Conceptualization and Prototyping of Unmanned Amphibious Aerial Vehicle for Water Quality Assessment

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Abstract: Unmanned Amphibious Aerial Vehicles (UAAV) are gaining significant interest in accessing remote water bodies and an ideal tool for limnologist in water quality assessment. In this article, conceptualization of UAAV by inculcating the principle of hovercraft and multirotor system is carried out in a systematic approach. The unconventional configuration of UAAV makes the conceptual stage as a challenging task in the design process. In order to overcome the challenges and strapped configuration of vehicle design, the authors exploited the design process, Thirteen conceptual models are evolved and the best UAAV design model is selected based on stability, provision for accommodating payload, endurance, air cushioning effect for effective gliding along the water bodies, payload carrying capacity and modularity in construction. In addition, design of payload bay, selection of material, estimation of endurance and center of gravity calculations are carried out for those designs. The finalized conceptual models are constructed and performance of amphibious vehicles is investigated for varying the payload. The conglomerate designs of UAAV are evaluated for the design requirements and the computational fluid dynamic (CFD) analysis is performed to measure its performance characteristics. The experimental prototype of UAAV is custom built to demonstrate the competency of UAAV through flying in air and hovering in water. The test results suggested that, the developed UAAV has tremendous impact on minimizing the efforts of human being in inspecting remote water bodies in proficient way.

Keywords: Amphibious UAV, Hovercraft, Multirotor, Design Process, CFD, Prototype.

1. INTRODUCTION

The growth of awareness in drinking water alarms the water quality monitoring agencies to conduct inspection on storage and handling techniques of water for quality purpose. Those inspections on water are classified into pre-treatment and post-treatment inspections. In order to produce a good quality of drinking water in an effective manner, it's important to know about the characteristics of raw water. This focuses on water storages for the quality of stored water and the continuous assessment of water bodies helps to understand the climatic changes in water. While assessing the water, a lot of problems can be faced by the inspection team like inadequate skilled personnel, lack of boats, transfer of germs, chance of drowning, temporal effects, etc. To resolve all the issues, it urges for a compact tool to do all the water quality assessment in water body. This brings the need of amphibious characteristics in role.

The wide reach of unmanned systems makes many researchers to develop tool for various water quality assessments. Banerjee BP, *et al*., (2018) [1] has developed an UAV to collect water samples from mines to test pH, electrical conductivity and dissolved oxygen of the stagnated water. Bershadsky D, *et al*., (2016) [2] evolved a submersible unmanned multirotor system to perform samplings on surface and under waters. Doi H, *et al*., (2017) [3] has used the unmanned aerial vehicle to collect eDNA samples to study about the biomass of aquatic organism. Husson E, *et al*., (2014) [4] used an Unmanned Aircraft System (UAS) to measure the metal content deposited in the boreal river and sampling was done in riparian basin to know the contamination of water due to mining activities. Koparan C and Koc AB, (2017) [5] has used a custom built hexacopter for doing an *in-situ* water quality assessment on surface of water to measure the parameters like temperature, electrical conductivity, dissolved oxygen and pH value. Ore JP, *et al*., (2015) [6] created an aerial water sampler for making spatial data of water reservoir with the sampling data of various locations. Ribeiro M, *et al*., (2016) [7] has successfully tested the deployment of sensors and made landing of UAV in water surface for water quality checks. Rodrigues P, *et al*., (2015) [8] has made a water proof UAV system for environmental monitoring applications and demonstrated the ability of landing and takeoff from water.

The study on existing unmanned systems for water quality assessment is used to understand and benchmark the design aspects of amphibious vehicle. The design of UAAV is started from identification and collection of requirements, development of conceptual

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design, evaluation of design, selection of model, fabrication and testing of the design. The methodology shown in Figure **1** is used to understand and derive the complete design of UAAV.

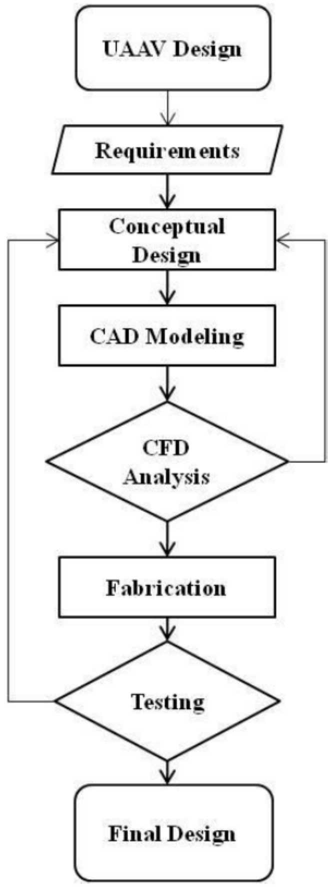

Figure 1: Design methodology of UAAV.

2. CONCEPTUAL DESIGN OF UAAV

Conceptualization is a process of evolving the ideas into design of fulfillment. In this case the design is distributed as hovercraft and multirotor design. The design parameters of hovercraft and multirotor are identified from the literature studies [9-15]. And the design constraints were found within the respective system for curtailing the design uncertainty.

The designed UAAV which needs to fly in air has multirotor and which needs to glide on water surface has hovercraft to perform water sampling analysis in various geographical locations of remote water body. The vehicle should provide space for accommodating the payload of 7kg to collect water samples of 2*l* from water body and to store the samples in a safe plastic container for laboratory testing. The in-house water sampler made up of different sensors is used to collect information of water parameters like pH, Turbidity, Pressure, Temperature, Electrical Conductivity for in-situ analysis of water quality. To systematize all the requirements, the following design process is envisaged.

The conceptual CAD models of different configurations of UAAV by changing the design variables are modeled based upon the perception of authors. Thirteen models of various compositions like changes in hull shape, type of lifting system, skirt type and classification of multirotor frames with respect to consistency of design variables are made by the authors for further design evaluation. The developed conceptual models of CM 1 to CM 6 for water quality application are shown in Figure **2** which are the baseline configuration of UAAV.

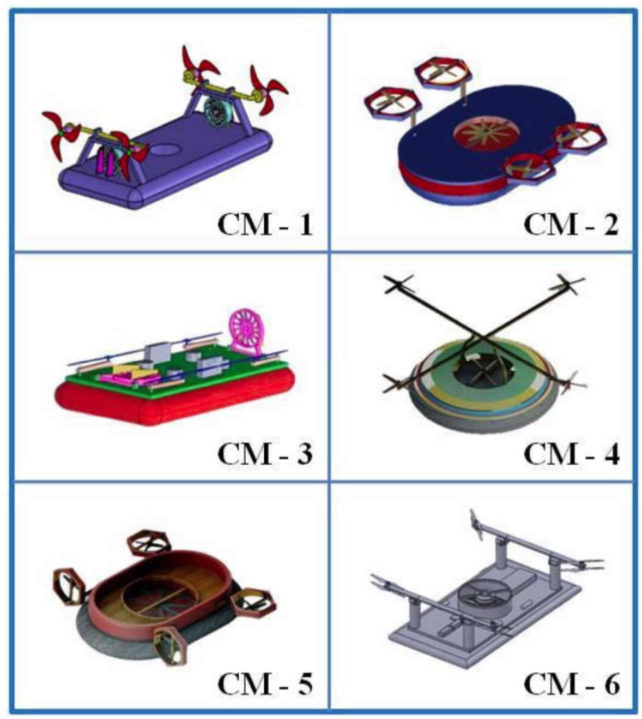

Figure 2: Baseline configurations of UAAV.

The design derivative of baseline model CM 6 is further experimented with various design alternatives and the conceptual models of UAAV CM 7 to CM 13 were developed in the form of length to width ratio of 2.

The model selected for further preliminary studies of UAAV is CM 13 shown in Figure **4**. It is a rectangular hull and H-frame multirotor configuration. To possess a good stability in nature, while operating in waters the above configuration has chosen.

The geometrical design of UAAV starts with the selection of skirt type and the design of hovercraft.

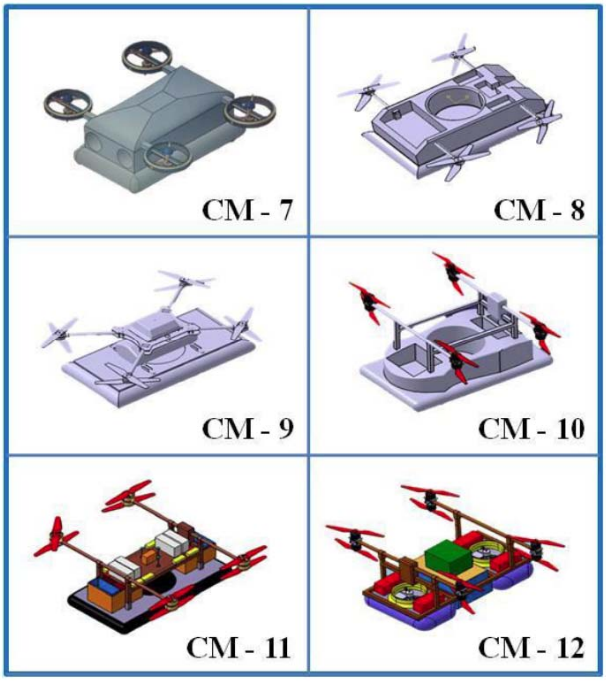

Figure 3: Derived configurations of selective model.

There are different types of skirts which are used for diversified applications. But the scenario like water sampling, a simple and smooth operation skirt is enough for design, so either an open skirt (or) a bag skirt with plenum chamber can be chosen for hovercraft model. The standard design formula (Amyot, Joseph R., ed., 2013) [16] is used to calculate the design parameters like maximum takeoff weight, length of the hovercraft, cushion area, cushion pressure, air escaping velocity, air escaping area, air flow rate and power required of hovercraft was listed in a Table **1**.

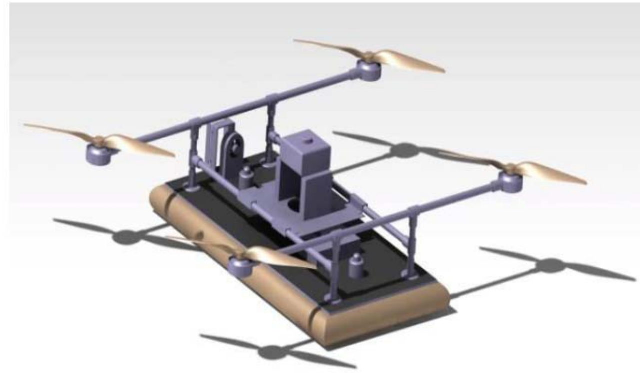

Figure 4: Conceptual Model 13.

The propulsion system is chosen based up on the maximum take-off weight (MTOW) of the UAAV. In this case the Max. Take-off weight includes the weight of hovercraft and multirotor which is approx 31.5kg. The payload fraction of the system is set to be 21.8% for design calculations. The design parameters of multirotor like lift and the thrust requirement of the system are calculated and listed in Table **2**.

The endurance of the vehicle is estimated to be 22mins and it will further extend based up on the power availability of the system. For this model CM 13, the maximum power consumption of the system for different modes of operation ranges from 2200watts to 3800watts.

The drift in C.G is very important to handle UAAV in safe flight conditions. The positions of C.G are calculated and mentioned in Table **3**. In order to balance the varying C.G of vehicle after collection of

Table 1: Design Parameters of Hovercraft

Design Parameters	Empirical Relation	Value	
Maximum Take-off weight	$W = m \times g$	310	N
Length of the hovercraft	$l = 2 \times w$	0.75	*m*
Cushion Area	$A_c = l \times w - \pi r^2$	0.375	m^2
Cushion Pressure	$P_c = \frac{W}{A_c}$	706.32	N/m^2
Air escaping velocity	$V_e = \sqrt{2\frac{P_c}{\rho}}$	33.95	m/s
Air escaping Area	$A_e = 2 \times (l \times w) \times h$	0.03175	m^2
Air flow rate	$Q_e = A_e \times V_e$	1.078	m^3/s
Power Required	$P_e = \frac{Qe \times \rho \times V_e^2}{2}$	3328	N.m/s

Table 2: Design Parameters of Multirotor

Design Parameters	Empirical Relation	Value	
Multirotor Frame Weight	W_f = *Multicopter Frame*	2.6	kg
Lift required for Multi-copter	$L_m = 1.8 \times W$	56.8	kg
Thrust per motor	$T = L_m/4$	139.5	N

Table 3: Tabulation of Centre of Gravity

Axes	Empirical Relation	Value
Centre of Gravity (CG), X-Axis	$C_{gx} = \frac{\Sigma W_i \times x_i}{\Sigma W_i}$	0.3745m
Centre of Gravity (CG), Y-Axis	$C_{gy} = \frac{\Sigma W_i \times y_i}{\Sigma W_i}$	0.3020m
Centre of Gravity (CG), Z-Axis	$C_{gz} = \frac{\Sigma W_i \times z_i}{\Sigma W_i}$	0.2230m

water, the payload is clamped and mounted at the centre of UAAV. The designed payload bay is used to accompany the volume of 2*l* water for the storage. The suspended sampler comprises of water quality sensors of pH, Turbidity, Electrical Conductivity and Dissolved oxygen is shown in Figure **5**.

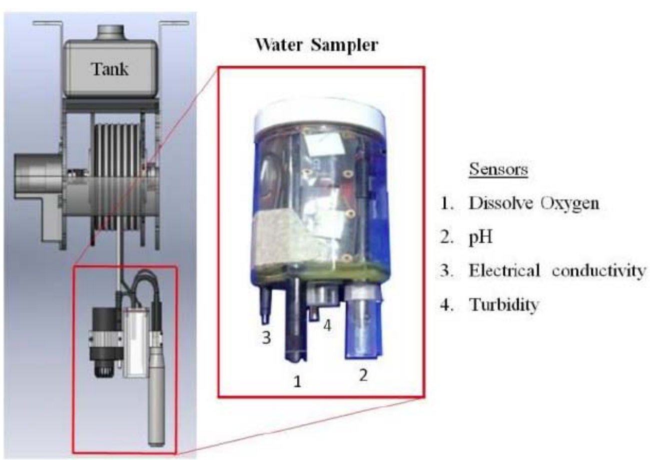

Figure 5: Typical payload system of UAAV.

3. CFD ANALYSIS OF UAAV

The aerodynamic analysis of UAAV with water sampler will help to understand the forces acting on it and the characteristics of airflow over the vehicle for different flight conditions. Drag is the major force acting on a vehicle with relative wind. The recirculation of flow, low pressure and high pressure regions in a flow are used to understand the flow properties. These characteristics of flow are influenced in flight performance parameters like speed, range, endurance, rate of climb, etc. And also it changes the behavior of vehicle in terms of stability. Hence an aerodynamic study of vehicle development is very important.

The conceptual model created in CATIA is processed on ANSYS platform for the further studies. The computational domain of 10 times greater in size is created around the object for avoiding the flow interaction on wall and formation of thickening boundary layers. To reduce the complexity of meshing, the symmetry plane with tetrahedral elements was used for meshing the geometry with scale factor of 0.5. The orthogonality and skewness check were carried out to determine the quality of meshing. The CFD analysis is performed by varying Angle of Attack (AoA) from 0° to -10° under the relative air velocity conditions of 5m/s to 10m/s.

The co-efficients of drag and lift are estimated for various wind conditions are given in Table **4**. It is observed that, the increase in AoA and wind speed causes increase in drag and decrease in lift. The simulations performed for the relative wind speed of 8.3m/s for varying AoA is shown in Figures **6** to **9**, since the maximum operating speed of UAAV is 30kmph.

It is observed from the images of velocity contour, the recirculation of air created a wake region due to loss of kinetic energy at top and rear side of the

Table 4: Estimation of Drag for Various AoA

Relative Wind Speed (m/s)	Parameters	Angle of Attack (AoA)			
		0°	-5°	-8°	-10°
5.0	C_D	0.489	0.346	0.364	0.382
	C_L	0.165	0.142	0.269	0.285
	Drag (N)	1.32	1.27	1.327	1.529
8.3	C_D	0.489	0.352	0.364	0.382
	C_L	0.165	0.156	0.272	0.249
	Drag (N)	3.639	3.582	3.654	4.213
10.0	C_D	0.489	0.349	0.367	0.379
	C_L	0.201	0.147	0.28	0.229
	Drag (N)	5.28	5.157	5.358	6.059

vehicle. But the flow attachment is happened immediately after the separation of flow over the body which will minimize the drag component of UAAV. The Figure **10** shows the results of aerodynamic analysis. The graph of C_d vs AoA is plotted for the values of Table **4** to compare the drags due to relative wind speed in UAAV with varying pitch angle. The graph shows that, no tremendous change in drag coefficient with variation of velocity. It is also found, the minimum drag coefficient for the UAAV is occurred at the range of -5° to -7° angle of attack.

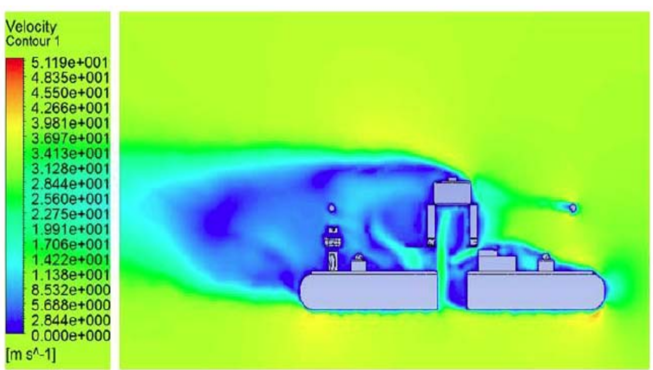

Figure 6: Velocity Contour at 0° AoA in Symmetry Plane.

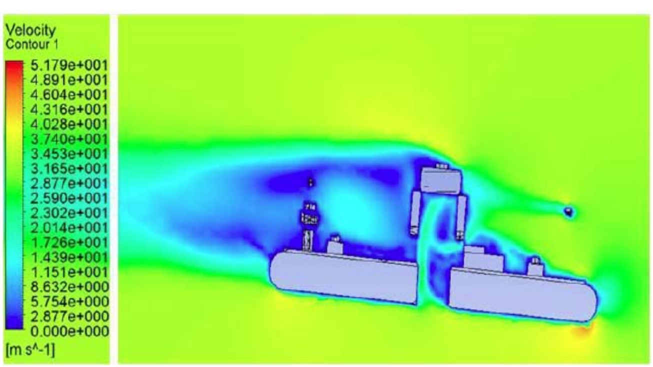

Figure 7: Velocity Contour at -5° AoA in Symmetry Plane.

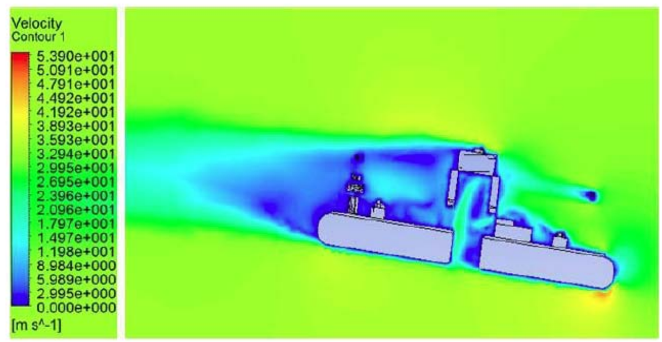

Figure 8: Velocity Contour at -8° AoA in Symmetry Plane.

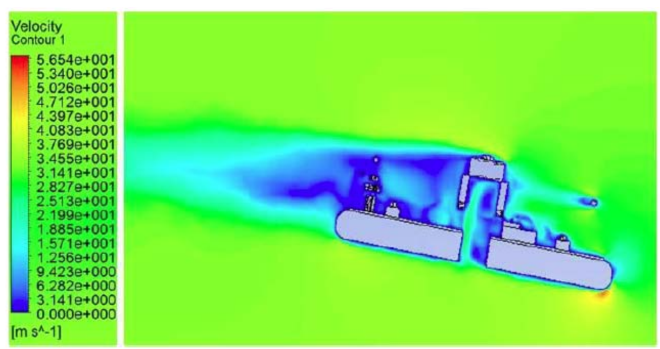

Figure 9: Velocity Contour at -10° AoA in Symmetry Plane.

4. FABRICATION OF UAAV

The precursor model of UAAV is constructed to testify and perceive the capability of flying and hovering on water surface. The fabrication is started with the stitching of skirt in a nylon impregnated urethane rip-stop material and the skirt holes are cut accordingly. The polyurethane foam is used to provide support in between the top and bottom surfaces of hull. The water resistant resin is used to adhere the sewn skirt with hull. The structural support of aluminium frame is used to carry the structural loads acting on the UAAV. The

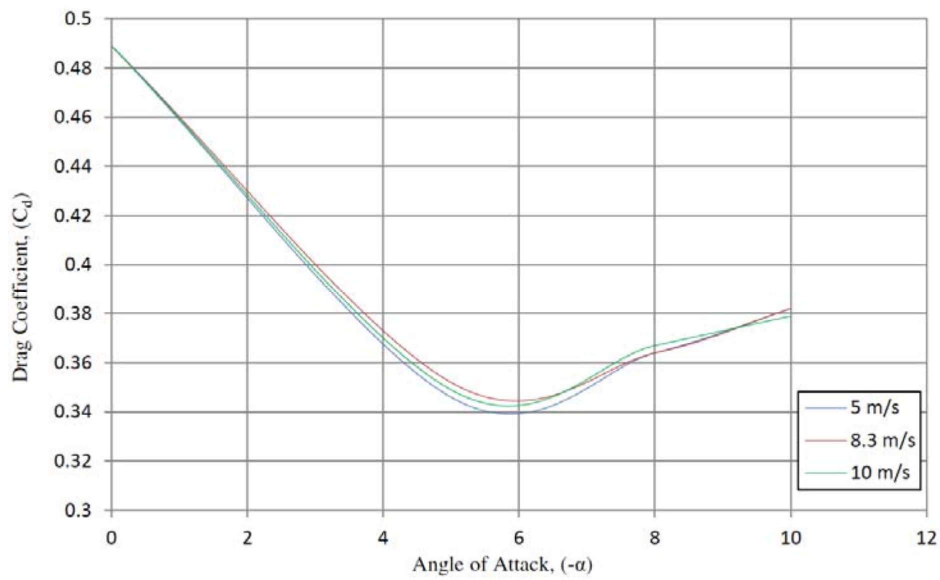

Figure 10: Drag coefficient vs Pitch angle comparison for different velocities.

load carrying member of multirotor are made up of hollow channel sections of aluminium. These frames are classified based up on their position in UAAV as vertical and horizontal frames. Before the integration of subsystems of UAAV, major components of hovercraft and multirotor are secured with suitable fasteners. The lifting motors of multirotor system are mounted at both the ends of horizontal frame. And electric ducted fan used in hovercraft is attached in their positions with the top surface of hull. The assembly of avionics systems of UAAV is taken place with connections of control components like electronic speed controller, servos, power distribution system, controller, batteries, receiver, telemetry etc.

The field testing of UAAV is conducted in our university at the ambience condition of light breeze with clear sky of 2m/s NE for flight test and stagnated water in pool with no disturbance state for water test of hovercraft. The Figures **11** and **12** shows the field trials of UAAV in airborne mode and gliding above water. For the initial level of testing, the payload of water sampling device is not attached with the system. The flying characteristic of UAAV above 5m from ground in air is fully stabilized. The static test of hovercraft in transverse and longitudinal directions possesses balanced air cushioning effect on both land and water surface.

5. CONCLUSION

The design of unmanned amphibious aerial vehicle for water quality missions is conceptualized successfully with the MTOW of 31.5kg by the thriving combination of hovercraft and multirotor. The conceptual model 13 is chosen based up on the attainment of design requirements like centralized payload mount, amalgam of operations in air and water, stability in performing course of missions and

Figure 11: Air borne of UAAV.

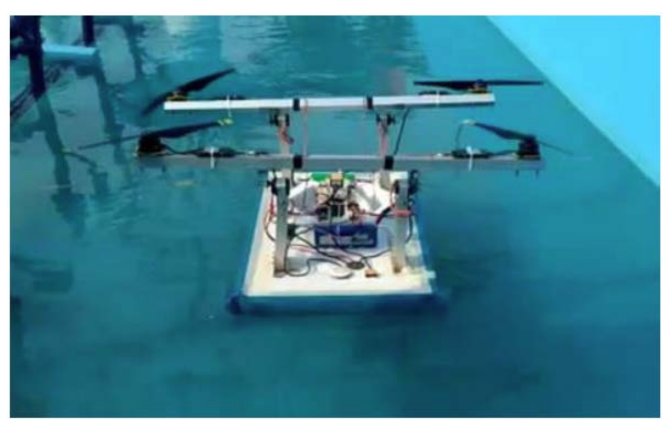

Figure 12: Gliding over water surface.

well balanced C.G positions. The performance of assembled model was prominent in the testing of skirt expansion of cushion pressure 706N/m2 and gliding on surfaces for a range period of 22mins. The evaluation of static stability of UAAV in hovercraft and multirotor modes is having excellent response. The CFD results reveal the aerodynamic aspects of vehicle are pleasing with early flow attachment after the body and maximum drag value of 6.0N for the normal operating conditions. For future endeavors, the dynamic testing of UAAV with water sampler in hovercraft mode on water and land has to be studied for performance improvements of vehicle. Also to elevate the payload fraction of the system, design optimization is required for reducing the structural weight of the UAAV.

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