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DIGITAL COLLABORATIVE DESIGN: AN INNOVATIVE FRAMEWORK IN AERONAUTICAL EDUCATION

Zhiyang CUI[1], Mingqiang LUO[1], Hu LIU[1], Xiaojian SUN[1], Zhenpeng JI[1] & Yongzhi HUA[2]

[1]School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China
[2]China Academy of Launch Vehicle Technology, Beijing 100076, China

Abstract

To follow the educational philosophy changes in Beihang University and to support the innovative design practice, a digital collaborative design framework is proposed to integrate design resources based on an enduring and evolutionary Authoritative Source of Truth (ASoT). The framework can support innovative aeronautical design for education in three patterns: single-course, multidisciplinary, and national. The scenario of the digital aircraft design project is introduced to apply the innovative design patterns. And the application of the framework to single-course and multidisciplinary in the project has shown its effectiveness in providing innovative design practice in aeronautical education.

Keywords: collaborative design, digital engineering, authoritative source of truth, aircraft design, education

1. Introduction

Aeronautics is a multidisciplinary field of study oriented to complex systems. Beihang University (formally Beijing University of Aeronautics and Astronautics, BUAA) has a history of 70 years in aeronautical education and has trained many outstanding talents for the industry. To follow the recent development of aeronautical engineering practice and offer better education opportunities to students, there are some novel objectives and philosophies of aeronautical education proposed at Beihang University: 1) Transition from teaching knowledge to developing competence and quality including systematic knowledge, global thinking, collaboration ability, global vision, and interests for aeronautics; 2) Inspire students to change from passive acceptance of knowledge to active learning and innovation; 3) Theory follows engineering practice closer and serves strategic needs; and 4) Support jointly teach of courses and cooperation between universities to achieve common progress.

The novel objectives and philosophies lead to requirements for the development of current teaching methods and patterns, including 1) a new innovative design pattern that combines competition and cooperation and can extend from a single discipline to a multidisciplinary, from a school to a whole country; 2) enabling research to support teaching, providing the tools and methods for innovative designs; 3) dynamic process management of innovative design constructing a virtual community for teachers and students to deeply participate in innovative practices together; 4) enduring deposit and sharing of design resources; and 5) virtual simulation experiments for students to immerse themselves in the experiments that used to be unaffordable in the past teaching, improving knowledge understanding and application.

To address the requirements mentioned above, a digital collaborative design framework for aeronautical education is proposed in this paper. This framework integrates software, hardware, data, and models of multidiscipline by an enduring and evolutionary authoritative source of truth (ASoT), supporting digital aircraft conceptual design in multiple layers of hierarchy. The ASoT, a core element of MBSE implementation, is one of five goals that make up the U.S. Department of Defense's Digital Engineering Strategy [1]. This goal moves the primary means of communication in engineering practice from documents to digital models and data. The ASoT enables access, management, analysis, use, and distribution of information from a standard set of digital models and data. As a result, stakeholders have the current, authoritative, and consistent information for use over the life cycle. In recent research at Beihang University, our team has defined the construction goals and methods and the architecture of the ASoT. And the main functionality of the ASoT is realized through the formalized data and models and a cloud-deployed collaborative platform. Then, the ASoT is applied successfully to civil aircraft pre-research [2] and UCAV (unmanned combat aerial vehicle) conceptual design [3].

The framework supports three patterns of aeronautical innovative design practice, providing students from different majors of study with innovative design opportunities around requirement-driven aircraft solutions. The patterns are the promotions of the competitive team design in the aircraft overall design course at Beihang University [4–6]. With industry experts involved in the whole process, the competitive team design provided opportunities for students to innovate innovative practices. Yet the competitive team design had some negative issues, e.g., heavy workloads, less supportive tools, wastes of design resources, etc. The application of digital systems and computer-aided design tools in aeronautical education has achieved good results in teaching practice [7–9]. Currently, the successful experience in single course needs to be extended to multiple courses of different majors and multiple universities through the application of the digital collaborative design framework.

This paper is organized as follows. Section 2 introduces the digital collaborative design framework, describing its components and three patterns of innovative practice supported, i.e., innovative design in a single course, multidisciplinary innovative design, and national design contest. Section 3 describes the digital aircraft design project at Beihang University and two cases of the project applying the digital collaborative design framework, i.e., competitive team design in aircraft overall design course and multidisciplinary team design in undergraduate thesis. Section 4 introduces the future development of the digital collaborative framework in education. And section 5 summarizes the research and draws conclusions.

2. Digital Collaborative Design Framework

The digital collaborative design framework is the core of innovative design practices in aeronautical education. It can integrate resources from multiple disciplines of aeronautics, providing students chances to involve in digital design in limited class hours. University-industry cooperation links industrial requirements and feedback to the framework, ensuring that the innovative design is close to engineering practice. The resources integrated into the framework are mostly collected from the research and teaching of multiple colleges and universities with aeronautic-related majors, as well as some commercial design and analysis tools. These design resources cover the design and virtual verification from the system of systems (SoS) to subsystems. The integration makes an effective way to apply university research achievements to education, enabling the innovative design to involve systematic and interrelated knowledge. The architecture of the digital collaborative design framework is shown in Figure 1. It consists of a hardware environment, a software platform, a design methodology, and three patterns of digital design practices.

2.1 Digital Aircraft Conceptual Design

Digital aircraft conceptual design is the methodology describing the basic steps of aircraft conceptual design in a digital environment, shown as the “V” in Figure 1. The methodology includes three layers of hierarchy: SoS, the system of interest (SoI), and subsystems. The input of the whole process is the industrial needs and requirements, and the output is the design proposal satisfying the design requirements and customer needs.

2.1.1 System Definition

System definition is the process that converts customer needs and requirements into complete and refined system design objectives that define the functions, performance, characteristics, and architecture of the aircraft. Typical activities of system definition include operation analysis, requirement analysis, and architecting. In operation analysis, analytical or simulation methods are applied to assess the effect of the flight mission and conclude the requirements for the best design proposal. In requirement analysis and architecting, formalized modeling language is used to define the SoI requirements, behavior, structure, and parameters, enabling a model-based systems engineering approach to capture the overall design objectives of the aircraft [10].

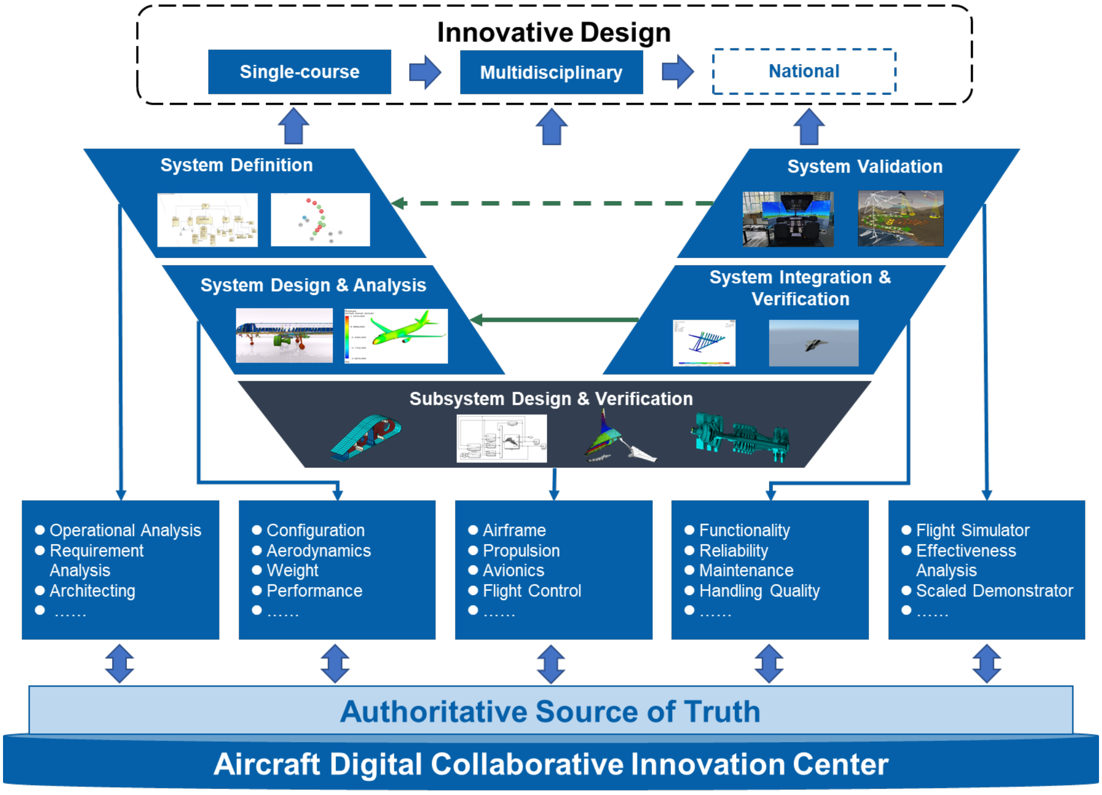


Figure 1 – Digital collaborative design framework.

2.1.2 System Design and Analysis

System design and analysis refer to the aircraft overall design, which defines the configuration of the aircraft and determines the preliminary solutions of propulsion, payload, and airborne equipment arrangements [11–14]. The aerodynamic performance, weight, and flight performance of the aircraft are assessed in system analysis. Meanwhile, the explorations of the aircraft overall design can derive subsystem requirements and refine SoI requirements.

2.1.3 Subsystem Design and Verification

Airborne subsystems usually include propulsion system, avionic, flight control system, mechanical system, electrical system, hydraulic system, environment control system, and airframe. In the subsystem design and verification process, a subsystem is designed based on requirements derived from aircraft overall design. And the results will be verified to meet the requirements. In the digital collaborative framework, we choose to design and verify some subsystems that are closely related to safety, flight performance, and functions of the aircraft, which include airframe, propulsion, flight control, and avionic.

Airframe design and verification include a preliminary design of airframe configuration and a high-fidelity assessment of structure loads. The design of landing gears is a critical point in this step with detailed load analysis, strength check, and optimization, resulting in dynamic parameters for the design of flight control laws for aircraft lading.

Propulsion system design includes the design of flow path, engine structure, inlet, and exhaust nozzle. Then the verification is based on the assessment of thrust, fuel consumption, electricity supply capability, infrared signature, and rotating turbomachinery dynamics.

The design and verification of flight control systems involve the design of control laws and the simulation of stability and maneuverability.

Avionic system addresses most of the functional requirements of the aircraft, e.g., sensing, communication, navigation, and information processing, which makes it the most complicated among the selected subsystems. Avionic system is also related to many non-functional characteristics such as weight, thermal, electricity consumption, etc.

In industrial aircraft design, propulsion and avionics systems are usually selected from existing products. However, in educational scenarios, it is difficult to obtain a considerable amount of detailed information on engines and avionics from many suppliers. Therefore, it is important for the framework to manage and reuse the design solutions from research and student design practices.

2.1.4 System Integration and Verification

The system and subsystem design results in many heterogenous models from multiple sources. In this step, the models are integrated to support virtual/semi-virtual verification of functionality, reliability, handling quality, maintenance, etc.

2.1.5 System Validation

The purpose of this step is to validate whether the design solution of the aircraft satisfies customer needs. The aircraft can be seen as a black-box, appropriately simplifying the inner structure and interfaces of the integrated model. The mission effectiveness of the aircraft is the main criterion to judge the design solution.

In the digital collaborative design framework, system definition and validation are defined as SoS layer activities. The reasons are 1) the focus of these activities is on how the aircraft behaves in the SoS and how it interacts with other elements in the SoS, and 2) these activities can provide feedback and refinement to the SoS.

2.2 Authoritative Source of Truth

The Authoritative Source of Truth (ASoT) is regarded as the software platform of the framework, connecting various resources such as software, hardware, data, model, etc. It also enables functions related to management and decision in the design process.

The ASoT consists of an aircraft data schema, a data parsing tool, an aircraft collaborative design platform, and an aviation knowledge base. Based on the schema of formalized models and data, interfaces can be constructed rapidly and flexibly between ASoT and various software and hardware, integrating the resources in the framework. The aircraft collaborative design platform and aviation knowledge base are implemented through a cloud-deployed software system, thus enabling the digital collaborative design framework to be constructed and used collaboratively across geographically distributed colleges and universities.

2.2.1 Aircraft Conceptual Design Schema

The aircraft conceptual design schema (ACDS) is defined through a three-layer architecture: meta-model, conceptual model, and instance model.

The architecture of the meta-model is shown in Figure 2. There are three layers of the meta-model: project, data package, and data item. Each layer of the meta-model has its children and attributes. Data package is the child of project and the parent of data item. The child of data item is defined as value. The ACDS currently supports a dozen data types for value, as shown in Figure 2. The attributes define some essential information of the meta-model for the management and usage of data, e.g., name, ID, version, user license, relationships, etc. Besides the three layers of the meta-model shown in Figure 2, another meta-model called category is defined with only a name and children. It is used when many models are in the same layer with certain relationships between them. For example, in the data package of aircraft configuration parameters, data items can be categorized as wing parameters, fuselage parameters, empennage parameters, etc.

The conceptual model is instantiated from the meta-model according to the operation of each discipline in aircraft conceptual design workflow. Project is instantiated to a set of data packages. Each data package corresponds to a workflow node based on specialization and labor division. And data items in each data package should be assigned a name and the type of value, which defines the data and models required when completing this part of the design. The assignment should be unambiguous, that the interpretation is unique to everyone who reads the conceptual model.

The instance model is instantiated from the conceptual model by assigning the values of data items to data and models of the actual design solution. Operations on the instance model (e.g., upload instance model to aircraft collaborative design platform) will add attribute information (e.g., version number, submission time, approval information) to it, which makes the instance model consistent and traceable in the ASoT.

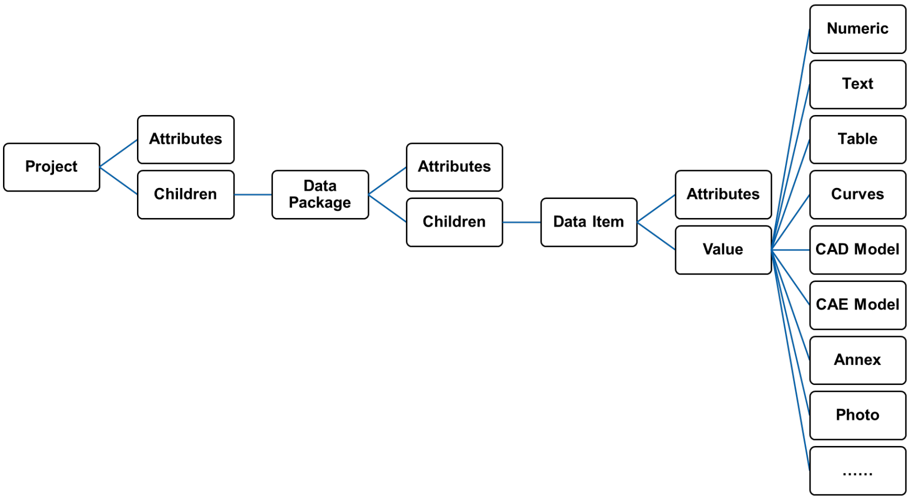
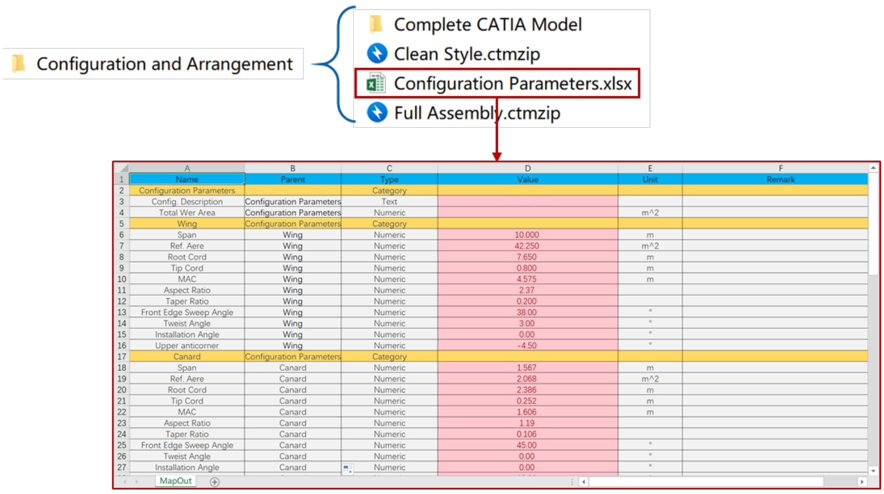


Figure 2 – The architecture of the meta-model of ACDS.

2.2.2 *Data Parsing Tool*

A standard expression based on JavaScript Object Notation (JSON) format is constructed for ACDS, enabling efficient data interactions. However, it is cumbersome to write heterogenous data and models into the JSON format manually and unpractical to customize data outputs to all design tools. Therefore, a data parsing tool is developed to parse heterogenous data and models in aircraft design to the standard JSON format.

The data and models of the aircraft are prepared in easily editable or tools-originally-exportable format. Then the data is edited as a non-JSON instance model according to some simple rules. Finally, the data parsing tool converts the instance model into JSON format. An example of a non-JSON instance model is shown in Figure 3. In educational practice, the instance model of ACDS is sent to students in non-JSON format. Students only need to edit or replace corresponding files when they submit their design solutions. The benefit is that there is no additional training for students to use ACDS, as well as the data in the instance model can be a reference in designing.



	A	B	C	D	E	F
1	Name	Parent	Type	Value	Unit	Remark
2	Configuration Parameters		Category			
3	Config. Description	Configuration Parameters	Text			
4	Total Wer Area	Configuration Parameters	Numeric		m^2	
5	Wing	Configuration Parameters	Category			
6	Span	Wing	Numeric	10.000	m	
7	Ref. Aere	Wing	Numeric	42.250	m^2	
8	Root Cord	Wing	Numeric	7.650	m	
9	Tip Cord	Wing	Numeric	0.800	m	
10	MAC	Wing	Numeric	4.575	m	
11	Aspect Ratio	Wing	Numeric	2.37		
12	Taper Ratio	Wing	Numeric	0.200		
13	Front Edge Sweep Angle	Wing	Numeric	38.00	°	
14	Tweist Angle	Wing	Numeric	3.00	°	
15	Installation Angle	Wing	Numeric	0.00	°	
16	Upper anticorner	Wing	Numeric	-4.50	°	
17	Canard	Configuration Parameters	Category			
18	Span	Canard	Numeric	1.567	m	
19	Ref. Aere	Canard	Numeric	2.068	m^2	
20	Root Cord	Canard	Numeric	2.386	m	
21	Tip Cord	Canard	Numeric	0.252	m	
22	MAC	Canard	Numeric	1.606	m	
23	Aspect Ratio	Canard	Numeric	1.19		
24	Taper Ratio	Canard	Numeric	0.106		
25	Front Edge Sweep Angle	Canard	Numeric	45.00	°	
26	Tweist Angle	Canard	Numeric	0.00	°	
27	Installation Angle	Canard	Numeric	0.00	°	

Figure 3 – An example of a non-JSON ACDS instance model.

The data parsing tool is highly extendable. It has a scalable infrastructure integrating several modules developed for different data formats. The scalable infrastructure only operates the reading of input files, the calling of different modules, and the merging of the output. And the modules parse the data in different formats independently. Such a mechanism ensures scalability and maintainability of the data parsing tool compatible with the upgrade of ACDS.

2.2.3 Aircraft Collaborative Design Platform

The aircraft collaborative design platform enables the most critical objects of the ASoT [3]. 1) It improves the models and data reusability. 2) It eliminates inconsistencies at different design stages. 3) It provides accurate models and data to the right users. 4) It reduces the complexity of the confusing and interlocking versions of models and data from many sources. And 5) It enhances management and assists in decision-making.

Based on the objects of the ASoT, the digital collaborative design framework can provide some advantages for teachers and students. Teachers can manage the authority of students' design teams, and control the accessible resources for students in different courses or teams. They can also review and compare students' design solutions and track the design progress. For students, the aircraft collaborative design platform can help them regulate their design workflow, provide convenient data interactions, help them with multiple solution version management, and generate reports to release the workloads.

2.2.4 Aviation Knowledge Base

The aviation knowledge base contains a large amount of data related to aircraft design, including existing aircrafts, engines, materials, airfoils, airborne equipment, etc. In the innovative design practice, students can search for data on the aviation knowledge base, process intelligent data analysis, and export the results. The data collected by students can enter the knowledge base with teachers' approvals and students' designs can also be archived, which enables the main aspect of the shared construction and usage of the digital collaborative design framework.

2.3 Aircraft Digital Collaborative Innovation Center

The Aircraft Digital Collaborative Innovation Center (ACIC) is a newly established laboratory of Beihang University serving as the hardware environment of the digital collaborative design framework. Its purpose is to build a systematic and digital collaborative design environment for future aircraft design and support the experimental and practical teaching of aircraft design-related courses. The ACIC has a distributed cross-campus hardware and software environment that covers an area of 700 square meters, including three different functional zones, i.e., MBCoDE (Model-Based Collaborative Design Environment), MBCoVE (Model-Based Collaborative Visualization Environment), and MBCoTE (Model-Based Collaborative Test Environment). Figure 4 shows the layout of the Aircraft Digital Collaborative Innovation Center. The establishment of the ACIC has completed in April 2022. In the future, it is planned to support the innovative design practice of more than 30 courses in aerospace engineering.

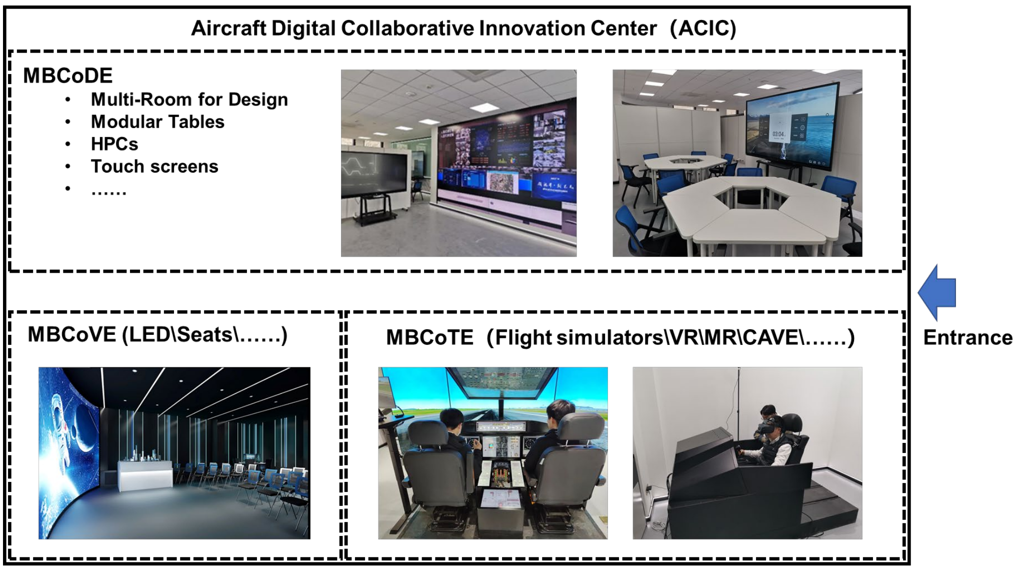


Figure 4 – Layout of the aircraft digital collaborative innovation center.

2.3.1 MBCoDE

In MBCoDE, there deploys multiple HPCs (high-performance computers), desktops with large touch screens, and modular tables in rooms separated by removable walls. Therefore, MBCoDE can meet various scenarios of collaborative design, from individual work to meetings for about 20 people. All the hardware in MBCoDE is connected to the Internet through a gigabit network. Hence the designers can access the ASoT and invoke design tools in HPCs. There also deploys the teleconferencing equipment for designers to work simultaneously online across geographies.

2.3.2 MBCoTE

MBCoTE is equipped with three flight simulators, two CAVEs (Cave Automatic Virtual Environment), and VR/MR equipment for virtual verification and validation of design solutions. The functions of MBCoTE in the schedule include handling quality assessment, virtual flight training, virtual assembly, virtual maintainability, etc. Like MBCoDE, MBCoTE's hardware is accessible to the ASoT, where models and data from the ASoT drive the flight simulator operation, providing 3-D models and scenarios to the CAVE and VR/MR equipment. Combining MBCoDE and MBCoTE, it can realize a model-based iteration of design and test, reducing design costs and cycles.

2.3.3 MBCoVE

MBCoVE contains an 8K curved LED (light-emitting diode) screen of about 30 m^2, dozens of seats, and professional sound equipment. It is a meeting space for proposal presentations and large-scale seminars and reviews. The ASoT is also accessible in MBCoVE through the network, supporting decision-making and real-time monitoring.

2.4 Innovative Design Patterns

The support of the digital collaborative design framework to aeronautical education is realized through three different patterns of digital innovative design practice: innovative design in a single course, multidisciplinary innovative design, and national design contest.

2.4.1 Single-Course

A single professional course usually involves aircraft overall or a particular subsystem. Hence the application of the digital collaborative design framework only requires system design and analysis or subsystem design and verification. In the single-course scenario, the system definition or requirements are usually posted by teachers. Based on the university-industry cooperation, the design requirements can converge the actual needs of engineering practice, improving students' understanding of industrial realities.

The innovative practice is recommended to be organized as competitive team design. Students form teams on their wills. And each team develops design solutions independently. Regular reviews should be organized to select and award the winner among the design teams. In this way, it encourages healthy competition among students and motivates them to produce better solutions.

2.4.2 Multidisciplinary

Multidisciplinary innovative design can cover the whole workflow of digital aircraft conceptual design. Students can work collaboratively to complete a complex aircraft design solution, including aircraft overall and the critical subsystems. In this scenario, teachers only need to post the top-level customer needs. And students explore independently to complete the system definition, design the aircraft and subsystems according to the requirements, and complete the analysis, integration, verification, and validation. Judge whether the system meets customer needs and design requirements, and complete optimization and iteration of the solution.

Multidisciplinary innovative design can support multiple professional courses in a single project and provide students with chances to be involved in comprehensive aircraft design practices. Students from different majors should be organized to form a design team and be assigned with special practical credits to support them participate in the innovation. In the multidisciplinary design practice, students will gain interdisciplinary experiences and knowledge and develop their teamwork skills and solidarity spirit.

2.4.3 National

The national design contest can extend the patterns of single-course or multidisciplinary to colleges and universities across the country. It can provide inter-school communication opportunities to students majoring in aeronautics from different universities. Using advantageous resources across the nation to realize the collaborative construction and usage of the framework, it aims to promote aeronautical education in all universities involved.

3. Digital Aircraft Design Project and Applied Cases

The digital aircraft design project is the main scenario planned for the application of the digital collaborative design framework. The project covers the third year and fourth year of undergraduate students at Beihang University, where students will involve in the design of an aircraft collaboratively. Two cases of the digital aircraft design project are also introduced in this section. The first case applies the digital collaborative design framework to competitive team design in a compulsory course at Beihang University. The framework ignites a change of paradigm from document-based design to digital collaborative design, addressing some issues preventing students from better innovation. Another case reports a novel pattern of multidisciplinary innovative design for the students in Beihang University, team design in undergraduate thesis, and the application of the digital collaborative design framework in this new pattern.

3.1 Digital Aircraft Design Project

The outline of the digital aircraft design project at Beihang University is shown in Figure 5. The project covers two years of undergraduate study, enabling students to participate the innovative design on three levels from simple to complex.

In the first semester of the third year, students will participate the digital design practice in professional courses. In this stage, the design practice in different courses is independent and is only a sketch of the systematic knowledge of their majors. In the second semester of the third year, the digital design practice of the whole school will curve a more complex solution through the integration of multiple professional courses. Then in the fourth year, students will participate the design practice at the university level, where students from different majors involve in the detailed design of the aircraft and its subsystems. The national design contest will extend the experience and organization of the digital design practice in Beihang to universities across the nation.

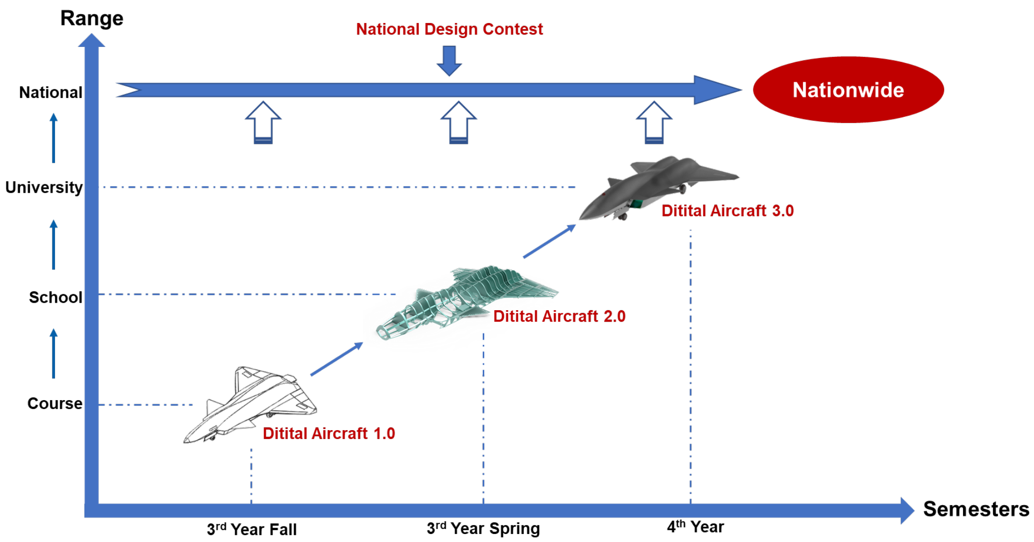


Figure 5 – The outline of the digital aircraft design project.

For a better understanding of the project, an example of how the project works in the School of Aeronautic Science and Engineering is presented here. The aircraft overall design course has already introduced the digital collaborative design framework to support the competitive team design in the 2021 fall. Students finish the solution of configuration, aerodynamics, weight, and flight performance in the first semester. Meanwhile, other professional courses are undergoing to prepare the necessary knowledge for the next step. Then in the second semester, students will participate in the professional design course to refine their design solutions after they are trained in systematic courses including aircraft overall design, aerodynamics, flight dynamics and control, structure mechanics, etc. Then in the next year, they can participate in the multidisciplinary team design for their thesis, where they will collaborate with students from different schools to develop an aircraft with subsystems including propulsion, avionics, flight control, etc.

3.2 Competitive Team Design in Aircraft Overall Design Course

3.2.1 Background

Aircraft Overall Design (AOD) is a compulsory course for third-year students in the School of Aeronautic Science and Engineering, Beihang University. Since 2006, competitive team design has been introduced in AOD courses as a design practice session [5] and has been given high weight in the evaluation of learning [6]. The competitive team design is simultaneous with the lectures in the AOD course. At the beginning of the semester, students form teams of no more than one leader and ten members. The teachers invite collaborators from the industry to post two requests for proposal, one for a civil aircraft and the other for a military aircraft. The student design teams have to choose one to respond and finish the design solution in the semester. Regular reviews are organized to evaluate students' design, selecting two champions for civil and military aircraft.

The competitive team design in the 2021 fall semester is shown in Figure 6. A total of 325 students took the AOD course. The school offered three classes of 100-120 students each. The students formed 32 design teams (DTs). 13 DTs chose the civil aircraft request for proposal, and 19 DTs chose the military. Each class was organized as a division for three reviews. After the reviews, champions from each division were invited to the final championships. The judging panel for the championships consisted of AOD course teachers and industry experts who selected the champion 1 DT for each civilian and military aircraft.

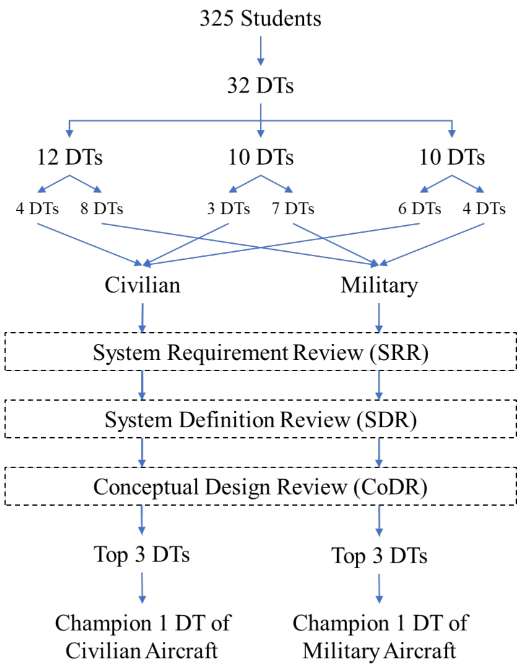


Figure 6 – Competitive team design in AOD course, 2021 fall.

3.2.2 Digital Collaborative Design in AOD

In the 2021 fall semester, the digital collaborative design framework has been applied successfully to all DTs involved in the AOD course. The application has ignited a change of design paradigm from document-based to digital, addressing some special issues found in the competitive team design of the AOD courses during the past several years.

1) In the past competitive team design, there were only rough provisions for the contents of the design solution for each review, resulting in problems such as the incompleteness of data and models, ambiguity of parameter definitions, non-uniformity of units, irregularity of document format, etc. In the 2021 AOD course, we developed an ACDS instance model for the AOD course according to the course lectures and the review requirements, shown in Table 1. Two sets of instance models (one for civil aircraft and one for military aircraft) were delivered to the students required to submit their designs as the way in the instance models. With the approval management function of the aircraft collaborative design platform, teachers can ensure that students submit their designs in the correct manner, thus facilitating the completeness and standardization of their design work.

Table 1 – Disciplines in ACDS instance model for AOD course.

Phases of Review	Discipline
SRR	Requirement Analysis
	Conceptual Sketch
	Initial Sizing
SDR	Propulsion
	Configuration Layout
	Overall Arrangement
CoDR	Aerodynamics
	Weight
	Performance
	Cost Analysis / Radar Detectability

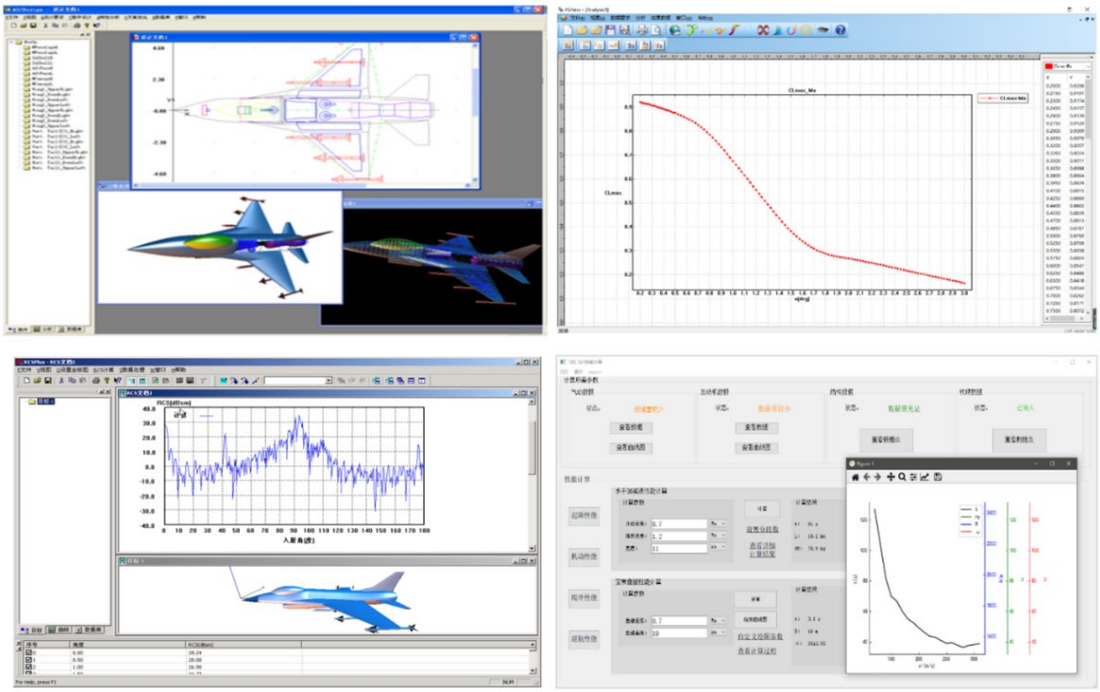


Figure 7 – Design tools available for students.

2) Compared to the heavy workloads of the innovative design, the class hours and supportive resources for the AOD course were very limited in the past, hindering students' innovation seriously. Since the AOD course in the 2020 fall semester, many AOD tools were provided to support students'

teamwork [4], e.g., rapid conceptual design, weight estimation, aerodynamic analysis, cost analysis, etc. Some of the tools have also integrated the input and output in the ACDS format, which enables easier data management and interaction. The ASoT also includes an aviation knowledge base that contains a large number of aircrafts, engines, airborne equipment, etc. The knowledge base has been accessible for all students to support their team design since 2021 fall. And in the meantime, students were permitted to edit the data in the knowledge base with approvals from the teachers, enabling the accumulation of the data in the knowledge base. Another feature that can significantly reduce the workload of students is the automatic generation of design reports on the aircraft collaborative design platform. Each DT is required to submit a design report at the end of the semester. When the ASoT was applied in 2021, students could download their design reports if they submitted their design solutions as required. The aircraft collaborative design platform automatically filled their data in a pre-formatted document, saving students from formatting, tabulating, drawing, etc.

3) In the current AOD course, the three reviews are based on documents and presentations. In the system requirement review (SRR) and the system definition review (SDR), all DTs are required to submit a PowerPoint document of their design solutions, and half of the DTs will be chosen randomly to make presentations in each division. The scores of SRR and SDR are mainly related to the submitted documents. In the conceptual design review (CoDR), all DTs are required to submit documents and make presentations. And the scores of CoDR consider both documents and presentations. The document-based reviews have two disadvantages: a) the documents only reflect the design results, preventing teachers from inspecting the design process during the reviews; and b) it is difficult to compare the design solutions of different DTs. The ASoT enables the design process management for teachers to understand the immediate status and the evolution of students' design solutions. The comparative analysis function of the ASoT helps teachers to select data from different DTs' design solutions for direct comparisons.

4) For the past five years, there were usually more than 30 DTs in each AOD course. Massive data and model resources were generated in the students' design process and wasted because of the lack of management. Since 2021, the DTs were required to submit their solutions to the ASoT. The data and models will support the construction of knowledge graph, enabling knowledge transfer, inference, and reuse.

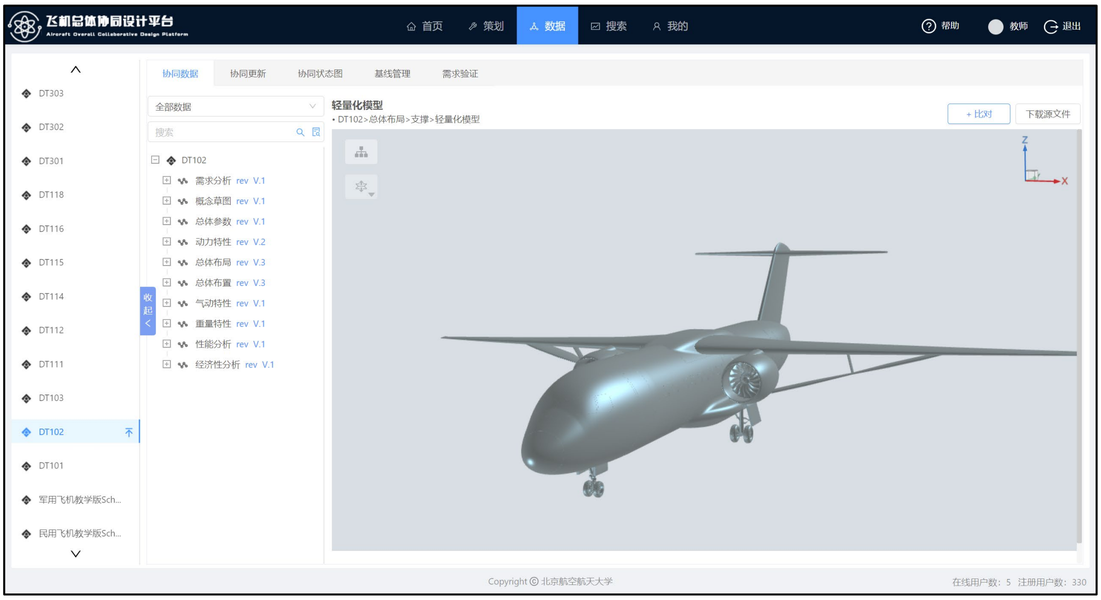


Figure 8 – Students' designs submitted to the aircraft collaborative design platform.

3.3 Multidisciplinary Team Design in Undergraduate Thesis

3.3.1 Background

Beihang University has a good tradition of students' participation in engineering practice in its 70-year history. In the 1950s, more than 1,500 students and teachers of Beihang University worked for 100 days to complete the development of a light passenger aircraft, "Beijing-1". The aircraft successfully made its maiden flight on September 24, 1958, creating a number of records, such as the shortest development time and the design and manufacture completed entirely by university teachers and students. Such innovative practice has become one of the important ways to test the achievements of education and to enhance the practical and innovative ability of students.

In the 21st century, digital technologies have made rapid progress and are increasingly being used in aircraft design. In order to provide opportunities for cutting-edge innovative practices in education and to nurture top innovative talent, Beihang University launched the digital aircraft design project as an important multidisciplinary engineering practice in the new era.

The multidisciplinary team design in undergraduate thesis is an important part of the digital aircraft design project at the university level. In the project, senior undergraduate students from different schools and majors will design an aircraft collaboratively using digital methods and technologies. Each student will be responsible for a part of the design task and complete their thesis based on the design tasks. The project will improve students' ability to solve complex engineering problems with comprehensive knowledge, strengthen students' practical innovation ability, and cultivate students' sense of cooperation and team spirit.

3.3.2 Development Plan

This project is planned to complete the design and begin the prototype of an unmanned aerial vehicle (UVA) in five years. The digital collaborative design framework will be applied in the design process, as well as other advanced technologies such as digital manufacture, digital verification, digital twin, knowledge graph, etc. The ACDS will be developed to cover the entire life cycle of aircraft, from conceptual design to manufacture and test. And from the third year, results and experiences of the first two years will be applied to support multiple team design projects, e.g., supersonic airliner design.

Table 2 – Development plan of multidisciplinary team design in undergraduate thesis.

Year	Project	Type	Iteration	ACDS	Design Stage	Verification	Digital Twin	Knowledge Graph
2022	Single	Military	None	Preliminary	Conceptual, Preliminary	Virtual	None	None
2023	Single	Military	Single	Preliminary	Conceptual, Preliminary	Virtual	None	None
2024	Multiple	Military Civilian	Multiple	Mature	Detail design	Virtual	Preliminary	None
2025	Multiple	Military Civilian	Multiple	Mature	Detail, Manufacture	Virtual, Semi-physical	Mature	Preliminary
2026	Multiple	Military Civilian	Multiple	Excellent	Detail, Manufacture	Virtual, Semi-physical	Mature	Preliminary

3.3.3 Current Progress

The design of the first year started in December 2021 and finished in June 2022. 26 students from four schools, with the indication of 19 teachers, will work on aircraft overall, propulsion system, avionic system, and flight control system based on the conceptual solution of the UAV.

The design has realized the system definition, system design and analysis, subsystem design and verification, and system integration and verification of the digital aircraft conceptual design. Two students from the School of Aeronautic Science and Engineering modeled the mission scenarios of the UAV, analyzed its requirement, and defined the architecture. Five students from the same school responded for aircraft overall design and analysis, including one for configuration, two for aerodynamics, one for weight, flight performance, radar detectability, and one for stability. The other two students designed the preliminary airframe, analyzed structure loads, and designed and optimized the landing gears.

Six students from the School of Energy and Power Engineering designed the propulsion system. One student designed the engine cycle and assessed the performance (thrust, fuel consumption, and electricity supply capability). One designed the engine structure and analyzed the load of the rotating turbomachinery. Two students designed the inlet and exhaust nozzle and simulated aerodynamic performance. The other two students researched on the infrared signature of the propulsion system.

Six students from the School of Automation Science and Electrical Engineering responded to the design and simulation of the flight control system. They divided the control law into five modules, taking-off, cruising, thrust vector control, and quaternion maneuver control. Each student responded to one module, and a student integrated the modules and designed the mode-switching algorithm.

Five students from the School of Electronic Information Engineering designed the preliminary architecture of the avionic system and proposed the detailed design of the airborne network for communication between avionic devices.

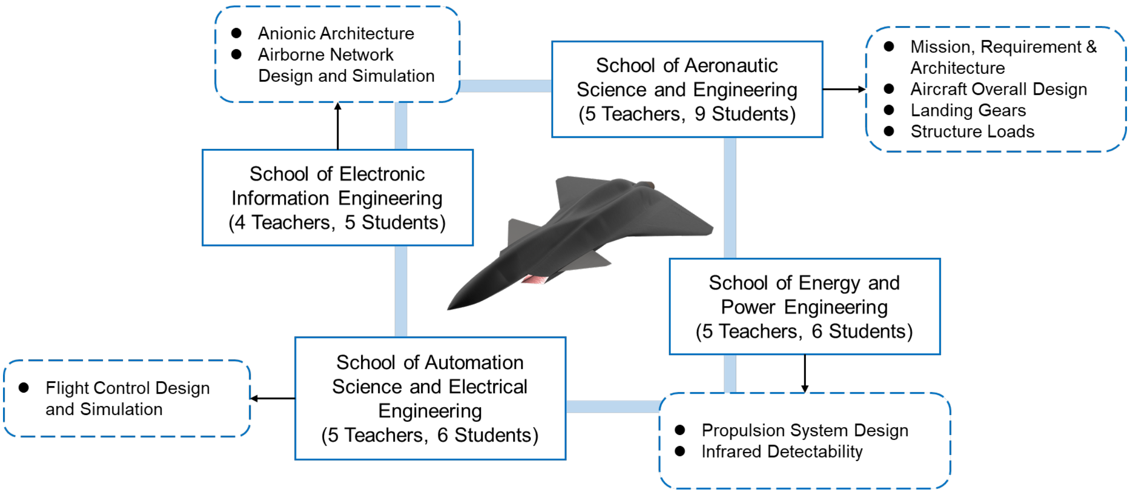


Figure 9 – Multidisciplinary team design in 2022.

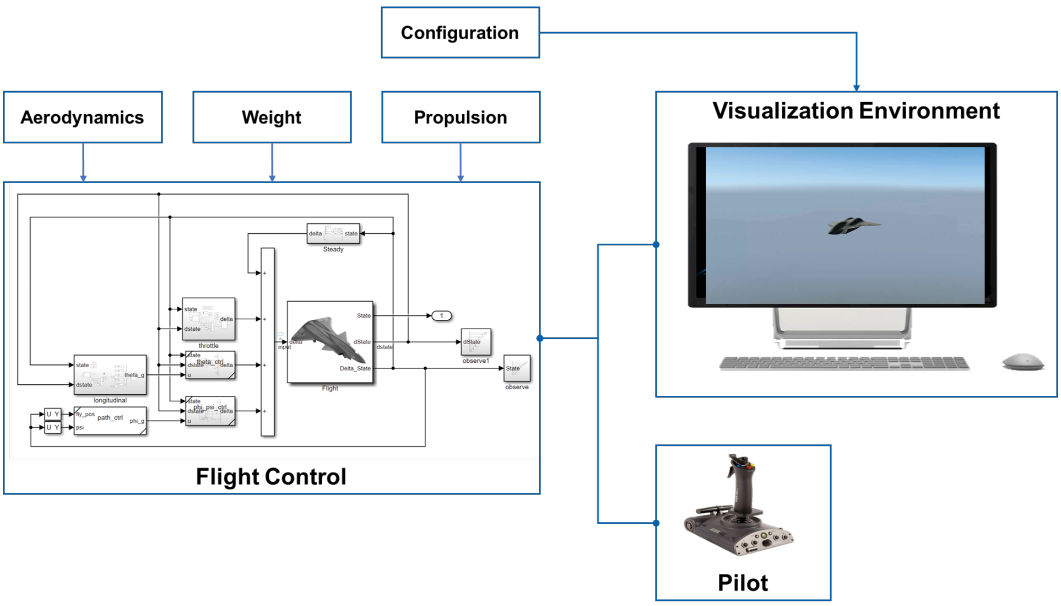


Figure 10 – Simulator integrated by aircraft overall and subsystems.

The design and analysis results of the aircraft overall, flight control system, and propulsion system were integrated into a simulator to verify the performance and handling quality of the UAV, shown in Figure 10. The interfaces based on the ASoT enabled the simulator to load any version of the aircraft and the subsystems, realizing quick and convenient virtual verification during the design evolution.

In the first year, the main effort of the multidisciplinary team design had focused on the improvement of the ACDS based on students' design results. The ACDS conceptual model used in aircraft overall design has successfully extended to the disciplines of subsystems. The improved conceptual model has clarified the digital preliminary design workflow and formalized the models and data in each discipline, which benefited the management of designs with the ASoT and the development of effective data interfaces between disciplines.

We have explored using the ASoT to manage the design process and data this year in the multidisciplinary team design. A major challenge coming next is the handover of the design project between the two grades of students. The multidisciplinary team design aims to form an enduring and evolutionary digital aircraft. Yet, in the previous ASoT application, there was no such scenario that needed to hand over the whole project, seriously challenging the consistency of the ASoT.

4. Future Works

For future works, the digital collaborative design framework will continue to be applied in the AOD course of Beihang University and evolve the way of application with the change of course content. Future aircraft are developing to be unmanned, intelligent, and modular, highlighting the impact of the aircraft's subsystems on its performance and functions. In the current team design in the AOD course, students usually lack consideration of subsystem design: they only make a list of subsystem equipment with layout location, ignoring the demonstration of subsystem functions and performance. Thus, our team will explore to introduce subsystem design to the AOD course and complete system integration, verification and validation. The innovative design in a single course will be extended to support other professional courses as well.

Multidisciplinary team design in the undergraduate thesis has successfully achieved the goals of the first year. According to its development plan, four critical issues should be addressed in the future. 1) Complete the system verification and validation, feedback to system definition and design, forming a "closed loop" in iteration; 2) support more than one multidisciplinary innovative design project; 3) develop ACDS to cover the aircraft lifecycle from design to maintain; and 4) develop advanced digital technology (e.g., digital twin and knowledge graph).

Figure 11 – Part of the outstanding design solutions in "Joint-Cup".

For the national design contest pattern, Beihang University has extended the competitive team design in the AOD course to the national engineering competition [15] which will be an important scenario to apply the digital collaborative framework. Beihang University led the first "Joint-Cup" design competition of advanced aircraft for college students in 2018. And in 2019, the "Joint-Cup" was approved to be one of the racetracks of the National Undergraduate Engineering Training Integration Ability Competition supported by the Ministry of Education of the People's Republic of China. Currently, nearly 1000 participants from 19 universities have been involved in the national aircraft design contests led by Beihang University. In the 2021 spring, only several design tools integrated into the ASoT were applied in the national design contest. However, it will take a step further to apply the digital collaborative framework in the next national contest referring to the pattern of the Beihang AOD course.

5. Conclusion

A digital collaborative design framework is developed and applied to aeronautical education. The framework is based on an enduring and evolutionary ASoT, supporting digital aircraft conceptual design. Three patterns of innovative design are developed to support aeronautical education: single-course, multidisciplinary, and national. The single-course and multidisciplinary patterns have been applied in the AOD course and team design in the undergraduate thesis. The result shows that the digital collaborative design framework effectively integrates design resources and supports students' innovative design practices. The digital collaborative design framework can provide a requirement-driven innovative design environment with advanced digital technology for aeronautical education and overcome the shortcomings of the current situation. Our team will continue improving the digital collaborative design framework to support more educational activities in a broader context.

6. Contact Author Email Address

Mingqiang Luo: e-mail: luomingqiang_buaa@163.com

7. Copyright Statement

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