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DESIGN CONCEPTION AND EVALUATION OF AN UNMANNED AMPHIBIOUS AERIAL VEHICLE USING SYSTEMATIC APPROACH

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Abstract. This article's incitement interprets Unmanned Amphibious Aerial Vehicle (UAAV)'s conceptual design process in a systematic approach. The UAAV is conceptualised to be an ideal tool for limnologists in water quality assessment. Integration of hovercraft with the multi-rotor system helps collect water samples from remote and inaccessible water bodies. The UAAV flies in multi-rotor mode, subsequently land and glide along the water surface in hovercraft mode. The new and unconventional vehicle configuration makes the conceptual stage a challenging one in the design process. To overcome the challenges and strapped configuration of vehicle design, the Authors used a systematic approach of scenario-based design, morphological matrix, and Pugh's method in the design process of the "Pahl & Beitz" model to retrieve the best possible UAAV design. The conglomerate design of UAAV is evaluated for its design requirements, and the computational analysis is performed to examine the mechanical strength and flow characteristics of UAAV. The experimental prototype of UAAV demonstrates the competence of flying in the air and hovering in water through field trials.

Keywords: unmanned amphibious aerial vehicle, design process, product design, user-centered design, scenario-based design, morphological matrix.

Introduction

Water pollution is a significant concern due to the discharge of industrial wastage, dumping of solid wastage, sewage, and other household garbage. The mixture of biological, toxic, organic, and other chemical compounds pollute the water resources inadvertently. It is essential to perform water quality inspections at regular intervals at the water reservoirs such as dams, lakes, rivers, and ponds. The collection of water samples in remote water bodies is challenging and time-consuming. The traditional method of collecting water samples using boats is cumbersome, and it is not easy to access remote water locations. While assessing the water, many issues are faced by the inspection team, such as inadequate skilled personnel, lack of boats, the transfer of germs, the chance of drowning, temporal effects, and so on. An efficient and swift assessment method is very much needed to characterise the long and broad water bodies. Unmanned Aerial Vehicles (UAVs) with floating arrangements (Esakki et al., 2019) are made to overcome these difficulties, as mentioned earlier. They can reach remote water bodies' locations, and water samples are collected in a toxic or highly contaminated water region. The extensive water bodies can be effortlessly covered and sampled in a time-effective manner, contributing to rapid water assessment.

The profound influence of unmanned system brings many researchers to develop a device for discrete water quality assessments. Banerjee et al. (2020) has invented a UAV to gather water samples from mines to examine dissolved oxygen, pH, and electrical conductivity of stalled water. Bershadsky et al. (2016) emerged a submersible UAV to achieve samplings from underwater and surface. Koparan and Koc (2017) used a hexacopter for performing in-situ water quality appraisal on the water's surface to amplify parameters such as electrical conductivity, pH value, temperature, and dissolved oxygen. A waterproof UAV system for environmental monitoring applications and autonomous take-off and landing capability from the water was shaped by Rodrigues et al. (2015). The integration of multi-rotor and hovercraft systems to perform amphibious characteristics such as flying, landing on the water surface, and moving along the water bodies is novel compared to the existing UAV systems and a very useful tool for water quality measurement.

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The Unmanned Amphibious Aerial Vehicle (UAAV) is a versatile tool for collecting water samples from various inland remote water bodies and inaccessible regions. The characteristics of unmanned and complexities of terrains in the alien region are demanding the vehicle to operate in various modes such as flying in the air as a multi-rotor to reach the inspection site in a short period and hovering on the water surface as hovercraft to collect water samples. The multi-rotor's competence helps to land the sampler on the water without any disturbance, and hovercraft are backing the smoother operations in wetlands. State of the art lies in designing a UAAV is the infusion of these two systems, such as multi-rotor and hovercraft as an integrated platform is the perception of stance.

The work described in this paper is an application of the conceptual design process of UAAV in a systematic approach to conceptualising an innovative tool for the limnologists to perform water quality inspections. The existing research studies on the creative design process (Tan et al., 2019; Nelson, 2018; Sokolowski & Meyer, 2019) reveal that there is no user involvement in physical product design though there are many predefined methodologies (Roozenburg & Eekels, 1995) and approaches (Baxter, 1995) seen in practices of product design. However, in this work, an industrial design process for addressing the real-time concerns arising out from customers to develop a state-of-the-art novel water quality assessment tool is evolved. The user-centric or user-centred design (UCD) is adopted to outline the essential requirements to pledge the design. The research practices in the design of such unconventional vehicles are not addressed in the existing literature. Hence, this work aims to conceptualise and identify the best conceptual design of UAAV for water quality monitoring in a systematic approach. The standard design process steps such as the collection of design requirements, creation of conceptual models (CM), selection of best designs, and evaluation using various techniques such as scenario-based design, affinity diagram, morphological matrices, Pugh's method, and other CAE tools are implemented in order to develop this framework.

1. Theoretical background

The theoretical studies are performed to explore the voids and complexities in the design process of UAAV and concerns with product design. Thus, a rigorous review is conducted to understand the suitable techniques and tools used in the product design, discussed in the following sections.

1.1. Challenges in design of UAAV

The derivation of a product's baseline configuration is the major challenge for any designer working during the conceptual stage (French, 1998). These challenges arise from sketching to setting up the components to configure the UAAV. In the conceptual design process, various UAAV designs are evolved, and they are evaluated based upon the satisfaction of design requirements. While framing up the priorities of customer requirements in the design of UAAV, few higher levels of consideration like performance characteristics are not suitable for selecting the vehicle's configuration due to the immeasurable nature of criterion. However, most designers are practising the selection of conceptual design as a derived form of their older versions with few modifications to satisfy the current design requirements (Ulrich, 2003). The reason for this might be the incompleteness of the explicit method in the UAV design process and the inadequacy of skills in choosing an efficient design. A few examples are Alam and Manoharan (2016) discussed an overview of amphibious UAV development for water quality measurement. They have not dealt with the detailed design aspects of amphibious UAV. Zhu et al. (2019) introduced the modelling and prototyping of a triphibious UAV. They have evaluated the performance of the vehicle analytically and experimentally without incorporating the detailed design process. Vijayanandh et al. (2019) described the Unmanned Amphibious Vehicle's conceptual design for identifying the cracks in dams. However, they have not explained the design approaches and methodologies of their proposed design.

While developing a novel hybrid concept of UAAV design, the absence of statistical and comparative data sheets of existing UAVs enable the designer to treat the conventional and standard procedures which are not valuable for the design process of UAAV. It may be difficult for designers and engineers to set up the functional characteristics of UAAV. To traverse the early stages of the design process and overcome the design uncertainty in developing a novel UAAV product, the Outside–in approach (Kim & Lee, 2010) of the industrial design method is adopted. Since the industrial design process is using user focus approaches, the non-addressable hitches of UAAV are resolved. In unconventional methodology, the new design's substantiation is critical (Ríos-Zapata et al., 2017). Hence, a systematic way of arriving at the vehicle's configuration is the eventual way to conceptualise UAAV.

1.2. Overview of design process

The design process is a sequence of action adopted by the engineers to design a new product classified into engineering design and industrial design (Lindbeck & Wygant, 1995). In general, the engineering design is a solution-focused method, and the industrial design is based on the analytical method and a systematic (Hanington, 2003) way of improving the design concerns. Hence, industrial design is widely adopted in industries for designing a new product.

1.2.1. Tools and techniques in design process

The industrial design process is quintessential in the product design, which involves the selection of the best conceptual design systematically by using the approaches such as Pugh's method, quality function deployment matrix (QFD) (Delano et al., 2000), and functional flow block diagrams (Sadraey, 2012). The following studies are conducted in the literature to explore the methodologies and techniques of existing automobile and aircraft components' existing structured design practices.

Many researchers (Kamal & Ramirez-Serrano, 2019) and engineers (Sun, 2014) used these methods in their design evaluation process. Altuntas et al. (2019) developed a customer-driven new product development of an electric vehicle for towing operations by finding customers' voice through QFD methodology. Tan (2000) has prescribed the QFD method for the conceptual design of high-altitude long-endurance (HALE) UAV. Sholeh et al. (2018) identified the aspects of developing a new product of sedan class automobile by using the morphological model, and importance-performance analysis (IPA) is conducted to assess an organisation's strength and weakness. Ul Haque et al. (2015) described buoyant hybrid aircraft's conceptual stages to select optimal configuration by employing Pugh's method for selecting the suitable design concept from multiple design variants. Engler et al. (2007) has developed a tool to select the product features by creating an interactive matrix with the consolidation of compatibility matrices and multi-attribute decision making (MADM) tool to formulate the design process systematically. Iqbal and Sullivan (2009) demonstrated the structured design methods for designing medium altitude long endurance (MALE) UAV by amalgamating the conceptual and preliminary design phases and used these data for high-fidelity CAE analysis.

1.2.2. User-based design approaches

The tendency of active user involvement in the design of new products is becoming common in many leading industries (Park, 2011) to fulfil the demand and compete in the market, which can be accomplished using standardised methods and approaches to gather data. They are utilised to design, develop, operate, and assess (Sharma et al., 2008) the product's performance. The following studies are made to address various user-based approaches like Kansei Engineering (KE), User-Centered Design (UCD), User Experience (UX) Design, Positive Design (PD) in product development.

The Kansei Engineering approach is used to adapt product design requirements by transferring the consumer's psychological outlooks into a design perspective (Nagamachi, 2002). For example, the Japanese companies Mazda and Sharp effectively utilized this concept in their product design (Tama et al., 2015). The UCD is a product development approach focusing on the user's satisfaction with a product (Buurman, 1997). It is primarily used in virtual systems and design interactions rather than physical product design (Abras et al., 2004). However, the rapid changes in the market make manufacturers use this concept to produce customizable products with customer requirements (Wu et al., 2009). UCD allows the users to specify requirements and attributes based on their desire through which end-user problems can be avoided in earlier stages. The UX design varies from UCD by continuous user participation in the design process (Hassenzahl et al., 2013). It is the user's exposure to a system or device representing the user's emotion, motivation, and action. The PD methodology developed by Martin Seligman and Mihaly Csikszentmihalyi (Seligman, 2004) improves users' emotions and happiness. Understanding nuances in positive emotions, determining the emotional intention of a product, and facilitating creativity in design conceptualisation (Desmet & Pohlmeyer, 2013) are the three components to frame up PD.

The literature studies reveal the differences in methodology and decision-making matrix of product development from case to case. The detailed interpretation of UAAV design problems and various design processes urges for more justifications and proper guidance in selecting a suitable design where engineering skills, fulfilling customers' requirements and global standards of a product are the aspects to be addressed. Hence, a suitable methodology has to be adopted before starting the design framework.

2. Design methodology

Nearly 70% of the design process issues are pertaining to inappropriate definition of the problem statement (Blessing & Chakrabarti, 2009). The mid-course corrections and re-design in product development will consume more cost and time. The decisions related to selecting models and choosing the best options for the post-design evaluation in the design process are crucial. To alleviate the current issues mentioned in the previous section, the Authors have used a systematic approach for conceptualising the UAAV design, which starts with considering user requirements analysis and ends up with the functional analysis of the selected conceptual model. The methodology proposed here (Figure 1) is a comprehensive form of acquiring the best configuration of UAAV, which shows the structure,

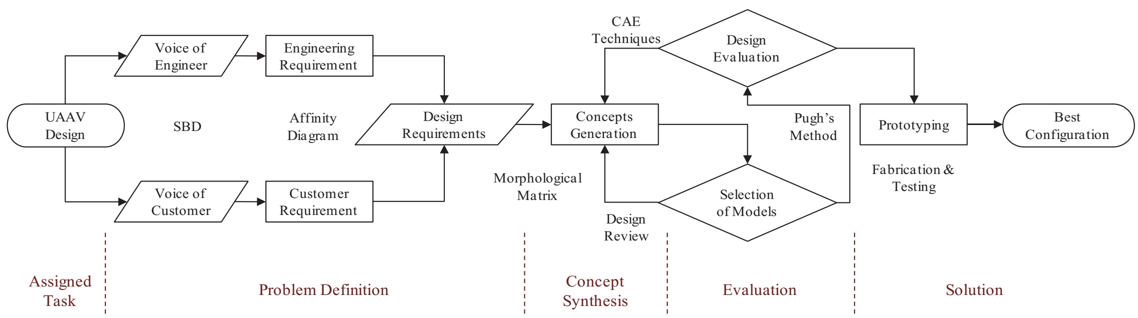


Figure 1. Design methodology of UAAV

sub-tasks, and methodology of the UAAV design process and the earlier section's standard structure.

The conceptual phase of the best known Pahl and Beitz consensus model is followed in the design process. It includes the assigned task structure, problem definition, concept synthesis, evaluation, and solution. The functions and methodologies used in each phase of design are discussed in the following sections.

3. Conceptual design of UAAV

The detailed implementation of each design step of the UAAV design process is discussed individually in the upcoming sub-sections.

3.1. Design requirements

The literature studies and the market survey are used to increase the product's solid insights for benchmarking customers' needs. The user-centric design approach of scenario-based design (SBD) is chosen to frame-up the operational requirements in the conceptual design process of UAAV for various missions. The needs and necessary characteristics of a UAAV are denoted as requirements. It is classified into customer and engineering requirements. The design factors are the essential characteristics to be followed in a design to address all the requirements. A thorough understanding of the customers' needs and wants, market trends, and competitiveness are the essential factors of the design process.

In this case, the user needs research to understand the user's requirements in which the quantitative research (QFD, (Theory of Inventive Problem Solving (TRIZ)) helps to understand the overall trends, the existing product (or) service, and the anticipated issues. It is not suitable for detailed understanding, new possibilities, and unanticipated issues.

For example, the House of Quality (HOQ) chart will not be completed without comparing the equivalent benchmark of design. Hence, the qualitative method of SBD is preferred for gathering user requirements. A similar methodology is discussed in Hsiao and Chou (2004). The information gathered from the users is used to interpret the scenario, and the storyboarding is used to extract the significant points and opinions of customers (voice of customer) and engineers (voice of engineer). Their needs are refined using the affinity diagram to find the design factors of UAAV.

The storyboard (Van der Lelie, 2006) helps showcase the scenes for a better understanding of the use of UAAV in the water quality assessment. Figure 2 shows the storyboarding sketch of SBD. The scenarios are divided into two modules, such as the present and future water quality monitoring. The result of storyboarding helps to understand and observe customers' and engineers' voices in water quality assessment.

3.1.1. Voice of customers

The selections of sampling location, water collection using a sampling device, and testing of samples in a laboratory are the basic requirements in the present water quality assessment scenario. The incursion of weeds and inhabitant of plants are the complications in reaching the sampling sites. The temporal effects may influence the data in the collection of multiple samples at various sampling sites. There are chances for accidents like immersion in water, chemical injury, and bacillus conveying to the personnel when sampling the pollutants. Thus a qualified and well competent team is essential for sampling in the deep waters.

3.1.2. Voice of engineers

Collection of water samples at distinct locations of water bodies in the form of flying and landing on water, gliding and hovering on the water surface are the missions of a UAAV. After completion of a mission, the tool should be properly packed and stored in the appropriate location. The UAAV should be capable of covering a wide range of water quality applications such as physical, chemical, and biological tests with differing payloads. More power is required by the vehicle to examine vast region in a single mission which increases the demand for endurance. Also, to gather precise water quality data, in-situ analysis has to be performed using various onboard water quality sensors for measuring the water quality parameters such as pH, Turbidity, Electrical Conductivity, Temperature, Dissolved Oxygen. Besides, for easy and effective transportation, the payload must be easily attachable and detachable from the UAAV.

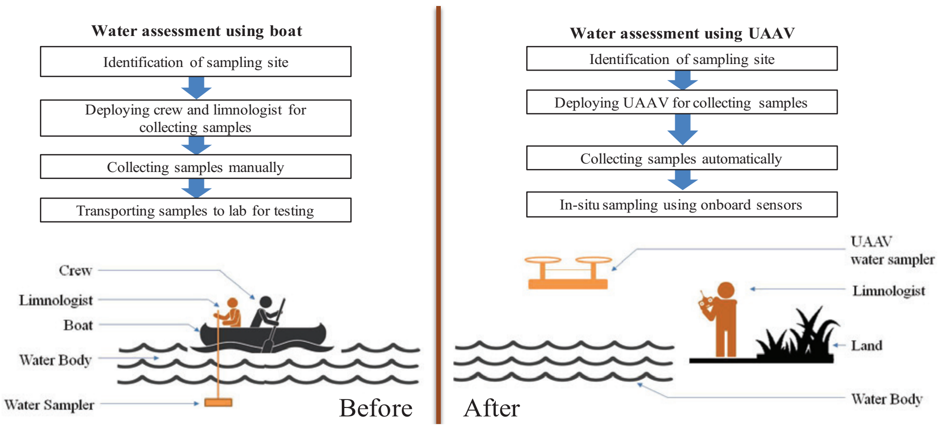


Figure 2. Storyboarding sketch – comparison of water quality assessment using boat and UAAV

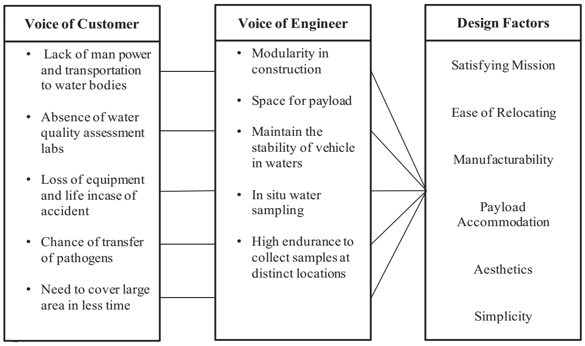


Figure 3. Design factors of UAAV by an affinity wall

The affinity diagram is considered for analyzing SBD's qualitative data in which the information is clustering, patterning, and relating the attributes with each other. The affinity diagram shown in Figure 3 is used to organize the customers and engineers requirements in a balanced state in which the affinity notes and observations of the user are clustered in the voice of customer table, and the resolution of engineer points are listed in the voice of the engineer table. It helps to understand the interrelations between the points and find the design factors based on physical properties and engineering characteristics in conclusive product attributes.

For example, to perform in-situ water sampling, the vehicle needs to have enough space to carry sensors and water storage modules onboard that determines the factor of payload accommodation. Similarly, the lack of workforce demands minimum components and modular construction. It reflects in design factor for ease of relocation and simplicity.

The aesthetics are incorporated into the list of design factors as a recommendation of the design team because it is believed that aesthetics is a crucial factor in the user experience. For a mission like water quality assessment, the vehicle should carry a water sampler to collect and store the water samples of 2 litres and glides on the water surface for the endurance of 40 min within a 2 km range at an operating speed of 30 kmph. In order to convince these hindrances, the following conceptual design process is contemplated.

3.2. Concepts generation

The theoretical analysis and prior studies are made to address the uncertainty of design process's in selecting surface and flying vehicles. The demanding characteristics of shallow water operation and fast transportation suggest hovercraft system. The conceptual stage is cleft with identifying design variables, generating concepts, and selecting the best design. The design secret of bringing the best conceptual design is making many models and selecting the outclass design (Pahl & Beitz, 2013). In this case, a concept generation technique of morphological matrix is used to gather information and generate concepts for different UAAV configurations. According to Altshuller (1984), the unorthodox combinations are the basics of creativity in the product design process. Based on that, the concept of morphological matrix is formulated. It is similar to the theory of inventive problem-solving approach that provides us with a systematic way of finding solutions by evaluating all the possibilities (Ölvander et al., 2009). The morphological matrix functions ascertain possible design variables, determine the compatibility among them, and identify the consistent combinations (Gorbea et al., 2010). The components that change vehicle configuration are considered design variables, which are shown in Figure 4.

It is evident that, the design variables for UAAV are various shapes of the hull, diverse types of skirts, lifting systems of hovercraft (Pavăl & Popescu, 2018), and frames of multi-rotor (Niemiec & Gandhi, 2016) respectively. The design alternatives with the respective coalition are alleged in Figure 5. The compatibility checks are carried out to determine each component's feasibility with other design variables (Ritchey, 2006), and it is observed that all the combinations of variables are not compatible with each other.

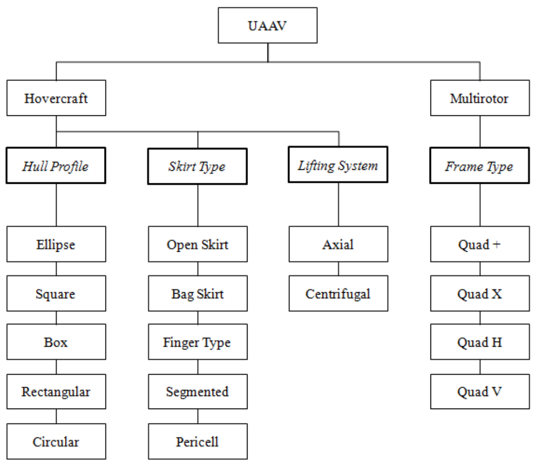
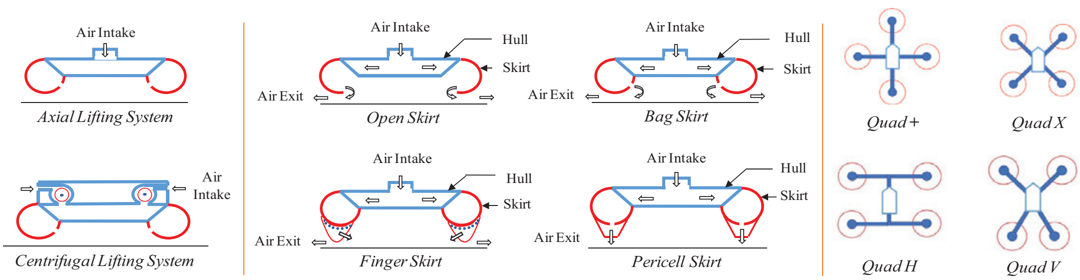


Figure 4. Morphological chart of UAAV



a) Types of hovercraft lifting system

b) Types of hovercraft skirts

c) Types of multi-rotor frames

Figure 5. Design alternatives of UAAV components: a) lifting system, b) skirt, c) multi-rotor frames

The compatibility matrix shown in Appendix Table A1 is used to formulate the possible ideas for various sets of configurations of UAAV. The variables are positioned in headers of the columns, and the options are given under each section of it. The correlation between the design variables of the hull, skirt, lifting system, and frame are given in Table A1. The values given in the compatibility chart are filled by the design team using pair-wise comparison technique, and it is used to presume the nature of consistent level, 1 is for highly consisted pair, 0.5 is for partially consisted and 0 is for the virtue of inconsistency.

The conceptual models are generated based upon the design requirements (DR) and the knowledge of amphibious characteristics (Ganesan & Esakki, 2019). The components of design variables are chosen to generate various conceptual models 1 to 13, listed in Appendix Table A2. The weightage score of 0.5 or 1.0 is given for each model's combinations according to the hull type's compatibility.

For example: In the row of CM 1 in Table A2 of the concept generation matrix, the selected variable sets are rectangular hull, open skirt, axial lifting system, and Quad H frame. By considering the rectangular hull as a reference for the model, the open skirt's compatibility score is looked up in Table A1. The consistency value of the pair is 0.5, which is observed and marked in the cell. Similarly, the values of 1.0 for the axial system and 1.0 for the Quad H frame are marked in the respective cells. These scores are summed together for understanding the consistent nature of the generated model. Based on these evaluations, CM 1 has obtained 3.5 out of 4 for the combination. Likewise, the values in Table A2 are filled for all the conceptual models.

In addition, the geometrical sizing and design constraints of UAAV are found through exploratory studies (Kamal & Ramirez-Serrano, 2019; Amyot, 2013). The length to width ratio (l/w) and bag pressure to cushion pressure (Pb/Pc) is assumed to be 2 and 1.3, respectively, and the same has been followed for the development of all the models. Table A3 in Appendix provides the design specifications of the developed conceptual models.

Before the selection of baseline configurations, design review is considered as a participatory design approach in validating the developed conceptual models. The design review committee is comprised of experts from industry and engineers working in product development. They discuss and brainstorm on the functionality, vehicle specifications, and design fulfilment of generated models. The verified and validated designs are chosen for further studies in the design process.

3.3. Design selection

The excerpt of best and baseline configuration of design of UAAV from 13 conceptual models (shown in Figure 6) is compassed by using the decision-making tool of Pugh's method. The selection of optimal configurations of UAAV conceptual models using Pugh's method is given in Appendix Table A5.

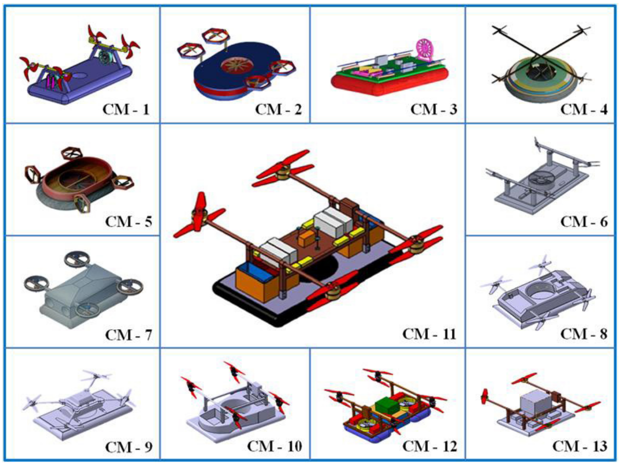


Figure 6. Conceptual models of UAAV

The evaluation factors are the standards adopted for assessing the fulfilment of design factors. The evaluation factors mentioned in Appendix Table A4 are derived from the design factors, which are defined in the requirement section. The experts' team from engineering design and product development has awarded the scores for conceptual models. The expert team's evaluation factors will be considered to provide design selection scores using Pugh's method.

Various conceptual models are considered, and the same is evaluated for the criteria mentioned in Table A4. Each criterion has its own weightage ranges from 1 (least preferred) to 10 (most preferred) based upon their significance in design. All the models are provided with a score by each criterion's satisfaction from 1 to 5. The model's overall score is the sum of products of weightage and the score of each criterion. For each model, the design attainment percentage is evaluated based on the overall score. However, (CM2, CM3) and (CM7, CM9) scores are similar and complex in decision making. To overcome this issue in design selection, a multi-criteria decision analysis technique namely Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is employed in numbering the position of conceptual models (Chakladar & Chakraborty, 2008).

The conceptual models which satisfy 75% of design requirements are chosen for further evaluation in the design process. Here CM 11, CM 12, and CM 13 have got a TOPSIS score of 0.897, 0.843, and 0.869, respectively. The derived design parameters like hull depth, cushion clearance, hover gap, hovercraft height, cushion area, cushion pressure, bag pressure, and air escaping area are chosen and given in Appendix (Table A6).

3.4. Design evaluation

The low fidelity CAE analysis is used here on selected models (CM 11, CM 12, CM 13) to determine the structural integrity and aerodynamic characteristics at specific conditions. The conditions such as various Angle of Attack (AoA), operating velocities, the vehicle's mass, and the

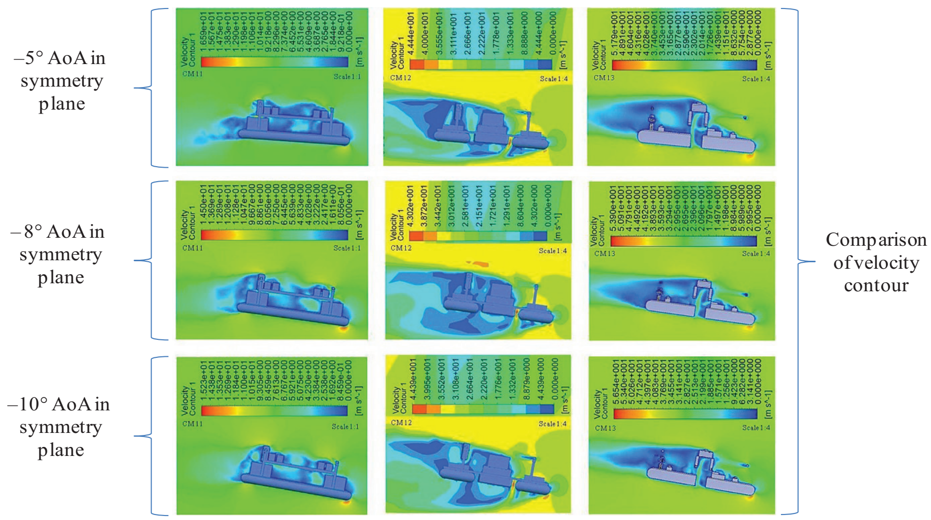


Figure 7. Comparison of velocity contour in the symmetry plane at a relative airspeed of 8.3 m/s

aerodynamic load produced due to flying are considered (Bhagat & Alyanak, 2014). The optimal coefficient of drag is evaluated through various operating conditions.

The model generated in CATIA is used for performing CFD analysis. The simulations are performed for the aerodynamic conditions to visualise the flow separation, adverse pressure gradient, and vortex formation during flying of UAAV. Using the ICEM tool, the geometry and the computational domains are meshed ten times larger than the model, which does not affect the boundaries' flow conditions. The mesh independence test is conducted to ensure solution accuracy. The quality checks of orthogonality and skewness are carried out for the meshed profile and they are found within the limit.

Figure 7 shows the comparison of simulation results of the velocity contour of UAAV for different AoA ranges from –5°, –8°, and –10° at a relative airspeed 8.3m/s (30 km/h). This comparative study reveals the influences of design in aerodynamic losses of conceptual models 11, 12, and 13. The result shows that the loss of kinetic energy and the velocity drop due to recirculation of flow in the top and rear side of the UAAV increases the total drag component. Figure 8 shows the effect of AoA on drag for various conceptual models, and it is observed that the CM 11 at approximately –5° AoA possesses minimal drag coefficient of 0.38 during the vehicle operating speed of 8.3 m/s.

The finite element analysis is performed to examine the strength and integrity of UAAV. The axial load of thrust force for maximum take-off weight (MTOW) is given at the arm structure's tip. The simulated results of static analysis of conceptual models 11, 12, and 13 shown in Figure 9 is used to understand the stress acting on the airframe and determine the maximum displacement of structure for the applied load.

Based on the CAE analysis, the aerodynamics characteristics, and structural components' rigidity with minimal deformation, CM 11 is chosen for further processing. The overall design score, including all other aspects, is infused to select CM 11 as the optimal design.

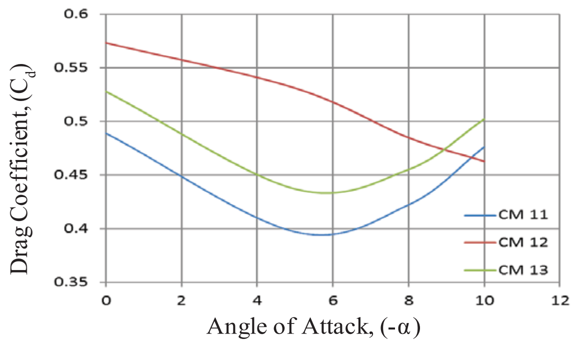


Figure 8. Drag coefficient vs Pitch angle comparison of conceptual models

3.5. Prototype

The industrial design process followed in the present work urges to clarify the selected model's engineering aspects, which are not for evaluating the selected design rather than demonstrating the functionality of UAAV. The prototype (CM 11) is built with four motors and other aspect of UAAV through combining hovercraft with central duct system is made with available components. In general, the co-axial configuration is preferred for making the UAV in a compact size to carry more payload. In this work, we have demonstrated with four motors. The modification of propulsion system from eight motors to four motors may not affect the performance characteristics of UAAV.

3.5.1. Fabrication

The fabrication of UAAV is split into the development of hovercraft and multi-rotor system. The skirt is the major component in hovercraft, which produces the cushioning effect for lifting the vehicle. Based on the types of operation in rough and smooth water, the selection of skirt type varies. A bag skirt with a plenum chamber design is chosen as a skirt for regular operations in still water in this work. The design of the skirt requires skill of curtailing and sewing. The tailored skirt is attached to

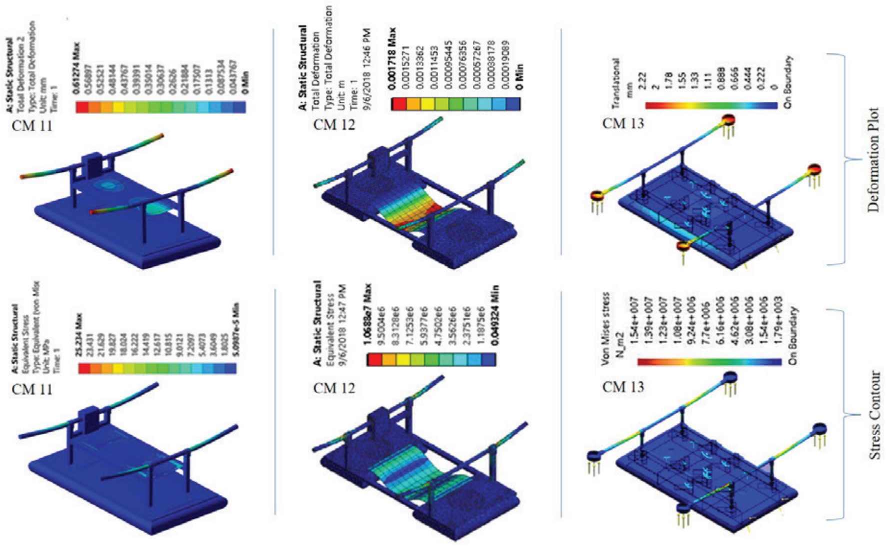


Figure 9. Deformation plot and stress contour of amphibious structures – CM 11, CM 12 and CM 13

Figure 10. An experimental test of UAAV in aerial mode and hovering in the water

the hull's bottom surface, and the air exit holes are incision into it for creating cushion pressure underneath of skirt. The plenum is constructed with polystyrene foam by providing air passage and buoyant chambers. It acts as a support to distribute the load between the hull's top and bottom surfaces. The electric duct fan is used to produce the airflow inside the skirt, which is attached to the hull's top surface, and the connections are made to control the speed of fan for the desired power requirements. The hollow channels of aluminium are used for the construction of load-carrying members of the multi-rotor system. The vertical column and horizontal arm are the primary elements in a multi-rotor system, and the lifting motors are attached at the outermost edges of the horizontal arm. The subsystems such as flight controllers, actuators, batteries, navigation systems, and communication devices are positioned appropriately on the UAAV structure to balance the centre of gravity.

3.5.2. Testing

As proof of concept, testing is performed to evaluate the design attributes and demonstrate the capability of UAAV in aerial flying and hovering mode in water. The integrated vehicle's outdoor flight test is tested on light breeze wind conditions of 2.8 m/s NE at our university. The static test of hovering and dynamic test of gliding on land at indoor conditions are carried out at our university, and the same on the water surface for an altitude of 5 m and 10 m are tested at water pool in the absence of atmospheric disturbances as shown in Figure 10. The test results show the UAAV possesses good stability in nature for both aerial and water operations.

Conclusions

A systematic design approach incorporating the SBD technique to gather data and morphological layout to satisfy the design requirements for designing a UAAV is well established. Pugh's evaluation method concerning various design criterions such as ease of relocating, manufacturability, payload accommodation, aesthetics, and simplicity resulted in the three best configurations, CM11, CM12, and CM13. Design evaluation is performed for these three UAAVs using CFD analysis. It is evident that CM 11 attained a minimum drag coefficient of 0.38 at approximately −5°AoA for the maximum operating speed of 8.3 m/s. FEA studies suggested that Aluminium material has achieved minimum deformation and stress. The multirotor and hovercraft systems are integrated, and various electronic modules are assembled. The developed prototype of UAAV is tested for its stability in air and water-borne modes. The dynamic stability of UAAV in air, above ground level of 5 m and 10 m is achieved good stable flight. The static stability of UAAV in the longitudinal and transverse direction is controlled effectively in both land and water. The developed UAAV can be well suited for collecting water samples and inspection remote water bodies using onboard in-situ water quality sensors. It is concluded that the proposed design methodology is suitable for designing UAAV for diverse applications in the designated missions. This research work provides an idea for the researchers to address the challenges of unconventional product design systematically. In future, the developed systematic approach can be well exploited to design a novel UAV for diverse applications.

Conflict of interest

The Authors affirm that there is no conflict of interest to be declared for this publication.

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Appendix

Table A1. Compatibility matrix of design variables

Compatibility Matrix		Hull Type					Skirt Type					Lift Sys.		Frame Type			
		Ellipse	Square	Box	Rectangular	Circular	Open	Bag	Finger	Segmented	Pericell	Axial	Centrifugal	Quad +	Quad X	Quad H	Quad V
Hull Type	Ellipse	1.0	0.0	0.0	0.0	0.0	0.5	0.5	1.0	1.0	0.0	1.0	0.0	0.5	1.0	1.0	0.5
	Square	0.0	1.0	0.0	0.0	0.0	0.5	1.0	0.0	0.5	1.0	1.0	0.0	1.0	1.0	0.5	0.0
	Box	0.0	0.0	1.0	0.0	0.0	0.5	1.0	0.0	0.5	1.0	1.0	1.0	0.0	0.5	1.0	1.0
	Rectangular	0.0	0.0	0.0	1.0	0.0	0.5	1.0	0.0	0.5	1.0	1.0	0.5	0.0	0.5	1.0	0.0
	Circular	0.0	0.0	0.0	0.0	1.0	0.5	0.5	0.5	0.5	0.0	1.0	0.0	1.0	1.0	0.0	0.5
Skirt Type	Open	0.5	0.5	0.5	0.5	0.5	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
	Bag	0.5	1.0	1.0	1.0	0.5	0.0	1.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0
	Finger	1.0	0.0	0.0	0.0	0.5	0.0	0.0	1.0	0.0	0.0	0.5	1.0	0.0	0.0	0.0	0.0
	Segmented	1.0	0.5	0.5	0.5	0.5	0.0	0.0	0.0	1.0	0.0	0.5	1.0	0.0	0.0	0.0	0.0
	Pericell	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5	1.0	0.0	0.0	0.0	0.0
Lift Sys.	Axial	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	1.0	0.0	0.0	0.0	0.0	0.0
	Centrifugal	0.0	0.0	1.0	0.5	0.0	0.0	1.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0
Frame Type	Quad +	0.5	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
	Quad X	1.0	1.0	0.5	0.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
	Quad H	1.0	0.5	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
	Quad V	0.5	0.0	1.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0

Note: 1.0 – highly consist; 0.5 – partially consist; 0.0 – in-consist.

Table A2. Concept generation matrix of models

		Hull Type					Skirt Type					Lift Sys.		Frame Type				Total
		Ellipse	Square	Box	Rectangular	Circular	Open	Bag	Finger	Segmented	Pericell	Axial	Centrifugal	Quad +	Quad X	Quad H	Quad V	
Conceptual Models	CM 1	x	x	x	1.0	x	0.5	x	x	x	x	1.0	x	X	x	1.0	x	3.5
	CM 2	1.0	x	x	x	x	0.5	x	x	x	x	1.0	x	X	x	1.0	x	3.5
	CM 3	x	x	x	1.0	x	0.5	x	x	x	x	1.0	x	X	0.5	x	x	3.0
	CM 4	x	x	x	x	1.0	0.5	x	x	x	x	1.0	x	1.0	x	x	x	3.5
	CM 5	1.0	x	x	x	x	0.5	x	x	x	x	1.0	x	X	x	1.0	x	3.5
	CM 6	x	x	x	1.0	x	0.5	x	x	x	x	1.0	x	X	x	1.0	x	3.5
	CM 7	x	x	x	1.0	x	0.5	x	x	x	x	x	0.5	X	x	1.0	x	3.0
	CM 8	x	x	1.0	x	x	0.5	x	x	x	x	1.0	x	X	x	1.0	x	3.5
	CM 9	x	x	x	1.0	x	0.5	x	x	x	x	1.0	x	X	0.5	x	x	3.0
	CM 10	x	x	x	1.0	x	0.5	x	x	x	x	1.0	x	X	x	1.0	x	3.5
	CM 11	x	x	x	1.0	x	x	1.0	x	x	x	1.0	x	X	x	1.0	x	4.0
	CM 12	x	x	x	1.0	x	x	1.0	x	x	x	1.0	x	X	x	1.0	x	4.0
	CM 13	x	1.0	x	x	x	x	1.0	x	x	x	1.0	x	X	x	0.5	x	3.5

Note: x – not applicable; scores (0.5–1.0) – values from compatibility matrix.

Table A3. Design specifications of conceptual models

Design Specification		Conceptual Models												
		CM 1	CM 2	CM 3	CM 4	CM 5	CM 6	CM 7	CM 8	CM 9	CM 10	CM 11	CM 12	CM 13
Hovercraft	Length (m)	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.7
	Width (m)	0.5	0.5	0.5	NA	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Height (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	No. of ducts	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0	2.0
Multi-rotor	Arm Length (m)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2
	Height (m)	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.3
	No. of Motors	4.0	4.0	4.0	4.0	4.0	8.0	4.0	8.0	8.0	8.0	8.0	8.0	4.0

Table A4. Design criterion and evaluation factors

Criterion	Evaluation Factors
Satisfying Mission	The model should be able to accomplish mission objectives. Vehicle design should be compatible with land and aerial missions.
Ease of Relocating	Minimum skills are required to assemble, disassemble, and re-assemble as its mounting differs from mission to mission. Should be easily transportable
Manufacturability	Minimum manufacturing processes should be used. Manufacturing techniques used should be cost-efficient.
Payload Accommodation	Sufficient space should be provided to accommodate different payload for multi-mission
Aesthetics	Components should be fairly assembled to provide an excellent appearance to the vehicle.
Maintenance	Components and systems should be repairable. No frequent maintenance should be required, and the maintenance cost should be nominal.
Simplicity	The design should be easily understandable, with no complex connections. Fewer components should be used.

Table A5. Design selections of conceptual models by Pugh's method

Conceptual Models		CM - 1		CM - 2		CM - 3		CM - 4		CM - 5		CM - 6		CM - 7		CM - 8		CM - 9		CM -10		CM -11		CM -12		CM -13	
Factors	Weightage	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S	Sc	S
Satisfying Mission	10	2	20	2	20	2	20	1	10	2	20	2	20	3	30	4	40	2	20	4	40	5	50	5	50	5	50
Ease of Relocating	10	1	10	2	20	2	20	3	30	2	20	2	20	3	30	4	40	4	40	4	40	5	50	5	50	4	40
Manufac-turability	9	3	27	3	27	3	27	4	36	3	27	4	36	3	27	3	27	3	27	3	27	4	36	4	36	4	36
Payload Accommo-dation	9	1	9	2	18	1	9	1	9	2	18	2	18	2	18	3	27	2	18	3	27	4	36	4	36	5	45
Aesthetics	8	2	16	1	8	3	24	2	16	3	24	3	24	3	24	2	16	3	24	3	24	4	32	4	32	4	32
Mainte-nance	7	3	21	2	14	2	14	3	21	3	21	3	21	3	21	3	21	3	21	3	21	4	28	3	21	4	28
Simplicity	7	1	7	3	21	2	14	3	21	3	21	3	21	2	14	3	21	2	14	3	21	4	28	3	21	4	28
Overall Score (300)		110		128		128		143		151		160		164		192		164		200		260		246		259	
DR Satisfaction %		36.7		42.7		42.7		47.7		50.3		53.3		54.7		64.0		54.7		66.7		86.7		82.0		86.3	
TOPSIS Score		0.174		0.280		0.271		0.310		0.359		0.371		0.438		0.607		0.442		0.645		0.897		0.843		0.869	
TOPSIS Rank		13		11		12		10		9		8		7		5		6		4		1		3		2	

Note: Weightage rated 1–10; score rated 1 (worst)–5 (Best), where: score – (Sc); Sum – (Σ).

Table A6. Design parameters of UAAV

Parameter	Empirical relation	CM - 11	CM – 12	CM - 13
Length to width	(l / w)	2	2	2
Bag pressure to cushion pressure	(P_b / P_c)	1.3	1.3	1.3
Forward thrust to overall weight during hovering	(T_f / W)	0.2	0.2	0.2
Propeller pitch to diameter	(p / d)	0.6	0.6	0.6
Vertical thrust to maximum take-off weight	(T_v / W)	2	2	2
Maximum take-off weight (W)	$m \times g$	269.78 N	309.01 N	299.20 N
Length of the hovercraft (l)	$2 \times w$	1.00 m	1.00 m	1.00 m
Cushion Area (A_c)	$l \times w - \pi r^2$	0.40 m^2	0.27 m^2	0.49 m^2
Cushion pressure (P_c)	$\frac{W}{A_c}$	674.44 N/m^2	1144.5 N/m^2	609.37 N/m^2
Air escaping velocity (V_e)	$\sqrt{2\frac{P_c}{\rho}}$	33.18 m/s	43.23 m/s	31.54 m/s
Air escaping area (A_e)	$2\times(l+w)\times h$	0.038 m^2	0.038 m^2	0.038 m^2
Airflow rate (Q_e)	$A_e \times V_e$	1.26 m^3/s	1.64 m^3/s	1.20 m^3/s
Power required (P_e)	$\frac{Q_e \times \rho \times V_e^2}{2}$	852.32 Watts	938.62 Watts	731.15 Watts
Required motor speed (N)	$\sqrt{\frac{L_m \times 10^{10}}{p \times d^3 \times 0.0283495 \times g}}$	4200 rpm	4070 rpm	4070 rpm
Thrust per motor (T)	$p \times d^3 \times N^2 \times 10^{-10} \times 0.0283495 \times g$	150 N	147.1 N	147.1 N
Lift required for multi-copter (L_m)	$2 \times W$	540 N	618 N	N