. The motor used is 775 DC motor has fullest speed of 3000RPM at 12V.

Next, in the experimental test, the servo ON means our $\tau_{control}$ for precession motion is being implemented to oppose the natural effect of the gyroscopic effect so that the counter-torque for rolling stabilization is effective. The roll testing is done repeatedly using lower weight of gyro of 247g to observe the difference in performance. The parameters of the 3D Printed Simplified-Hull Model can be referred to in Table 2 where the selection is based on equation (5)-(10) while the parameters of gyrostabilizer(flywheel) can be referred in Table 4. The graphs in this paper are generated using MATLAB software.

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Table 4: Parameters of 182g weight of Gyro.

Parameters	Value
Main body Mass, m_b	1.6 kg
Gravitational Force, g	9.81 m/s^2
Gyro Mass, m_g	0.182 kg
Gyro Radius, r_g	0.039 m
Moment of Inertia, I	1.1368 x 10-4 kgm2
Gyro angular speed, Ω	3000 RPM

Table 5: Parameters of 247g Weight of Gyro.

Parameters	Value
Main body Mass, mb	1.6 kg
Gravitational Force, g	9.81 m/s2
Gyro Mass, mg	0.247 kg
Gyro Radius	0.0445 m
Moment of Inertia, I	2.4456 x 10^{-4} kgm^2
Gyro angular speed, Ω	1235 RPM

Results and Analysis

Results Trial on 182g Gyro Disc Weight

In the first test, it is observed that when a force is excited with gyro system turn off, the maximum rolling amplitude is 300 and the time taken for its to settle before reaching zero-degree angle is about 3 seconds.

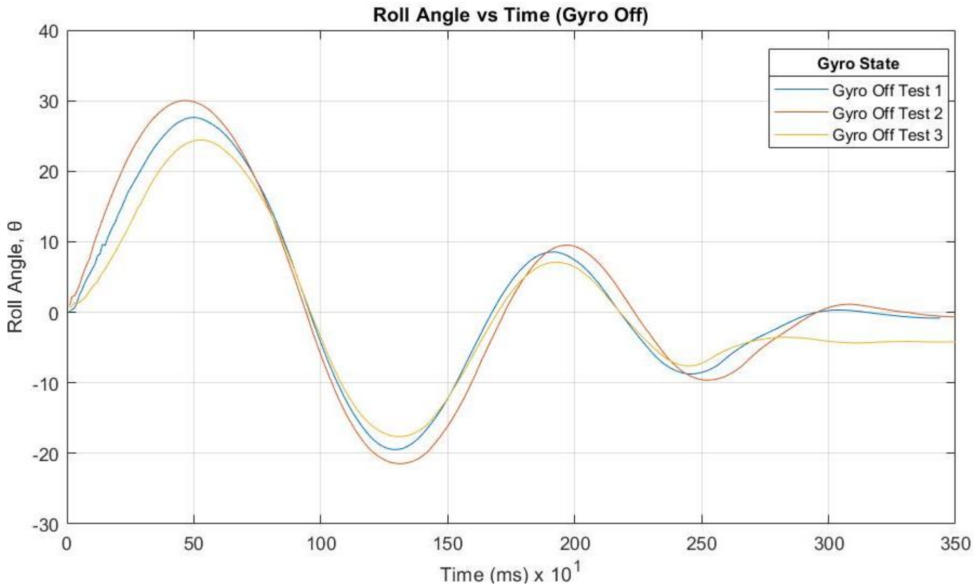

Figure 7: Roll Angle vs Time for 182g Gyro Disc in Off Gyro State

Next, upon applying the same force while passively turning the gyro, rolling amplitude has been slightly reduced to 250, and it takes 2 and a half seconds to settle rolling. It can be observed there is a slight noise in the rolling. This is due to the vibration induced by the rotating disc.

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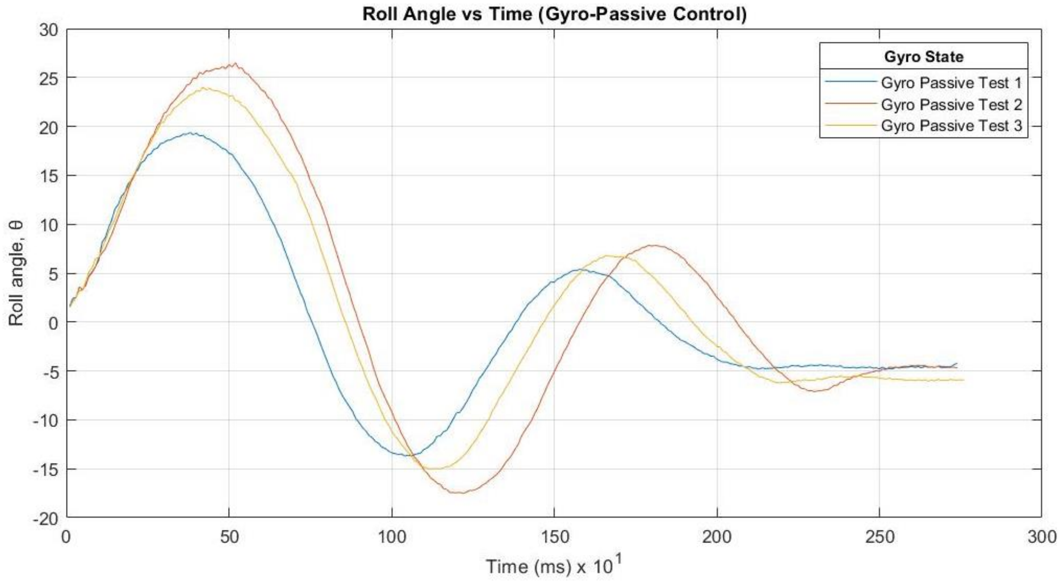

Figure 8: Roll Angle vs Time for 182g Gyro Disc in Passive Gyro State.

Lastly, the roll angle shown in Figure 9 below is illustrating the rolling when the state of the system is active. The rolling is being reduced proportionally as well as the settling time. Table 6 shows the comparison of the different gyro system state or condition and its contribution to rolling reduction.

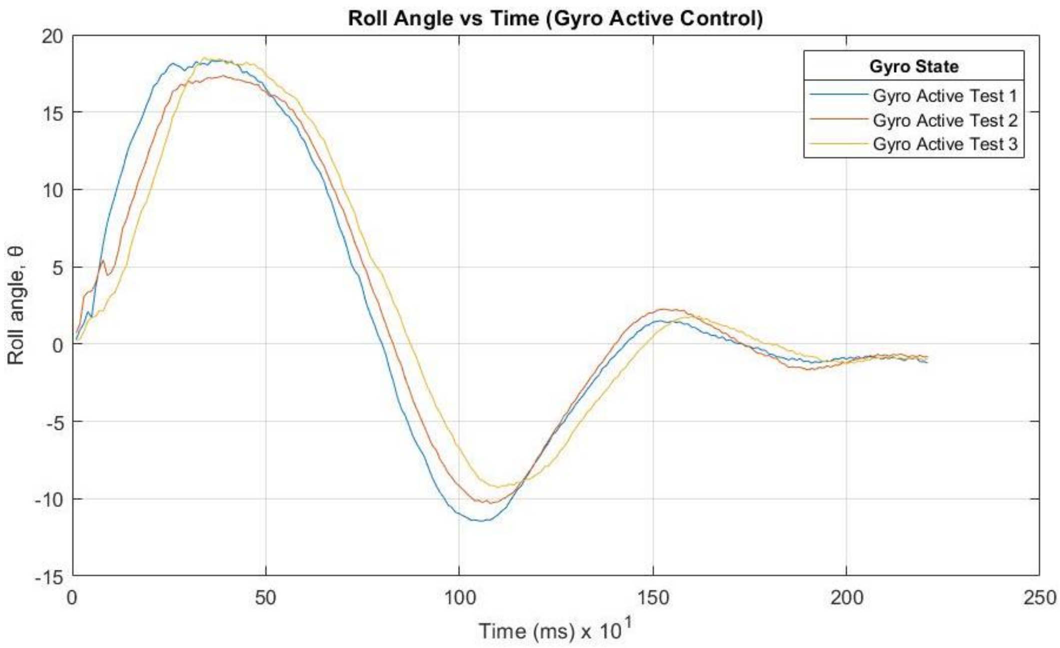

Figure 9: Roll Angle vs Time for 182g Gyro Disc in Active Gyro State.

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Table 6: Comparison of the Gyro Condition based on Control.

No.	Condition	Trial	Highest Roll	Settling Time (s)
1	Gyro Turn Off	1	27.62^0	3.05s
2		2	30.02^0	3.1s
3		3	24.42^0	2.8s
1	Gyro Turn On (Passive Control)	1	19.37^0	2.3s
2		2	26.51^0	2.5s
3		3	24.02^0	2.25s
1	Gyro Turn On (Active Control)	1	18.34^0	2s
2		2	17.36^0	2s
3		3	18.53^0	2s

It is observed that the active control of gyro does improve the rolling reduction of the simplified hull model based on ground testing. On contrary, passive control gyro does reduce the rolling but it is not significant due to the weight of the disc provided is just sufficient for the counter-precession in control. Passive control might be able to reduce significantly when the weight used is much bigger leading to an enormous moment of inertia where the external force excited will have no interruption on the system. The percentage of roll reduction can be calculated in terms of highest roll in various control test using equation below:

Average of Highest Roll of System upon Gyro Turn Off:

$$\frac{27.62 + 30.02 + 24.42}{3} = 27.35^0$$

Average of Highest Roll of System using Gyro Passive Control:

$$\frac{19.37 + 26.51 + 24.02}{3} = 23.3^0$$

Average of Highest Roll of System using Gyro Active Control:

$$\frac{18.34 + 17.36 + 18.53}{3} = 18.07^0$$

Percentage of Roll Reduction when using Passive Control as compared to Off Condition:

$$\left|\frac{23.3^0 - 27.35^0}{27.35^0}\right| x\ 100\% = 14.81\%$$

Percentage of Roll Reduction when using Active Control as compared to Off Condition:

$$\left|\frac{18.07^0 - 27.35^0}{27.35^0}\right| x\ 100\% = 33.93\%$$

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Results Trial on 247g Gyro Disc Weight

The roll reduction performance for 247g with 50% speed is tested on active control only to observe the performance between 182g of gyro disc. The reason for not using higher speed than that is due to the increase in vibration proportionally that leads to distortion in IMU reading. In the next Figure 10, a bigger mass of gyro weight is used to see the difference in the rolling motion of the simplified-hull model. It can be illustrated that the maximum rolling is reduced below 150 in the first test which is much better as compared with previous active control using 182g weight. However, a noisier graph can be seen. This is because of a bigger vibration produced using a bigger weight. Table 7 shows the recorded data of the 3 trials of 247g gyro system based on active state.

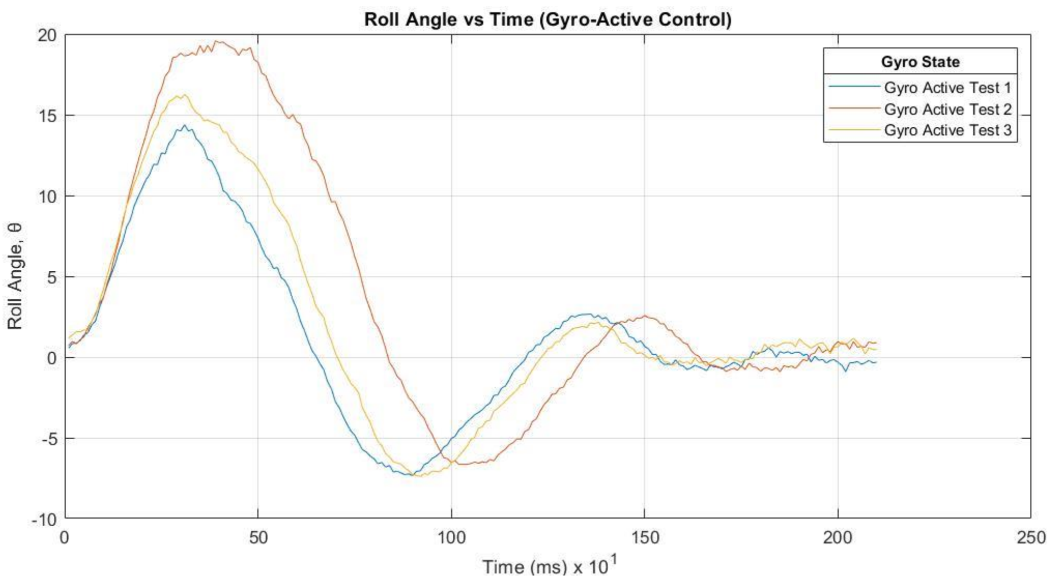

Figure 10: Roll Angle vs Time for 247g Gyro Disc in Active Gyro State.

Table 7: Recorded Data of Gyro Active State using 247g Weight.

No.	Condition	Trial	Highest Roll	Settling Time (s)
1	Gyro Turn On (Active Control)	1	14.38^0	1.75s
2		2	19.58^0	1.75s
3		3	16.25^0	1.75s

Conclusion

This paper proposes the usage of single-axis gyrostabilizer on a 3D-printed scaled-simplified hull model experimented on ground approach as illustration of rolling reduction of the vessel. Mechanically, increasing the weight of the disc and speed can reduce the unwanted rolling correspondingly. Passive control manages to reduce rolling by 14.81% while active control used in the system enable to enhance gyrostabilizer stability in terms of highest rolling reduction by 33.93% as compared to natural rolling without gyrostabilizer turning ON. Using Fuzzy-Logic Control, this research objectively achieves in improving the roll reduction compared to natural control, thus leading to a feasibility study on implementation of gyrostabilizer on a small vehicle such as unmanned surface vehicles (USV).

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A various way of enhancement could be improved in term of reducing the overall performance such as by customizing and dedicating a specific control, improving through tuning and filtering any noise to achieve a better efficiency and deliver a confident implementation of stabilizer particularly in the water environment. To add, a more gyrostabilizer mechanism, to explore on its modularity design, leading to a expedient installation on USV.

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