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CONTROLLING UNMANNED SURFACE VEHICLE ROCKET USING GPS TRACKING METHOD

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ABSTRACT

An unmanned surface vehicle (USV) is operated on the water surface for specific purposes. USV can be used in waters that cannot be entered by crewed boats, such as environments with high levels of threat or that are contaminated by nuclear, biological, or chemical waste. USVs can also be used for surveys in shallow waters, escorting military weapons, collecting environmental data, and coordinating with other underwater vehicles such as automated underwater vehicles. This study designs and develops simple USV rockets for maneuvering on the water surface. First, a simple USV system is designed. Next, mechanical and electronic components are selected, and the control program is implemented using the Arduino Mega 2560 microcontroller. Finally, the USV motion kinematics are analyzed, rocket thrust force is tested, and torque generated by the electric ducted fan (EDF) motor is measured. Ultimately, a rocket system with weight of 3920 g and length, width, and height of 720 mm, 500 mm, and 420 mm, respectively, is developed. The USV rocket is driven by an EDF motor with voltage and current of 1600 kV and 160 A, respectively, an electronic speed control, 6X Turnigy FHSS remote control, and two 18.5 V Li-Po 5500 mAh batteries as a power source. The USV has a maximum thrust of 40.7 N with torque of 1.41 Nm. Kinematics parameters such as angular acceleration and linear acceleration were also determined.

Keywords: Control; GPS; Kinematics; Unmanned surface vehicle

1. INTRODUCTION

An unmanned surface vehicle (USV), also called an autonomous surface vehicle (ASV) or automatic vehicle, is operated on the water surface for specific purposes. USVs use the global positioning system (GPS) to determine the direction of vehicle movement (Manley, 2008; Richard, 1958).

USVs can be used in waters that cannot be traversed by a crewed boat, including environments with high levels of threat or that have been contaminated by nuclear, biological, or chemical waste (Rujian et al., 2010). They are an efficient tool for risk assessment in shallow water environments and water-land interface zones such as the near surf zone in marine coast. Ferreira et al. (2009) presented the results of autonomous bathymetric missions with the ROAZ ASV. This vehicle system can be applied in different applications (Syam, 2016). Furthermore, a vision-based obstacle detection system has developed for USVs to support and to complete

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various tasks autonomously (Wang et al., 2011). Moreover, a trajectory planner has been developed to allow USVs to safely reach a destination in a collision-free manner (Svec et al., 2014).

USVs can be used to survey shallow waters, escort military weapons, collect environmental data, and coordinate with automated underwater vehicles (AUVs). The USV data has higher precision than AUV data because a GPS is installed in the USV mainframe (Naeem et al., 2007; Vogeltanz, 2016).

Rockets were first developed during World War 2 for military purposes. Since then, they have been used for various peacetime purposes such as launching satellites into orbit, performing atmospheric monitoring, and conducting research (Richard, 1958). In a manner analogous to how rockets were designed to fly in the air, the authors have designed a USV rocket that can be used for movement on the surface.

This paper presents the design of a simple USV rocket and the analysis of the thrust produced by its motor. Kinematics are calculated to realize better USV rocket performance. The USV body consists of a hull that thus enables the rocket to move balance with the proportional size of the rockets and to load more weight. The USV's electronics system consists of an Arduino Mega 2560 as a controller system, a GPS device as a coordinate system, and an electronic speed control (ESC) as a motor driver. It is expected that this rocket system can enable a USV to reach a destination with precise timing.

2. UNMANNED SURFACE VEHICLE

2.1. Structure of USV

In the proposed USV system, the rocket is positioned on the water surface in a cantilever hull catamaran configuration similar to that of ship models, as shown in Figure 1. This double-hull prevents roll and pitch motions and keeps the USV position balanced. The double hull also affords easy maneuverability and stability under excessive load (Murphy et al., 2011). The direction of motion can be controlled in a simple manner by using a single fin.

Figure 1 Proposed USV rocket with double hull

2.2. Rotation System of USV

The equation of motion of the USV rocket uses the body axes as the reference system, as shown in Figure 2. The positive *X*-axis is along the longitudinal axis in the forward direction; the positive *Z*-axis is along the vertical axis in the downward direction, that is, along the plane of symmetry in the downward direction, and is perpendicular to the *X*-axis; and the positive *Y*-axis is along the lateral axis toward the right, that is, perpendicular to the plane of symmetry, and is perpendicular to both the *X*- and *Z*-axes (Jorgensen, 2011).

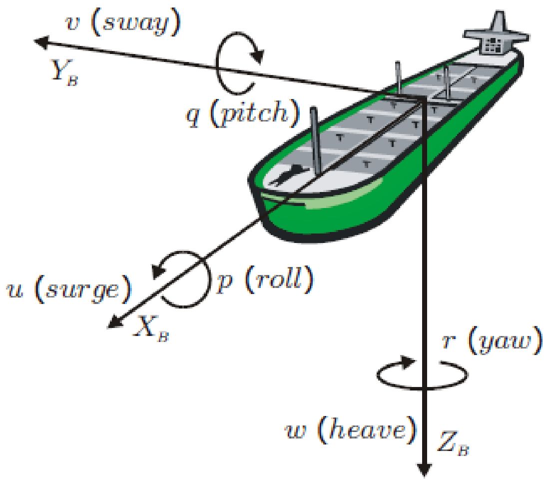


Figure 2 Rotation system of USV (Jorgensen, 2011)

2.3. Equation of Motion of USV

Equation 1 is the Newton-Euler formula to describe the dynamics of objects that are influenced by external forces F^B (N) and moments τ^B (Nm).

$$\begin{bmatrix} mI_{3x3} & 0_{3x3} \\ 0_{3x3} & I \end{bmatrix} \begin{bmatrix} \dot{V}^B \\ \dot{\omega}^B \end{bmatrix} + \begin{bmatrix} \omega^B \times mV^B \\ \omega^B \times I\omega^B \end{bmatrix} = \begin{bmatrix} F^B \\ \tau^B \end{bmatrix} \tag{1}$$

where

m : mass (kg)

V^B : $[u\ v\ w]^T$; linear velocity of body (m/s)

ω^B : $[p\ q\ r]^T$; angular velocity of body (rad/s)

I : inertia of tensor (Nms^2)

0_{3x3} : zero (null) matrix with size 3×3

I_{3x3} : identity matrix with size 3×3

Because the cross product of vectors can be expressed in a skew-symmetric matrix multiplication, Equation 2 is given as

$$\boldsymbol{a} \times \boldsymbol{b} = \begin{bmatrix} \mathbf{0} & -\boldsymbol{a}_3 & \boldsymbol{a}_2 \\ \boldsymbol{a}_3 & \mathbf{0} & -\boldsymbol{a}_1 \\ -\boldsymbol{a}_2 & \boldsymbol{a}_1 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{b}_1 \\ \boldsymbol{b}_2 \\ \boldsymbol{b}_3 \end{bmatrix} \tag{2}$$

Equation 3 shows the diagonal matrix for the inertia of the tensor:

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{3}$$

2.4. Thrust of USV

The forces acting on the rocket include gravity, thrust, and air friction. Gravity works at the *center of gravity* of the rocket along the Z-axis. Equation 4 shows the gravity F_G^B acting on the *body frame*.

$$F_{grav}^B = R_E^B \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} = \begin{bmatrix} mg\sin\theta \\ -mg\sin\phi\cos\theta \\ -mg\cos\phi\cos\theta \end{bmatrix} \tag{4}$$

The driving force is the total thrust produced by the electric ducted fan (EDF). It is always directed along the *X*-axis. The rocket moves with constant thrust parameter b (Ns^2), and the thrust F_{dr}^{B} is given by Equation 5:

$$F_{dr}^{B} = b.\Omega^2 \tag{5}$$

Air friction or drag force acts on the rocket USV in the direction opposite to that of USV motion. This affects the acceleration of the body frame along the *X*-*Y*-axis. Equation 6 shows the drag force for constant μ (kg/s).

$$F_{ham}^{B} = \begin{bmatrix} -\mu u \\ -\mu v \\ 0 \end{bmatrix} \tag{6}$$

Water resistance is equivalent to the square of the velocity, and it also depends on the size and shape of the object, as shown in Equation 7. C is the dimensionless friction coefficient; A_i, the area affected by the barriers (m^2); and ρ, the density of air (kg/m^3).

$$F_{air}^{B} = \begin{bmatrix} -\frac{1}{2} C A_x \rho u|u| \\ -\frac{1}{2} C A_y \rho v|v| \\ -\frac{1}{2} C A_z \rho w|w| \end{bmatrix} \tag{7}$$

2.5. Moment of USV

The moment is given by force multiplied by the distance to the axis of rotation. Equations 8–12 show the velocity of the F (rad/s), velocity of EDF Ω (rad/s), rocket length *l*, and drag factor *b* (Nms^2). A roll moment is applied by moving the control fins to produce roll via the aileron.

$$\tau_{roll} = bl(\Omega^2) \tag{8}$$

The control fins can be used to produce elevator pitch motion; the moment of the pitch is

$$\tau_{pitch} = bl\frac{\sqrt{3}}{2}(\Omega^2) \tag{9}$$

The fin rudder can be used to produce yaw motion; the moment of yaw is

$$\tau_{yaw} = d(\Omega^2) \tag{10}$$

The rotation of the EDF affects the gyroscopic effect of the propeller as follows:

$$\tau_{gyro} = \begin{bmatrix} -J_r\dot{\theta}\Omega_r \\ J_r\dot{\phi}\Omega_r \\ 0 \end{bmatrix} \tag{11}$$

Here, J_r is the inertia of rotation of the EDF (Nms^2), and Ω is the angular velocity of the EDF.

The torque is the difference in the rotational acceleration of the EDF:

$$\tau_{counter} = \begin{bmatrix} 0 \\ 0 \\ J_r \dot{\Omega}_r \end{bmatrix} \tag{12}$$

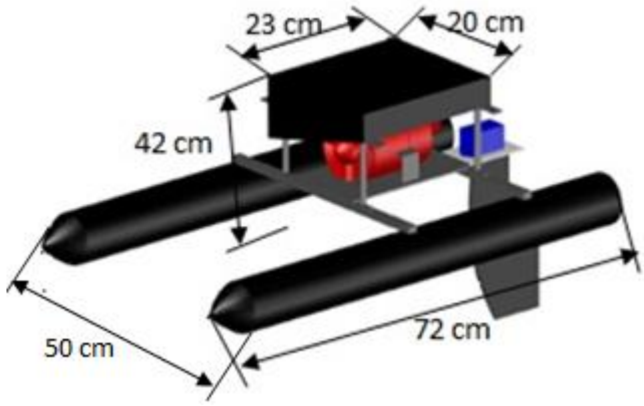


Figure 3 Design of USV rocket

3. METHODOLOGY

3.1. USV Design

The USV design is similar to that of a catamaran. The rocket frame consists of two main hulls that are symmetrical on the right and left sides. These hulls improve the rocket's maneuverability. The hull construction enables the rocket to maneuver with good balance, and the relatively large rockets afford greater carrying capacity, as shown in Figure 3.

The carrying capacity required determines the length, width, and height of the rocket that will be constructed. The rocket-type catamaran has better power load factor, maneuverability, and stability. The fins at the back of the rocket help propel the vehicle along the water surface. An EDF is used as the driving system.

The rocket hull is made of polyvinyl chloride (PVC) with 3-inch diameter. The rocket hull is circular in shape to reduce water resistance during maneuvering. The top side of the frame is made of aluminum because of its low weight and high strength. The USV, including the box components, has length, width, and height of 72 cm, 50 cm, and 42 cm, respectively. The weight of the rocket, including the electronic charge, is 3.92 kg; the weight of the electronics alone is 1.6 kg. The rocket has 12 leaf propellers of 90-cm diameter that are made of aluminum. The leaf propellers convert the turning force of the motor into a propelling force, and their shape and number affect the rocket speed.

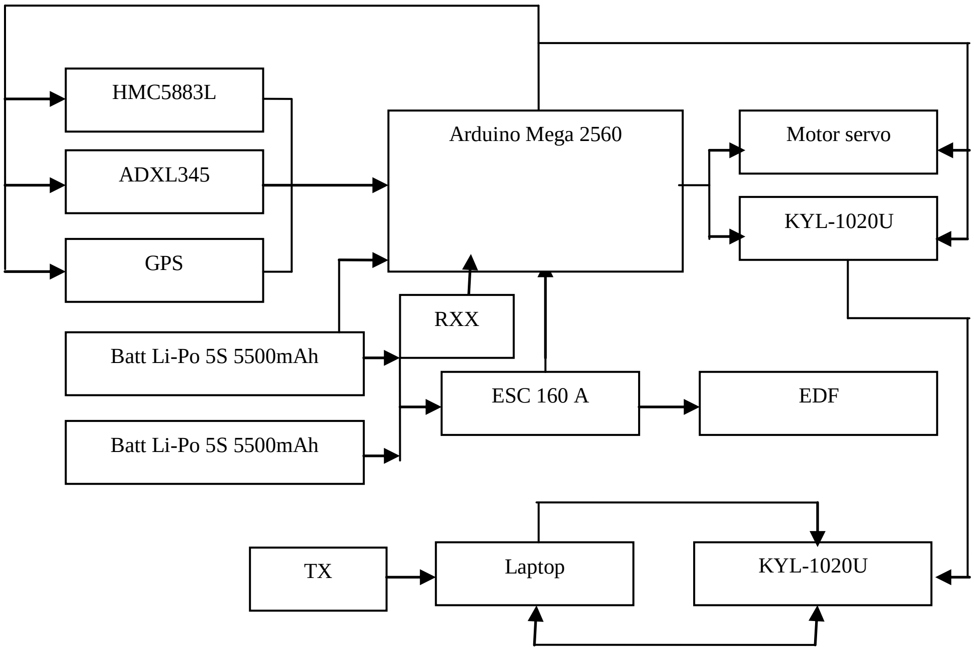


Figure 4 Electronics system of USV

3.2. Electronics System

The electronics system of the USV includes the Arduino Mega 2560 as a controller system, a GPS device as a coordinate system, an ESC as a motor driver, an EDF motor, a motor servo for driving the vehicle, and a KYL-1020U remote system for transmitting data to the operator. The electronics system is shown in Figure 4. Arduino Mega 2560 contains the ATmega 2560 microcontroller with a bootloader for reprogramming the Arduino IDE. The HMC5883L magnetometer is used to generate the direction of the USV trajectory path. The ADXL345 accelerometer is used to determine the pitch and roll of the vehicle. The current coordinate position of the vehicle is obtained using a GPS with distance, velocity, and directional accuracy within 2.5 m, 0.1 m/s, and 0.5°, respectively. The KYL-1020U transceiver is used as both a transmitter and a receiver for wireless radio frequency communication.

3.3. Interface of USV

Figure 5 shows the user interface of the USV. The user interface is designed using the Python programming language, and it uses Google Earth. The input data is analyzed to determine the roll, pitch, and yaw; direction and distance of target; and trajectory of USV.

Figure 5 Python-based USV interface system with Google Earth

The USV position is obtained in real time by using Google Earth. Google Earth is used to display the USV position because it is inexpensive and user-friendly. The USV trajectory is indicated using the Placemark tool. The experimental location is a lake in Hasanuddin University. The Placemark position is obtained from the current USV position and updated from the coordinate measurement position, as shown in Figure 5.

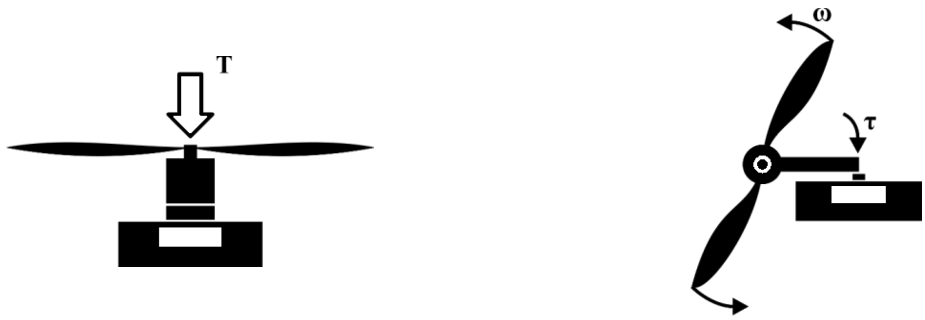
The USV trajectory is displayed in real-time by using Google Earth and is stored at microcontroller memory, then, it is processed using Python Software. The data obtained from the Python Soft is send to the operator via Arduino Microcontroller.

3.4. Experimental Procedure

One EDF motor is used in a lifting test to check the effect of the thrust force and torque.

3.4.1. Measurement of USV rocket thrust

The experimental result of the thrust force of the EDF and motor agrees with the direction of the adopted force. To determine the thrust force, a digital scale is installed in the motor. The EDF is installed in an upside-down position to gain more force from the motor.



(a) Thrust of propeller (b) Measurement of moment of propeller

Figure 6 Propeller design of USV system

3.4.2. Measurement of moment

To use the motor torque of the EDF during operation, the motor is mounted on an arm on the USV frame at a certain length. The arm is connected to the digital scale to measure the rotation of the motor.

4. RESULTS AND DISCUSSION

4.1. Experimental Results

The rocket has four fundamental movement directions: throttle, roll, pitch, and yaw. The throttle movement is controlled by changing the electronic ducted fan (EDF) speed. The linear motion of the rocket along the water surface is controlled by the roll, pitch, and yaw angles. The fin in the straight-up position is used to propel the USV in the forward direction. The rudder fin is used to generate turning motions (right or left). The aileron fin controls the roll angle.

The EDF produces forward thrust by pressing air in the backward direction. Because the thrust generator is placed outside the mass center, differential thrust force changes can be used to rotate the rocket. The rotary motor generates torque in the direction opposite to that of motor rotation. However, the center of gravity of the USV is supported by the hulls (left and right sides) and therefore it can only be maneuvered using the throttle and yaw motions. The pitch and roll motions are considered zero.

4.1.1. Throttle controller

One of the main controllers of the rocket is the throttle controller for controlling the horizontal movement of the rocket. - Because the slope of the fin is fixed, then the direction of rotation of the thrust is also fixed. By increasing or decreasing the throttle, the rocket will move forward with high or low speed, respectively.

4.1.2. Yaw controller

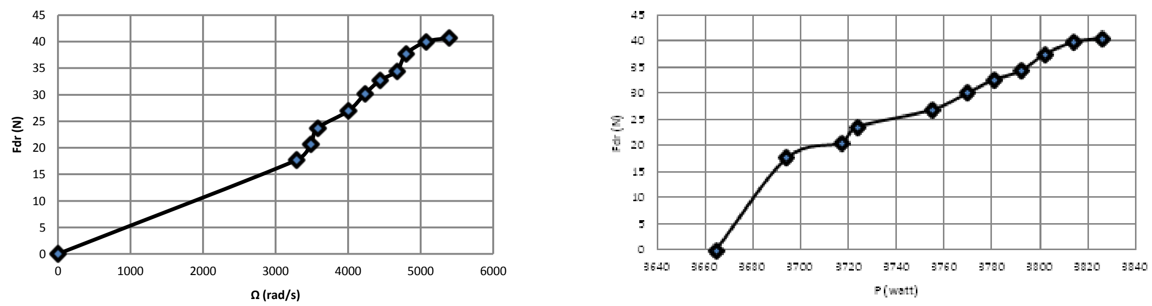
The yaw controller rotates the rocket along the *Z*-axis. Yaw control is performed by moving the rudder fin. For example, when the rudder fin is moved to the left, the vehicle turns right and vice versa - without generated the trust from - EDF changing-. Therefore, the total thrust does not change.

The movements of the rocket through air are identical to those on the water surface. However, the USV rocket movements are simple because of its low elevation. In principle, an EDF is much easier to operate in a USV rocket because the total mass of the rocket is not dependent on the motor. The USV rocket has limited roll and pitch movements because its two hulls limit angular movements.

4.2. Discussion

4.2.1. Measurement of thrust

The motor thrust is influenced by the angular velocity of the EDF. If the pitch angles of the propeller are fixed, then the thrust is adjusted by increasing or decreasing the angular velocity of the propeller, as shown in Figures 7a and 7b.



(a) Relationship between thrust F_{dr} (N) and angular velocity Ω (rad/s)

(b) Relationship between thrust F_{dr} (N) and power *P* (W)

Figure 7 Measurement of thrust

Propeller has large mass. Figure 7a shows that Ω increases linearly with F_{dr}. This is similar to the relation between *P* and F_{dr}, because the more the power supplied, the more is the increase in F_{dr}, as shown in Figure 7b. Figure 8 shows the thrust coefficient.

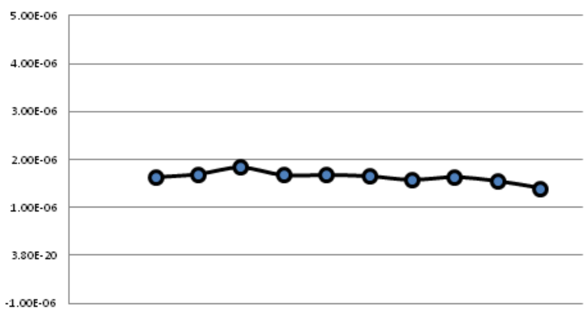
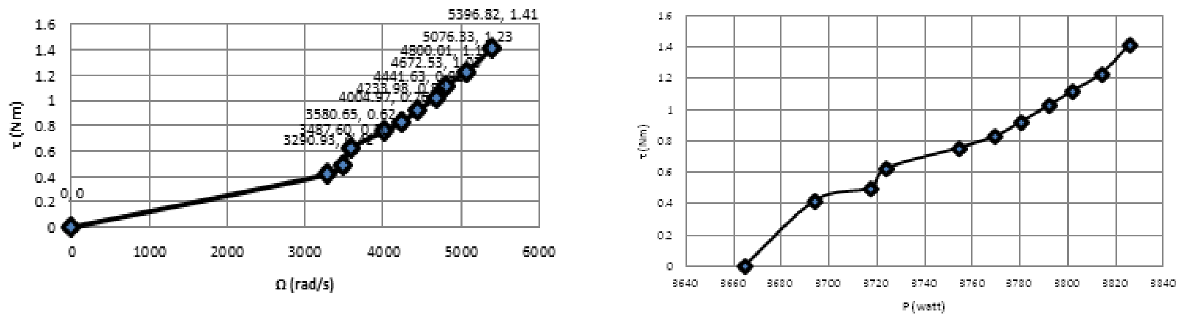


Figure 8 Thrust coefficient *b* (Ns^2)

4.2.2. Measurement of moment

The propeller is rotated by the motor, where moment is generated in the direction opposite to that of propeller rotation. In addition, the rocket power is improved by using the moment magnitude of rotation around the *Z*-axis. The engine speed and generated torque increase in linear proportion to each other because the magnitude of power affects the rotation speed, as shown in Figures 9a and 9b.



(a) Relationship between moment τ (Nm) and angular velocity Ω (rad/s) (b) Relationship between moment τ (Nm) and power *P* (W)

Figure 9 Measurement of moment

5. CONCLUSION

A USV rocket with weight of 3920 g and length, width, and height of 720 mm, 500 mm, and 420 mm, respectively, is developed. The rocket can move in four directions: throttle, roll, pitch, and yaw. However, movement is possible only in two directions (throttle and yaw) because of the limitation on the rocket's maneuverability. The USV rocket is driven by an EDF motor with voltage and current of 1600 kV and 160 A, respectively, ESC, a 6X Turnigy FHSS remote control, and two 18.5 V Li-Po 5500 mAh batteries as a power source. The motor can generate a maximum thrust force of 40.7 N at maximum rotation of 5396.82 rad/s. The magnitude of the moment at maximum rotation is 1.41 Nm.

6. ACKNOWLEDGEMENT

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