32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Conceptual Design of a Fixed-Wing Aquatic UAV Using Knowledge Based Engineering

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Abstract

Aquatic unmanned aerial vehicle (AquaUAV) combines both of the operations in the air and water. It possesses bright wide prospects in military and civil field. Especially for fixed-wing AquaUAVs, they are easier to meet the design requirements of low power consumption and long endurance flight. For specific mission requirements such as navigation under the water, it is hard to rapidly reconstruct a new robust design software for mission evaluation by traditional method. Knowledge based engineering (KBE) is a technique which owns extremely high efficiency for reuse, extension and maintenance of domain knowledge of new concept design. KBE is capable of rapidly building new robust design tool and maintaining the data traceability during the design process. In this paper, KBE is used for building a design tool for AquaUAV conceptual design. The system modeling language (SysML) is used for knowledge representation of conceptual design of AquaUAV. The represented knowledge includes both the structures and the behaviors of AquaUAV conceptual design. Moreover, Common Parametric Aircraft Configuration Schema (CPACS) is used as the central data format served for efficient data exchange and transformation within the design tool. In this research, in order to get a well underwater performance, the AquaUAV is designed to be manufactured by 3D printing technique. The performance about the underwater balance of the AquaUAV has been evaluated by the design tool produced by KBE and the feasibility of manufacturing the designed AquaUAV fully based on 3D printing technology has also been validated by flight test.

Keywords: AquaUAV, conceptual design, KBE, 3D printing

1. Introduction

Rapid Operational Responsiveness (OpRes) is an essential quality to evaluate the performance of an Unmanned Aerial Vehicle (UAV) platform according to the research of Simon W Miller et. Al [1]. One of the most important components of OpRes is the tools to assist UAV design. Due to the multi-disciplinary and multi-fidelity nature of aircraft design, aircraft design is usually carried out in a multidisciplinary integrated design software. However, for the existing design software, domain-specific engineering knowledge is tightly integrated with knowledge execution. It is very difficult to reconstruct a new robust design software for specific mission requirements.

Compared with the traditional aircraft integrated design software, Knowledge based engineering (KBE) can rapidly build new robust design software and maintain the data traceability during the design process. KBE is a technique combining artificial intelligence (AI) and computer science for complex product design [2]. It is capable of representation, reuse and maintenance of engineering knowledge. KBE distinguishes itself from other knowledge-based (KB) technique by extremely high efficiency for geometry manipulation and data processing. The design knowledge can be represented by engineers via a standard knowledge representation methodology. Then the represented engineering knowledge can be translated into code for execution automatically.

As a new notional UAV, the aquatic unmanned aerial vehicle (AquaUAV) can combine both of the operations in air and water domains. It has drawn great interest both in military and civil fields. The development of AquaUAV capable of operating seamlessly both under the water and in the air has become the focus during the past few years. Within the past decade, the design of an AquaUAV was usually done in a bio-inspired way. The bio-inspired design makes use of the efficiency of

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already perfect natural designs such as diving birds and flying fishes [3-7]. The first cross-domain fixed-wing AquaUAV was developed by Warren Weisler et al. [8]. This fixed-wing AquaUAV presented untethered dynamic and energetic characterizations from the tests between the aerial flight and underwater locomotion transition. For fixed-wing AquaUAVs, they are easier to meet the design requirements of low power consumption and long endurance flight [9]. So in this paper, KBE technique is used to build the design software application for conceptual design of fixed-wing AquaUAV.

2. Knowledge Based Engineering

Here, the definition of knowledge based engineering from La Rocca [10] which is more preferred in the field of aircraft design is quoted as follows:

Knowledge based engineering (KBE) is a technology based on the use of dedicated software tools called KBE systems, which are able to capture and systematically reuse product and process engineering knowledge, with the final goal of reducing time and costs of product development by means of the following:

- *Automation of repetitive and non-creative design tasks*
- *Support of multidisciplinary design optimization in all the phases of the design process*

Fig. 1 shows the methodology of developing a new KBE application. In order to build an KBE application for solving a specific domain problem, the development usually goes through four main phases. At first, the engineers need to identify whether there is a necessity to create a new KBE application or just to modify an exited one for this problem. Next, the knowledge of this problem should be represented by using a knowledge representation methodology. Then the represented knowledge is translated into codes and packaged into an executable application. Finally, this application will be deployed on the computers.

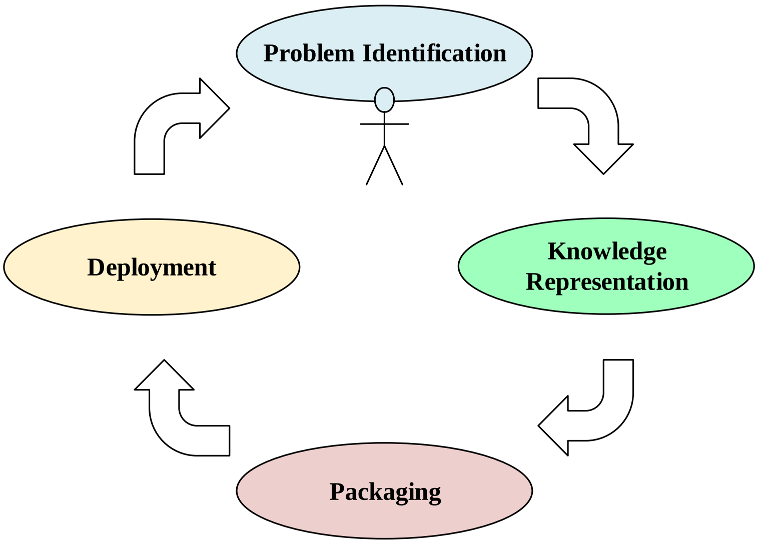

Fig.1 The methodology of developing a KBE application

Knowledge representation is the most important part of the methodology of developing a KBE application [11-13]. In recent years, system modeling language (SysML) has been applied to support aircraft design [14, 15]. Using SysML can make the aircraft product knowledge stored, modified and communicated in a consistent and concise way. SysML has been accepted as an industry-adopted language supported by a variety of tools for modeling and processing. Moreover, it can reduce the development time by automatic transformation from the represented knowledge to code. In this paper, SysML is used for knowledge representation of the conceptual design of AquaUAV.

3. Knowledge representation of conceptual design of AquaUAV

In this section, SysML is used to represent the knowledge of AquaUAV conceptual design. The block definition diagrams (BDDs) are used to describe the structure of conceptual design and the activity diagrams (ACTs) are used to describe the process of conceptual design.

3.1 Structure of AquaUAV conceptual design

In Fig. 2, BDD is used to define the components of AquaUA. Each component is modeled by a block element. The relationship between the components is represented by part association link indicating the affiliation of components.

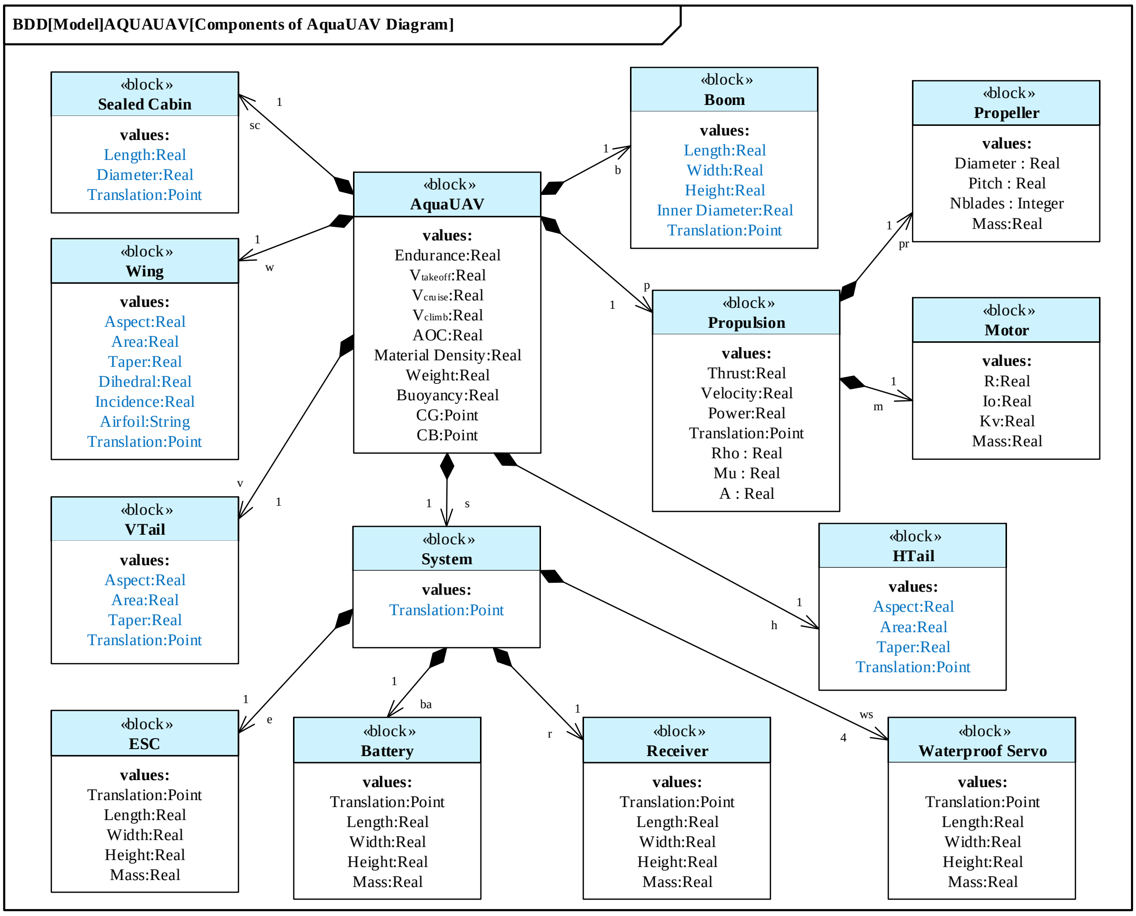

Fig.2 The components of AquaUAV in Block Definition Diagram

Buoyancy and weight are important properties of AquaUAV. For making AquaUAV capable of navigating underwater efficiently, the buoyancy and weight should be balanced. The buoyancy may be slightly larger than weight so that the vehicle can be able to return safely to the surface once the system breaks down. The center of buoyancy (CB) and the center of gravity (CG) are also important properties for underwater operation. The CB should be placed forward the CG so that AquaUAV can be nose-up relative to horizontal when it is in the static balance under the water, which is be benefit for egressing from the water. This AquaUAV is designed to be manufactured by Additive manufacturing (AM). UAV components can be produced via automatic process without tooling or molds, AM can reduce development times and costs significantly and has promise for providing new opportunities for UAV design [16-18]. The property material density of AquaUAV should equal to the density of material for 3D printing. Polylactic acid (PLA) is a common material used for 3D printing. PLA is used as the material for airframe. Therefore, the density of material is 1.26 g/cm3. As the density is close to that of water, it is helpful for efficient underwater navigation. The properties of AquaUAV such as endurance, takeoff speed (Vtakeoff), cruise speed (Vcruise) and so on are mission reqirements.

For all other components, the geometric properties such as length, width, height, translation are all design variables. These design variables should meet the mission requirements and the constraints among weight, buoyancy, CG and CB mentioned above. A modular airframe will be easy to be manufactured by 3D printing. So the fuselage is replaced by a boom. The boom is a carbon tube with rectangular cross section. All the other components can be attached to the boom. Equipments without waterproof treatment are all contained in the sealed cabin. The sealed cabin is also used for trimming the CB. The tips of the wing are made open. This will help the AquaUAV to achieve near-neutral buoyancy under the water by allowing the water enter the wing during ingress. The system of the AquaUAV consists of an electronic speed controller (ESC), a battery, a receiver and four waterproof servos. The system is regarded as a concentrated mass and used to trim the

CG of the AquaUAV. The AquaUAV is designed to be electric-powered, the propulsion consists of a motor and a propeller. It is necessary to evaluate the electric power for outputting the required propulsion power represented by the value of thrust multiplied by velocity. In order to calculate electric power, the properties used to characterize a motor should include mass, resistance (R), no-load current (I0), and rotation speed per volt (Kv). The rotation speed is defined as revolutions per minute (RPM). As for propeller, the properties should include mass, diameter, pitch and the number of blades (Nblades). The performance of the combination of motor and propeller must also consider the influence of media for operation. Therefore, the properties of the propulsion also contain the density (Rho), coefficient of kinematic viscosity (Mu) and speed of sound (A) of the media.

In Fig. 3, BDD can also be used to define the behaviors for AquaUAV conceptual design. Each behavior is modeled by an activity element. As shown in Fig. 3, the conceptual design activity contains other activities including maximum lift coefficient (CL_{Max}) estimation, wing loading (W/S) estimation, power to weight ratio (P/W) estimation, sketch drawing, aerodynamic analysis, propulsion analysis, zero-lift drag coefficient (CD0) estimation, battery specific energy (E_{spec}) and battery specific power (P_{spec}) calculation.

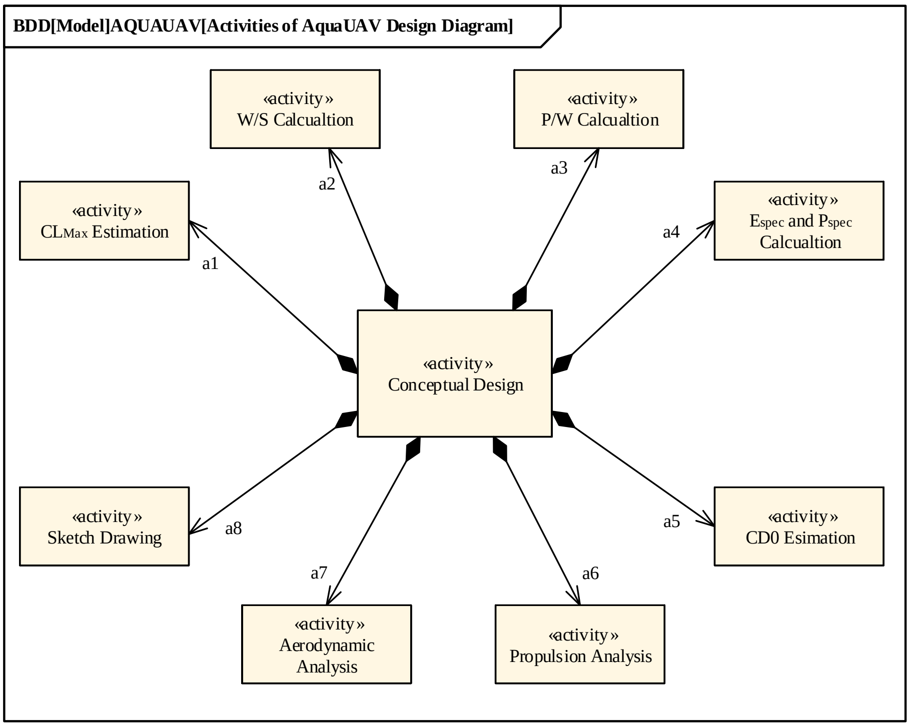

Fig.3 The behaviors of AquaUAV design defined in Block Definition Diagram

3.2 Process of AquaUAV conceptual design

Usually, automatic design by KBE application was driven by rule-based production inference engine. Process knowledge is represented in IF->Then rules. For a problem with complex logical relationship, this inference mechanism owns high execution efficiency. However, it is a hard job to represent complex process knowledge in a rule-based way with correct logical relationship. Fortunately, SysML provides ACT to describe the process of an activity. Therefore, in this section, ACTs are used to describe the process of AquaUAV conceptual design. As shown in Fig. 4, the representation of conceptual design process by ACT consists of a number of nodes and flows. The process begins from the initial node and follows the direction of flows. Once the flow passes by an action node, it is fired to call a piece of external codes that perform the process described by the action. The call behavior action node can call another behavior. When the flow reaches the final node, the activity will be terminated.

For conceptual design of AquaUAV, the influence of the buoyancy and the center of buoyancy should be considered. Therefore, two additional action nodes for calculating the buoyancy and the center of buoyancy have been added into ACT in Fig. 4.

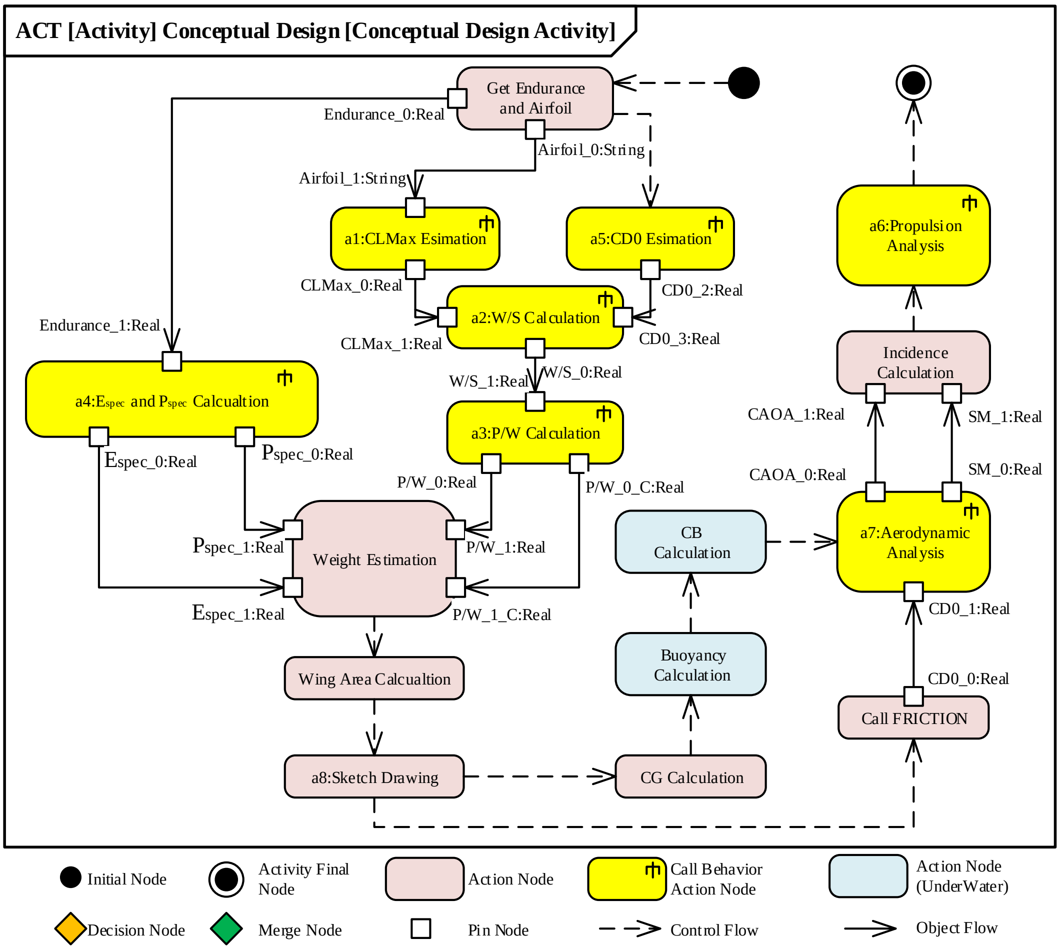

Fig.4 The conceptual design in Activity Diagram

The value of CL_{Max} is calculated based on the results provided by XFOIL [19] as shown in Fig. 5a. XFOIL is an analysis and design program for low Reynolds number of airfoils. The initial value of CD0 is calculated based on the statistical model of conventional layout provided by Raymer [20] as shown in Fig. 5b. The sketch of AquaUAV has been drawn by AnyCAD [21]. AnyCAD is a professional 3D graphics component for visualization and geometry modeling. AnyCAD that used in this paper is a free package in version 2013.

Based on the sketch, the FRICTION action in Fig. 4 will call FRICTION [22] program to perform the calculation of CD0 accurately. FRICTION is a program from the Virginia Tech aerospace engineering aerodynamics and design software collection. FRICTION can provide the estimation skin friction and form drag for use in aircraft preliminary design. This program is valid for incompressible flow at low Reynolds number.

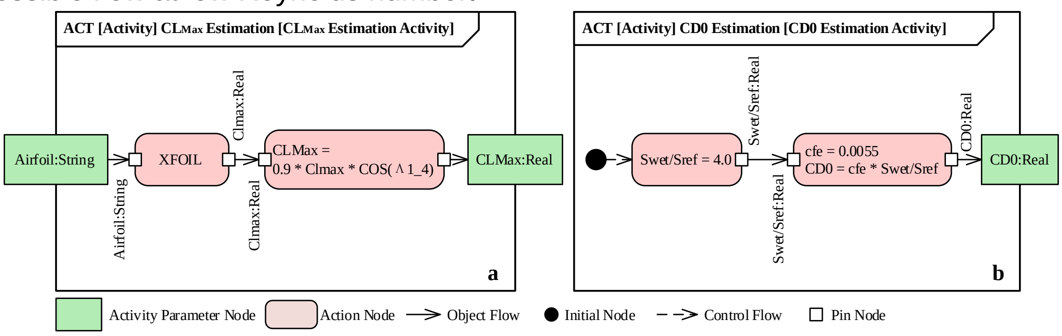

Fig.5 The CL_{Max} estimation and CD0 estimation in Activity Diagram

The ACT of W/S calculation activity is shown in Fig. 6a. By comparing the W/S at takeoff, cruise and stall, the minimum value is taken as the W/S of the AquaUAV. In Fig. 6b, by using W/S as input, the P/W at takeoff, climb and cruise is calculated. The maximum value is used as the P/W of AquaUAV. Meanwhile, this activity also outputs P/W_C (power to weight ratio at cruise).

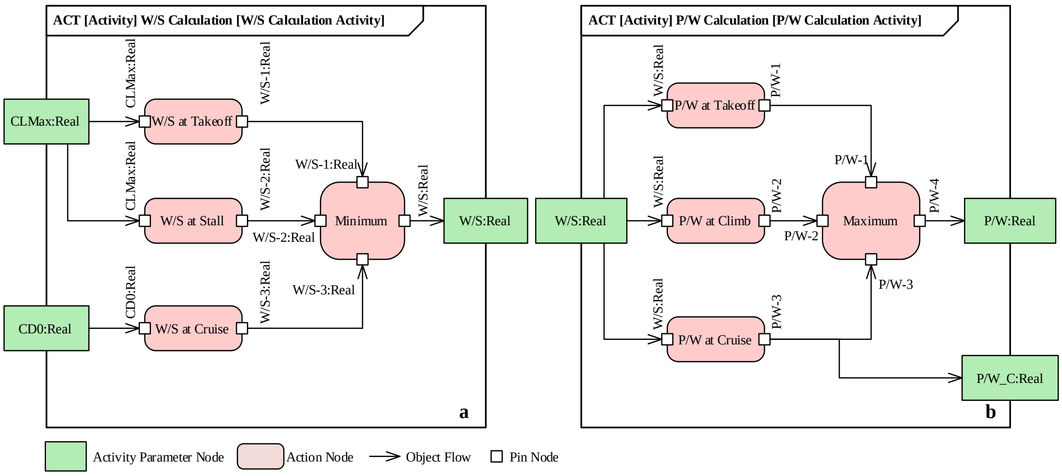

Fig.6 The of W/S and P/W in Activity Diagram

In Fig. 7a, for calculation of the mass of battery, the values of E_{spec} and P_{spec} should be determined. As the values of E_{spec} and P_{spec} vary with the design endurance, the values can be gotten directly from the battery specific energy and specific power curve. In Fig. 7b, AVL [23] which is a vortex lattice method is employed to make aerodynamic analysis with low speed inviscid flow and stability/control analysis. It can evaluate the cruise angle of attack (CAOA) and the longitudinal static stability represented by static margin (SM). As AVL is an inviscid code, CD0 must be provided before AVL runs.

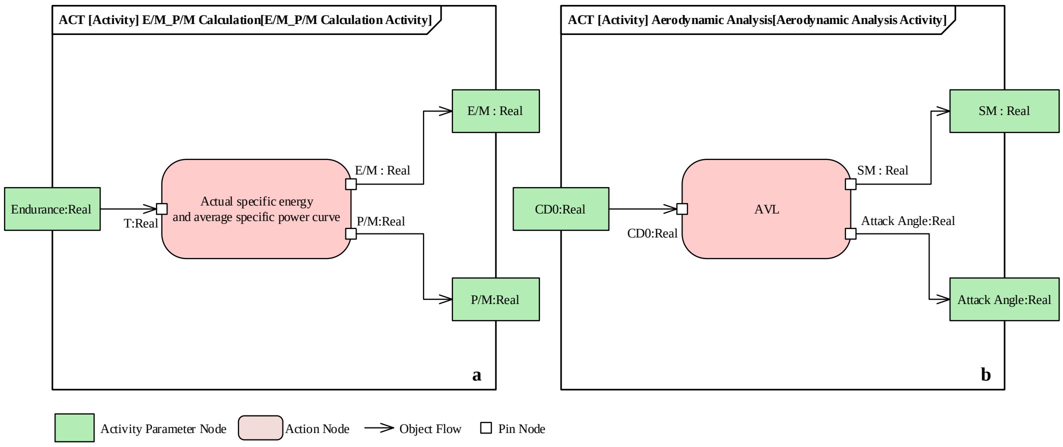

Fig. 7 E_{spec} and P_{spec} calcualtion activity ACT

Fig. 8 provides the process of propulsion analysis. This analysis is to judge whether the propulsion can meet the requirements of power. QPROP [24] is used to evaluate the electric power of propulsion in a precise way considering thrust, power and efficiency. QPROP is a numerical analysis software to predict the desired performance of propulsion for a given combination of motor and propeller.

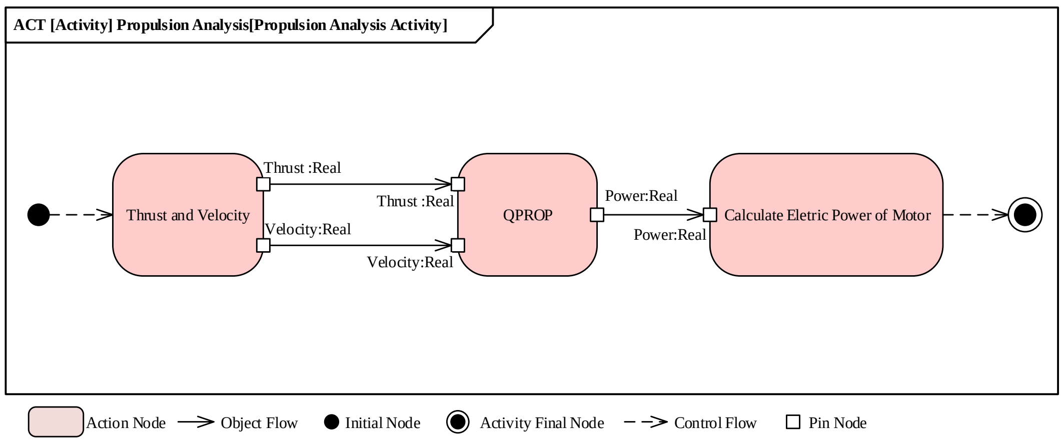

Fig. 8 The propulsion analysis activity ACT

SysML is an extension of UML (United Modeling Language) [25]. UML is mainly used for specifying software. Therefore, SysML can be translated into any programming language such as

Python, Java and C# for being implemented. After the engineering knowledge has been represented in SysML, it will be translated into codes. Moreover, in order to capture the process knowledge represented by an action. A python script file is used to describe the process within the action. This script file can run independently even without the architecture. This will make it easy to reuse.

4. Central data format

The conceptual design of aircraft is usually a multidisciplinary problem. It is necessary to use a variety of analysis tools to assist design. However, the management of data transformation and exchange usually does not follow a uniform standard. This makes the data management become hard to reuse. Especially as the problem becomes more complex, there may be more tools which need to be introduced into the design process. The number of ad-hoc interfaces needed to connect the tools for data management will become a disaster for multidisciplinary design.

In order to make aircraft design in a collaborative and efficient way, Common Parametric Aircraft Configuration Schema (CPACS) [26] has been proposed. CPACS is an open source extensive XML schema to standardize the description of an aircraft including geometry, performance and so on. In the developed KBE application for AquaUAV conceptual design, CPACS is used as a central data format to support multi-disciplinary collaborative aircraft design. In Fig. 9, the analysis tools for AquaUAV conceptual design including AnyCAD, XFOIL, AVL, FRICTION and QPROP are all made CPACS-enable. Each of these tools can read a CPACS-file as an input and append its results to the same format after executing its calculation.

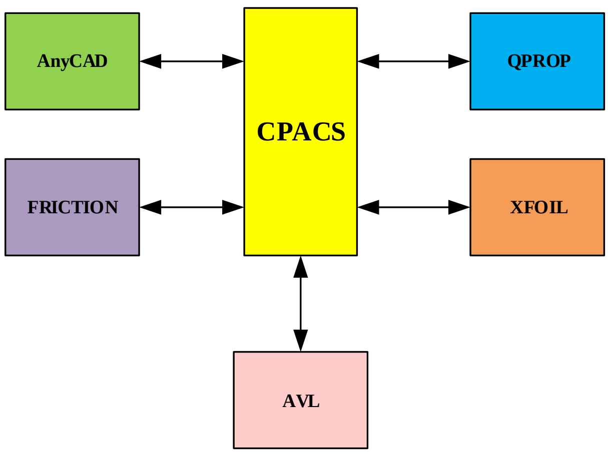

Fig. 9 Interface architecture in the KBE application for AquaUAV conceptual design

5. Application: Conceptual Design of a Fixed-Wing AquaUAV

After the codes have been translated from the design knowledge represented in SysML, the codes will be packaged into a KBE application. Then the KBE application will be deployed on computers to automate the conceptual design of a fixed wing AquaUAV.

This KBE application can rapidly generate a CAD model that meeting mission requirements in table 1 and can navigate under the water. The CAD model generated by KBE application is shown in Fig. 10. The specifications of system and propulsion are provided in Table 2. The design results are provided in Table 3.

Table 1 Mission requirements

Parameter	Value
Takeoff speed	10m/s
Cruise speed	15m/s
Stall speed	8.5m/s
Rate of climb	2m/s
Angle of climb	30deg
Endurance	30min

Table 2 Specifications of system and propulsion

Parameter	Value	Mass
Waterproof servo	Kingmax 9g	18 * 4g
Receiver	Futaba R7008SB	10g
ESC	Hobbywing 40A	40g
Battery	Li-po eagle 2200 mAh	180g
Propeller	APC 8060	6g
Motor	Sunnysky KV1250	58g

Table 3 Design results

Parameter	Wing	Horizontal Tail	Vertical Tail	Seal Cabin	Boom
Span	1.1m	0.33m	0.13m	-	-
Area	0.151m^2	0.024m^2	0.0093m^2	-	-
Airfoil	NACA 2412	NACA 0012	NACA 0012	-	-
Incidence	3deg	-	-	-	-
Dihedral	2deg	-	-	-	-
Taper	0.618	0.611	0.36	-	-
Aspect	8	4.552	1.82	-	-
Mass	243g	65g	43g	61g	50g
Length	-	-	-	0.2m	0.64m
Diameter	-	-	-	0.03m	-
Inner Diameter	-	-	-	-	0.06m
Width	-	-	-	-	0.01m
Height	-	-	-	-	0.01m

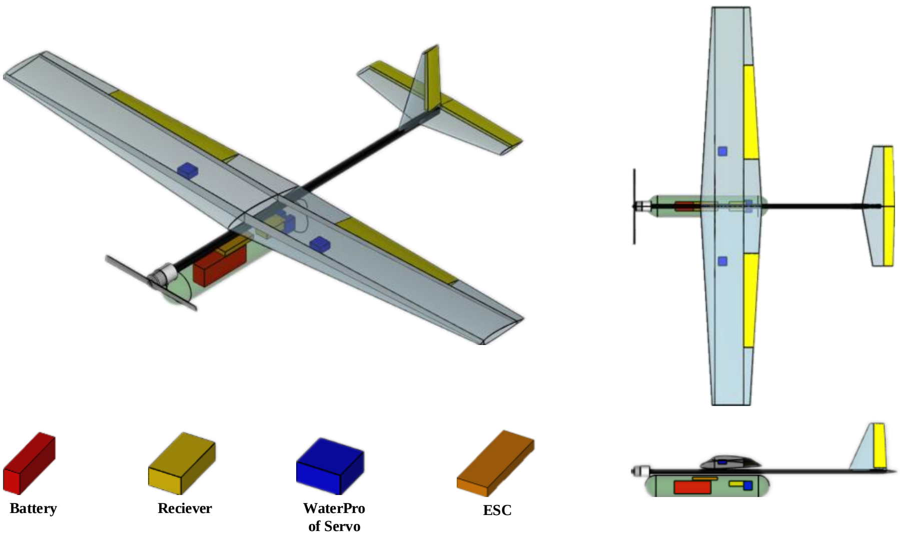

Fig.10 The CAD model of AuqaUAV

As mentioned in section 3, the buoyancy, the weight and the position of the CB relative to the CG are important for underwater balance. The automatic sizing may not well meet the design requirements of underwater balance. By using this KBE application, the size of components can be adjusted to make the airframe suitable for underwater balance manually. In Fig. 11, the position of CB of AquaUAV is behind the position of its CG. By trimming the size of the sealed cabin in Fig. 12, the position of CB can be in front of the position of CG, which is proper for underwater operations.

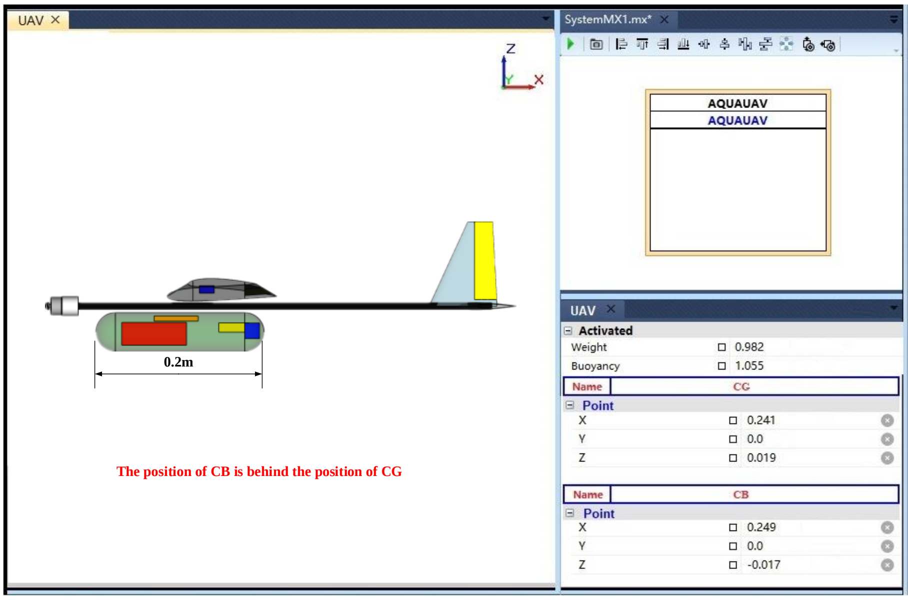

Fig. 11 The airframe without proper CG and CB

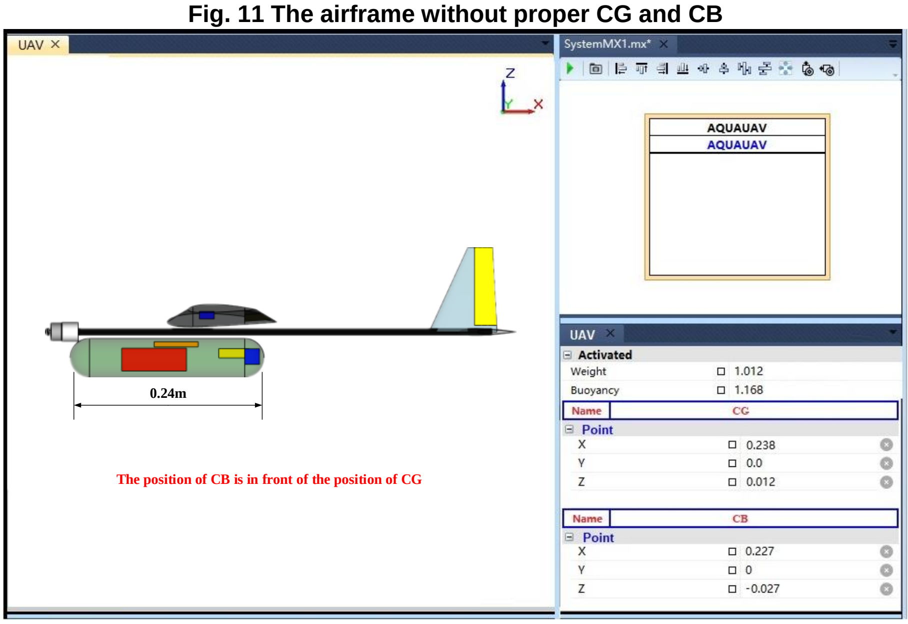

Fig. 12 The airframe with proper CG and CB

From Fig. 12, it can be found that the weight of the AquaUAV designed to be manufactured by 3D printing may be larger than that by traditional manufacturing technique. Therefore, the feasibility of manufacturing the designed AquaUAV fully based on 3D printing technology should be validated. The STL files of a RC UAV which can be 3D printed were downloaded from www.eclipson-airplanes.com. This RC UAV is also with conventional layout and used as the prototype for validation of the manufacturing the designed AquaUAV by 3D printing. As shown in Fig. 13, the original STL UAV model was modified to be with the same features including size, propulsion, avionic system, weight and CG as those of the designed solution. Once the prototype has been prepared, a RAISE 3D PRO+ 3D printer is used to manufacture the parts with PLA material. Then it takes about a week to make and assemble the test prototype before the 3D-Printed RC UAV started the real flight in the air shown in Fig. 14.

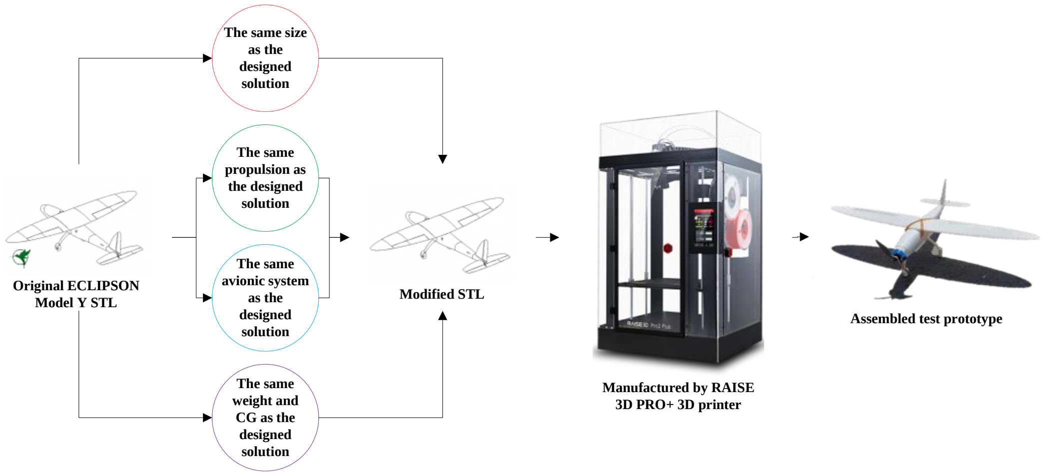

Fig. 13 Manufacture of the prototype for the validation of the feasibility of manufacturing the designed AquaUAV fully based on 3D printing technology

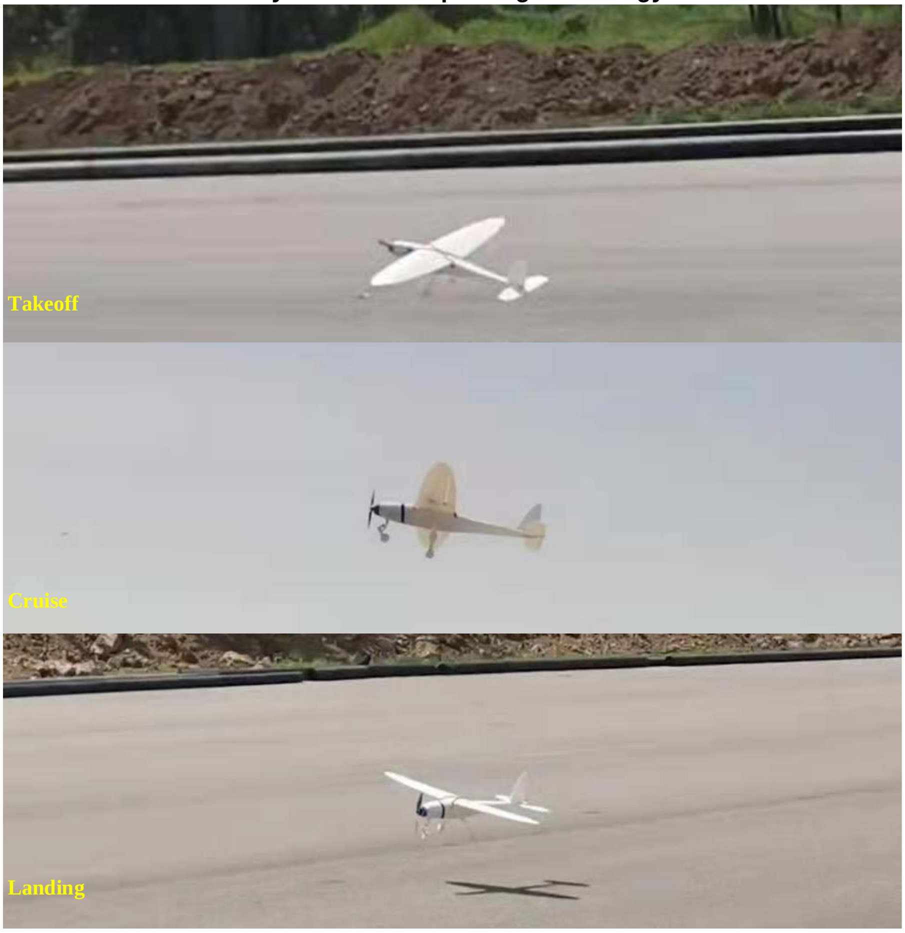

Fig. 14 The first flight of the 3D Printed RC UAV for testing

6. Conclusions

In this paper, knowledge based engineering (KBE) technique is used for automation of the conceptual design of aquatic unmanned aerial vehicle (AquaUAV). The engineering knowledge of the conceptual design of AquaUAV has been represented in SysML for supporting the development of KBE application. Moreover, Common Parametric Aircraft Configuration Schema (CPACS) is used as the central data format to support the multi-disciplinary collaborative conceptual design. Design tools (AnyCAD, FRICTION, QPROP, AVL and XFOIL) can read and save data directly from CPACS file for efficient data management. In this work, the design results and CAD model were generated by the KBE application, which proves the capability of geometry manipulation and data process of the KBE application. The feasibility of manufacturing the designed AquaUAV fully based on 3D printing was also validated.

KBE can connect the design requirements to Computer-Aided Design (CAD) models and improves the rapid operational responsiveness (OpRes) of the UAV platform by reducing the design and costs in the design process.

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8. Copyright Issues

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