Design and Architecture of an Amphibious Reconnaissance Vehicle capable of Aerial and Underwater Operations

Anant Shukla [1[0000-0002-3332-8761]] and Rishav Choudhary [2[0000-0002-6843-7343]]

[1, 2] SRM Institute of Science and Technology, Kattankulathur, Chennai, India
[1] `as4698@srmist.edu.in`
[2] `rishavchoudhary_skc@srmuniv.edu.in`

Abstract: Most drones tend to be waterproof however very few of them can function in a submersible environment. Our proposal seeks to design an Amphibious Reconnaissance Vehicle capable of flight in aerial and underwater mode. The proposed design is of a coaxial octocopter in X8 configuration to provide additional thrust and improve the stability and manoeuvrability of the vehicle. The vehicle is designed for this purpose and can take off from a remote station (land or a remote ship) nearby and then travel underwater to a designated target. It has a range of four kilometres and is capable of having a smooth and cost-effective transition from aerial to underwater configuration with the help of onboard hydraulic cylinders. The vehicle produces a combined thrust of 8.8kg and functions autonomously in the air with the pilot having the option to take control whenever the need arises. In the air, the flight controller is capable of performing tasks such as autonomous flight control, hovering about a point, and highly stabilized flight in order to get a stable video feed. Once the vehicle reaches the target ship, it autonomously does surveillance of the ship's deck and detects any anomalies or anything suspicious. It does so with the help of image processing. Throughout the flight and the underwater commute, an obstacle avoidance system detects any possible obstacles and avoids them with the help of the ultrasonic sensors and the on-board computer calculating the modified flight plan.

Keywords: Amphibious Vehicle, UAV, AUV, Underwater, Surveillance, Autonomous, Amphibious Reconnaissance Vehicle

1 Introduction

The Amphibious Reconnaissance Vehicle was developed for a project for DRDO in order for utilising the concept of an aerial drone and adapt it to work in an underwater environment. The concept of a vehicle capable of flying and swimming is a potential breakthrough into broadening the application of UAVs. Due to the significant difference of the physical properties between the air and the water, it is difficult to design a feasible aquatic–aerial vehicle capable of deploying into the air and transitioning into an underwater environment to perform a task. Hence on a technical level, the attempts to design such a vehicle seem ambitious however the potential capabilities of this vehicle have an impact in many fields.

The ARV has the means to map the ocean quickly and efficiently. Structures of watercrafts like ships and submarines, oil rigs, pier etc. have components above and below water. In such cases, the ARV can be utilised to perform surveillance operations in aerial and underwater conditions.

2 Vehicle Design

2.1 Overview

The design of the Amphibious Reconnaissance Vehicle (ARV) is such that it combines the functions of an autonomous underwater vehicle (AUV) and an unmanned aerial vehicle (UAV)

The vehicle has been designed to approach the target for performing aerial and underwater surveillance operations while avoiding detection at all times. This task is accomplished in six stages. Each stage has been explained in detail below:

2.2 Stages of Operation:

2.2.1 Aerial Operation:

Once the location of the target has been determined, the ARV will autonomously take off from the ground station which can either be the coast or a friendly ship which is nearby. At this stage of the operation, the hydraulic cylinders on board the vehicle will be kept empty. The vehicle will take off with its propellers aligned with the vertical axis and it will then fly to the surface of the water and land on it. The drone will now have the capability to move on the surface without sinking. The direction of the vehicle's movement and the height to which it can fly will be determined by the thrust produced by its individual motors which in turn, is controlled by the speed of rotation of the propellers. During the testing phase it was determined that the maximum thrust that a single motor can produce at full throttle is 1168 grams.

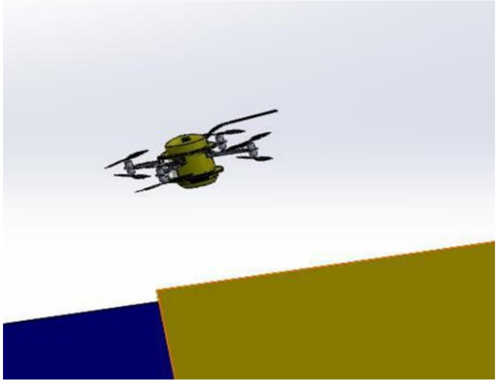

Figure 2: Takeoff from Ground Station

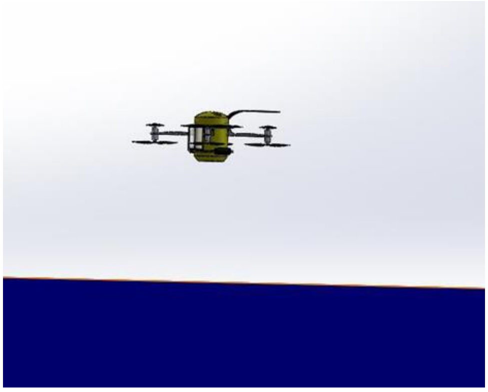

Figure 1: Aerial Operation

2.2.2 Aerial to Underwater Transition:

After landing on the surface of the water, all of the vehicle's eight propellers will be stopped. The vehicle has been designed to ensure that the total mass of water displaced by the vehicle will be equal to the weight of the vehicle, at which point the force due to buoyancy and the force due to weight in the opposite direction will become equal and the vehicle will not sink any further.

The first pump will be activated, causing the water outside to enter the on-board hydraulic cylinders till it completely fills up with water. This operation will have two consequences.

Hence as a result of the aerial to underwater transition operation, the propellers will be aligned with the horizontal axis and the vehicle will be configured for underwater operations.

2.2.3 Underwater Operation:

The ARV will now travel to the target using the eight propellers working underwater. The telemetry data on the ground station gives the pilot the capability to be able to navigate the vehicle to the target manually. The outer surface of the drone has been designed in such a manner that it does not have any concave curvature which can reflect back sonar waves thereby enhancing the stealth capabilities of the vehicle. A mast is designed to ensure that the GPS module and the Radio Receiver does not come in contact with water at any point of time during the mission, hence preventing any RC link loss or loss of GPS lock.

2.2.4 Underwater to Aerial Transition:

Twenty seconds before reaching the target's GPS coordinates, the ARV will start emptying its cylinders and initiate the underwater to aerial operational transition. This stage is similar in nature to the aerial to underwater operational transition stage. The empty cylinders cause the centre of mass of the vehicle to go back to its original position. The change in the centre of mass position will result in a righting torque, thereby causing the whole vehicle to start pitching up by ninety degrees. This will result in the propellers being aligned with the vertical axis and therefore configured for aerial operations.

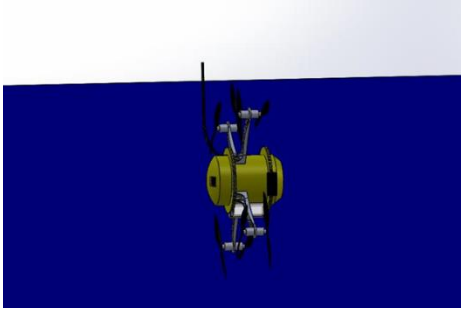

Figure 3: Underwater Operation

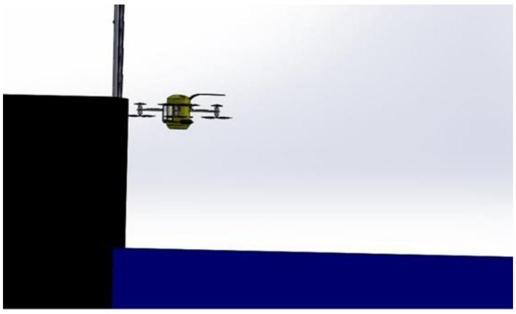

Figure 4: Surveillance Operation

2.2.5 Aerial Operation and Surveillance:

The ARV will now start flying in the air and start to proceed closer towards the target in order to do surveillance. During this time, the pilot along with the team will have a live view of the entire target and another feed of the image processing camera's data will go to another ground station computer to search for the pre-fed image template to perform object search and detection. The results of both these feeds coming from the cameras will be displayed on the computer.

This task will be performed autonomously with the help of a pre-uploaded mission on the flight controller which can be modified as per real-time requirements. If a further need of inspection is there or any other unforeseen requirement comes up, the pilot can take manual control of the vehicle.

2.2.6 Return to Ground Station:

After completing the surveillance of the target, the ARV will now land on water and follow the above steps in the reverse order for it to go back to the ground station.

2.3 Prototype 1

2.3.1 Design

The frame of the ARV is an octocopter with four arms kept 90 degree apart and powered by eight coaxially mounted BLDC motors producing a total thrust of 8.8kg. This X-8 configuration provides additional stability and manoeuvrability. For additional strength, the mainframe uses two sets of octagonal aluminium plates which are used to hold the electronics cabinet and the propeller arms together. Aluminium is chosen since it is lightweight, cheap and has a high strength to weight ratio.

2.3.2 Mechanical Specifications

Table 1. Table captions should be placed above the tables.

Parameter	Value
Weight of vehicle (cylinders discharged)	5.347 kg
Weight of vehicle (cylinders charged)	5.711 kg
Buoyant force created	49.376 N
Time for discharging and charging cylinders	152 seconds
Turning torque produced without propeller assistance	0.59 Nm
Balanced centre of buoyancy (in mm) (x, y, z)	-5.23, 331.24, 0.00
Balanced centre of mass (in mm) (cylinders discharged) (x, y, z)	-5.23, 278.39, 0.00
Balanced centre of mass (in mm) (cylinders charged) (x, y, z)	-14.7, 287.54, 0.00

2.3.3 Electronics Compartment

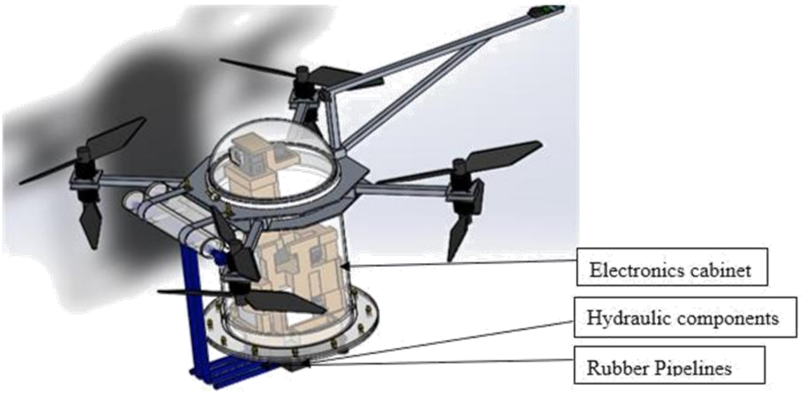

Figure 5: Electronics cabinet of the ARV (Prototype I)

The electronics are housed in an airtight compartment to prevent the onboard electronics from coming in contact with water. The cabinet weighs 4.188kg and is installed in the middle of the frame. Its structure is made out of transparent acrylic with a thin layer of rubber installed as a cover to enhance fluid dynamics. The inner support structure is built from balsa wood to fix the positions of the components. The main camera is positioned 12cm above the propellers allowing only a very small portion of the vehicle to remain above the surface of the water during the live video feed thereby avoiding detection. To ensure that the buoyancy centre lies above the centre of mass and their perfect alignment, the components in the cabinet have been moved to the lower section of the cabinet with the upper section relatively empty and both the centre of mass and buoyancy have been balanced to align them together.

2.3.4 Hydraulics

The Hydraulics compartment is placed beneath the electronics cabinet to facilitate the smooth transition from aerial operation configuration to underwater operation configuration and vice-versa. While operating as an aerial vehicle, the axis of the propellers needs to be aligned with the vertical axis whereas while operating as an underwater vehicle, the axis of the propellers needs to be aligned with the horizontal axis.

During the underwater operation, the vehicle will attempt to align its centre of mass and buoyancy centre with the vertical axis. Hence, a change in the centre of mass position will cause a change in the orientation of the vehicle and this is controlled by the charging and discharging of the on-board hydraulic cylinders.

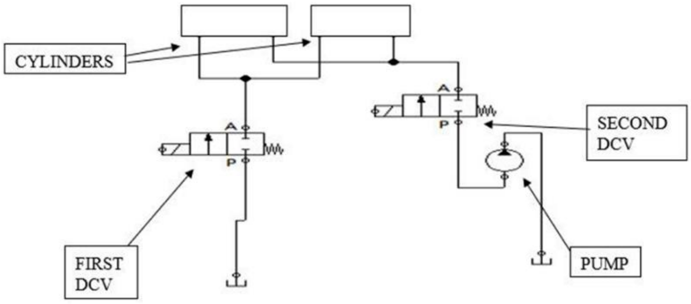

Figure 6: Hydraulics Circuit

The movement of water in the cylinder is controlled with the help of a (Generic DC 12V 5.5m 1000L/H Brushless Motor Submersible Water Pump) hydraulic pump and two 2/2 solenoid-controlled spring return Direction Control Valves (DCVs).

While operating in the air, the cylinders are kept empty. Once the vehicle is completely submerged in water, the first DCV (on the left side) is energised allowing water to enter its cylinders, causing it to pitch downwards and configuring it for underwater operation.

During the underwater operation, the cylinders are filled and the DCVs are de-energised. After reaching the target, the ARV will need to empty its cylinders to configure for aerial operations. Hence, the second DCV is energised, the pump is switched on and water sucked out of the cylinders. This causes it to pitch upward and configure for aerial operation.

2.4 Prototype 2

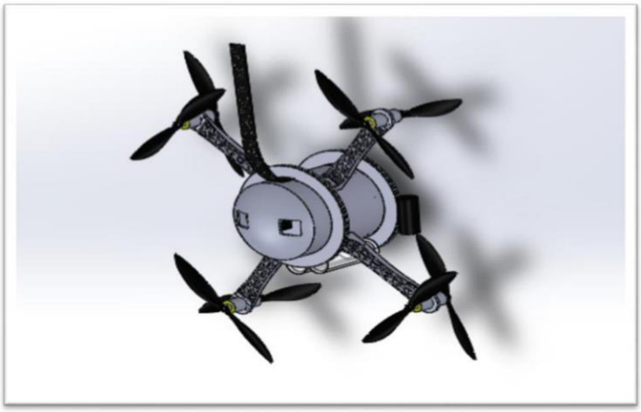

Figure 7: Prototype 2

The design is improved by using a lightweight and durable glass fibre reinforced plastic body to give structural integrity and shape to the whole drone. This structure is designed and manufactured in such a way that enables it to support the cantilever loads of the propeller arms, mountings for internal systems and also the aerodynamic outer structure for its smooth propulsion through fluidic mediums (i.e. aerial and underwater).

2.4.1 Design

The design is improved by using a lightweight and durable glass fibre reinforced plastic body to give structural integrity and shape to the whole drone. This structure is designed and manufactured in such a way that enables it to support the cantilever loads of the propeller arms, mountings for internal systems and also the aerodynamic outer structure for its smooth propulsion through fluidic mediums (i.e. aerial and underwater).

2.4.2 Material

The main structure is made of glass fibre reinforced polymer composite, which is an advanced material consisting of thermoset matrix material reinforced by fine strands of glass fibre mat. The structure is made of single layer of glass mat and double layered structure at some points which requires high rigidity. This has a thickness of 2-3 mm and has low density (0.9-1.0 g/cm^3). Thus, the whole structure weighs lighter than the Acrylic (1.2 g/cm^3) structure used in Prototype-I.

The propeller arms commercially bought arms made up of polyamide nylon. They were modified according to the need of mounting two BLDC motors onto the single arm coaxially in the opposite direction. This setup was experimentally tested before being implemented in the final design, which proved to be a better alternative to the previously used Aluminium channel in Prototype-I, which was comparatively heavier.

2.4.3 Structure

Being an X-8 motor configuration, the four arms need to project radially outwards in four perpendicular directions from the circumference of the body. In order to mount the arms on to the body, Stainless Steel L- shaped channels are being implanted into the composite structure in a cross configuration, providing rigid cantilever support at the circular periphery.

The drone is made of 3 sub-bodies, namely; Upper (Surveillance system) Cabinet, Central (Electronic Control system) Cabinet and Lower (Power system) Cabinet.

The upper body has two transparent sheets of clear Acrylic (Poly-methyl methacrylate, PMMA) embedded into the glass fibre layers of the composite body. This provides a window for the surveillance system to detect the outer surroundings, while the system is isolated inside the cabinet.

The bodies are attached to each other by placing a leak-proof flange structure at each of the two intersections i.e., at Upper Body-Central body intersection and other at the Bottom Body-Central body intersection. This flange is made up of lightweight polypropylene, consisting of two O-rings grooves on either side. O-rings pair along with silicone sealant on each side flange promises leak-proof sealing, keeping the inside totally free of water in immersed conditions.

All these 5 parts (3 body parts and 2 flanges) along with arms are also secured with Stainless Steel struts running through the extended collar at each intersection and propeller arms which keep the total structure in the same secured position. This total setup assures structural stability and rigidity, is light weight and provides a waterproof interior.

2.4.4 Electronics Compartment

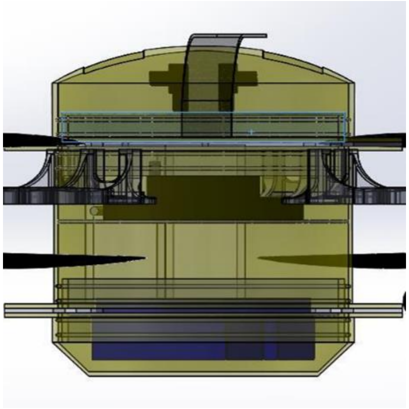

Figure 8: Electronics Compartment of Prototype 2

The Electronics cabinet is made out of glass fibre having nylon flange coupling with O rings and is designed to meet multiple requirements of the vehicle. First, the on-board electronic components need to be protected from the water outside. This has been accomplished with the uses of two nylon flanges and four O rings on each flange. The two rings, primary and secondary, form a waterproof barrier between the flange and the outer surface of the cabinet. This has been done on either side of the flange.

The second requirement is that the buoyancy force created by the vehicle should equal its weight. In this aspect of the design, the electronic cabinet plays a critical role being the largest part in the vehicle and has been designed taking this factor into consideration.

The third requirement is that the cabinet needs to be able to provide easy access to all the components. This has been done by subdividing the cabinet into several sub-compartments.

2.4.5 Hydraulics

During the underwater operations, the vehicle is designed to exploit one of the fundamentals principles in the working of underwater vehicle. The principle is that an underwater vehicle always has a tendency to align its buoyancy centre and its centre of mass with the vertical axis and that the buoyancy centre is always above the centre of mass. All underwater vehicle is inherently designed to ensure that its buoyancy centre and centre of mass are aligned and that the former is positioned above the latter as such a configuration would naturally enhance the stability of the vehicle during operations being in line with its nature physical tendencies.

The vehicle has two onboard hydraulic cylinders and is equipped with two pumps. One of the pumps is used to make water enter the cylinders while the other pump is used to remove water from the cylinders. The total volume of the cylinders is 250mL. The vehicle is designed to ensure that when the cylinders are kept empty, the buoyancy centre and centre of mass are both aligned with the vertical axis and that the buoyancy centre lies above the centre of mass and that weight of the vehicle matches the buoyancy force created by the water it displaces.

During the aerial operations, both cylinders are kept empty. In order to transition to the underwater operational configuration, the onboard cylinders need to be filled. When the cylinders are filled completely, two phenomena occur. First, the additional mass causes the vehicle to begin to sink. Second, when the cylinders are filled, they cause the centre of mass of the vehicle to shift by 5.261mm towards themselves. This results in a turning couple of 2.237kgf due to the buoyancy force and weight of the vehicle which causes the vehicle to pitch down. Now the propellers are aligned with the horizontal axis and hence configured for underwater operations. In order to transition to aerial operational configuration again, both the cylinders are emptied. The resultant reduction in weight causes the vehicle to come to the surface. The centre of mass subsequently returns to its original position and this causes the vehicle to pitch up and hence configure for aerial operations again. This procedure needs to be carried out when the vehicle has reached the target and needs to conduct surveillance operations again.

2.5 Electronics (Common for both Prototype-I and Prototype-II)

The electronics for the vehicle have been chosen so that they are highly redundant. Another constraint present was that they had to occupy minimum space and weigh less in order to increase range and flight time. A combination of:

i. Microprocessor for the flight controller
ii. Microcontroller for underwater controller
iii. Low level microcontroller for general purpose operations like obstacle avoidance, and operation of valves.

The flight controller uses a telemetry link of 900Mhz.The microcontroller is plugged into the USB of the on-board computer and this serial link is used to communicate with the Arduino microcontroller.

2.6 Communication Links

The vehicle is using four communication links in total for:

1. Telemetry: 900MHz
2. Pilot RC control: 2.4GHz
3. First Person View (FPV)
    a. First Person View (FPV) 1: 1.2GHz
    b. First Person View (FPV) 2: 5.8GHz

The above-mentioned frequencies were chosen after seeing any possible interference and provide maximum range.

1. **Telemetry:** 900MHz: The modules chosen for telemetry are the RFD 900 which operate at 900MHz. With a half wave monopole 2.1dBi antenna, it provides a range of more than 30-40kms LOS.
2. **Pilot RC control:** 2.4GHz: The pilot RC control works on 2.4GHz and provides a range of 5kms. If need arises, with a help of a 433MHz Arkbird repeater, the range can be increased to 20-25kms.
3. **FPV (First Person View):** 1.2GHz and 5.8GHz. Considering both Aerial and Underwater operations, we have chosen FPV cameras which operates at different frequencies because 1.2GHz provides higher penetration and the 5.8GHz with the right antenna provides high range at lower power input.

2.7 Autonomous Capabilities

The vehicle is capable of having manual pilot control as well as complete autonomous capabilities.

The vehicle has 2 controllers:

1. Flight controller: For Aerial Operations
2. Underwater controller: For Underwater Operations

The Control between both the controllers can be shifted with the help of a switch on the pilot RC and an 8-channel relay on the vehicle.

3 Performance Testing

3.1 Thrust measurement of a single motor with propellers of different diameter

This test was done to determine the thrust of a single motor for different propellers. However, before implementing these motors in the ARV, the maximum thrust needs to be separately determined. This task has been accomplished with the help of a weight scale. The given motor is attached to the top of a weight. As the propeller rotates, it produces a thrust in the upward direction causing the motor to be pushed in the downward direction towards the weight scale. Thus, the reading obtained in the scale is the thrust produced by the motor.

Figure 9: Single motor thrust measurement

Sr. no	Propeller Diameter (inches)	Throttle (%)	Thrust (grams)
1	8	20	143
		40	338
		60	583
		80	813
		100	929
4	10	20	167
		40	457
		60	769
		80	1018
		100	1168

3.1.1 Inference

The experiment shows that a single motor can provide a maximum thrust of 1.168 kg. Hence the use of 8 such motors would provide a maximum thrust of 1.168 x 8 = 9.344 kg.

3.2 Thrust measurement of 2 motors mounted coaxially

3.2.1 Test Goal

To determine the thrust generated by two coaxial mounted motors fitted with 10-inch propellers, efficiency of a co-axial mount configuration and optimum weight of the vehicle. In the previous experiment, it was determined that a single motor can generate a maximum thrust of 1.168kg. Hence, theoretically, the use of two motors should provide a maximum thrust of 2.336kg. However, in a coaxial mount, there is always is some loss in the total thrust generated and it is critical to determine the actual thrust generated in a co-axial configuration to calculate the optimum weight of the vehicle. The arm is connected to a rectangular plywood piece the setup has a pivot. The other end of the plywood piece rests on the top of a weight scale. When the motors rotate, they produce a thrust in the forward direction, this causes the setup to rotate in the counter clockwise direction about the pivot putting pressure on the weight scale.

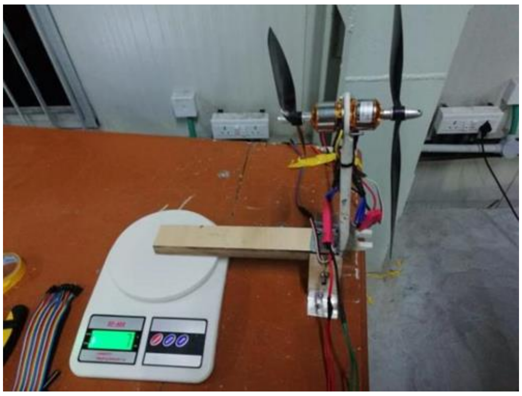

Figure 11: Coaxial Thrust measurement setup (2)

Figure 10: Coaxial Thrust measurement setup (1)

3.2.2 Observation

Sr. no	Propeller Diameter (inches)	Throttle (%)	Thrust (grams)
1	10	20	250
		40	670
		60	1128
		80	1530
		100	1730

3.3 Calculations

Maximum thrust of a single motor (from previous experiment) = 1.168 kg.
Therefore, Maximum thrust with two motors = 1.168 x 2 = 2.336 kg.
Actual maximum thrust with co-axial configuration = 1.730 kg.

Hence, efficiency = 1.750 / 2.336 = 0.7405 = **74.05 %**.

As there are four such arms,
Maximum thrust generated by the vehicle = 1.730 x 4 = **6.92 kg**.
For maximum efficiency, the weight of a multirotor should be half its max thrust.
Therefore, recommended weight = 6.92kg / 2 = **3.46kg**.

3.4 Inference

The experiment shows that two co-axially mounted motors can provide a maximum thrust of 1.730kg and the recommended weight of the vehicle for an octa-quadcopter is 3.4 kg. Hence the vehicle will have designed to not exceed this weight limit during aerial operation.

4 Conclusion

A detailed design report and features of the Amphibious Reconnaissance Vehicle have been stated. The overall aim of the research was to design a feasible and efficient ARV capable of operating in manual and autonomous mode. It is noted that Prototype II displays better advantages over the first prototype in terms of modularity and aerodynamic propulsion. By using advanced materials like composites, the structural weight can be reduced without compromising on strength. The thrust measurement process provides an insight about the optimum weight of the vehicle. It gives a clear indication of the amount of weight which can be distributed across the vehicle without causing any failure. To validate the conceptual design, flight tests are to be conducted in the future.

References

1. G.Santhan Kumar, Unnikrishnan V. Painumgal, M.N.V.Chaitanya Kumar, K.H.V.Rajesh, Autonomous Underwater Vehicle for Vision Based Tracking, International conference on Robotics and Smart Manufacturing (RoSMA2018), Procedia Computer Science 133 (2018) 169–180.
2. Pulkit Sharma, Arockia Selvakumar A, Conceptual Design and Non-Linear Analysis of Triphibian Drone, International conference on Robotics and Smart Manufacturing (RoSMA2018), Procedia Computer Science 133 (2018) 448–455.
3. Xingbang Yang, Tianmiao Wang, Jianhong Liang, Guocai Yao, Miao Liu, Survey on the novel hybrid aquatic–aerial amphibious aircraft: Aquatic unmanned aerial vehicle (AquaUAV), Progress in Aerospace Sciences 74 (2015) 131–151.