Synthesis Lectures on Mechanical Engineering

SYNTHESIS
COLLECTION OF TECHNOLOGY

Mohammad H. Sadraey

Unmanned Aircraft Design

A Review of Fundamentals

Second Edition

Springer

Synthesis Lectures on Mechanical Engineering

This series publishes short books in mechanical engineering (ME), the engineering branch that combines engineering, physics and mathematics principles with materials science to design, analyze, manufacture, and maintain mechanical systems. It involves the production and usage of heat and mechanical power for the design, production and operation of machines and tools. This series publishes within all areas of ME and follows the ASME technical division categories.

Mohammad H. Sadraey

Unmanned Aircraft Design

A Review of Fundamentals

Second Edition

Springer

Mohammad H. Sadraey
School of Engineering, Technology,
and Aeronautics
Southern New Hampshire University
Manchester, NH, USA

ISSN 2573-3168 ISSN 2573-3176 (electronic)
Synthesis Lectures on Mechanical Engineering
ISBN 978-3-031-67794-6 ISBN 978-3-031-67795-3 (eBook)
https://doi.org/10.1007/978-3-031-67795-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

NASA Global Hawk

Preface

The Unmanned Aerial Vehicle (UAV) is a remotely piloted or self-piloted aircraft that can carry cameras, reconnaissance sensors, missiles, or other payloads. All flight operations (including take-off and landing) are performed without on-board human pilot. These diverse systems range in cost from a few hundred dollars to tens of millions of dollars. Range in capability from micro air vehicles weighing much less than a pound to aircraft weighing over 40,000 pounds. The design of manned aircraft and the design of UAVs have some similarities and some differences. They include: 1. Design process, 2. Constraints, and 3. UAV main components. A UAV designer must own technical/engineering skills and be aware of a. Latest UAV developments, b. Current technologies, c. Know lessons learned from past successes and failures, and d. Designer should appreciate the breadth of UAV design options.

A design process requires both integration and iteration. A design process includes: 1. Synthesis: the creative process of putting known things together into new and more useful combinations. 2. Analysis: the process of predicting the performance or behavior of a design candidate. 3. Evaluation: the process of performance calculation and comparing the predicted performance of each feasible design candidate to determine the deficiencies. A designer needs to know how to integrate complex, multi-disciplinary systems and to understand the environment, the requirements, and the design challenges.

In the second edition, three new topics of air vehicle aerodynamic design, structural design, and propulsion system design were added, while the topic of guidance system was removed. Many sections have completely been revised and further exposed, multiple new topics are introduced, and many new techniques and products are added. The objective of this book is to review the design fundamentals of Unmanned Aerial Vehicles and their related systems.

It will have 12 Chapters. Chapter 1 covers design fundamentals and design disciplines. This chapter covers UAV classifications, design project planning, decision making, feasibility analysis, systems engineering approach, design groups, design phases, design reviews, evaluation, and feedback. In Chap. 3, preliminary design is discussed which covers conceptual design and initial sizing. Air vehicle aerodynamic design, structural design, and propulsion system design are reviewed in Chaps. 4, 5, and 12, respectively. Chapter 2 is dedicated to the payload selection and design. Topics include measurement devices, antennas, radar, civil payloads, military payloads, disposable payloads, imagery equipment, payload handling, payload management, and payload-structure integration.

Chapters 6–10 are dedicated to the autopilot design. It covers dynamic modeling, control system design, navigation system design, and microcontroller. This part will discuss the topics such as aircraft aerodynamic forces and moments, stability and control derivatives, transfer function model, state-space model, aircraft dynamics, linearization, fundamentals of control systems control laws, conventional design techniques, PID control, optimal control, robust control, digital control, stability augmentation, coordinate systems, inertial navigation, way-point navigation, sensors, actuators, avionics, gyroscopes, GPS, navigation laws, flight path stabilization, turn coordination, command systems, modules/components, flight software, commercial autopilots, software developing, software languages, control surfaces design, integration, and full autonomy. A few advanced topics such as detect (i.e., sense)-and-avoid, automated recovery, fault monitoring, intelligent flight planning, artificial intelligence, and manned-unmanned teaming will also be reviewed in these chapters.

In Chaps. 10 and 11, equipment design is presented which includes ground control station, communications systems, and launch and recovery systems. The following topics are discussed in these two chapters: ground element types, portable ground station, mission control elements, remote control personnel, support equipment, transportation, coordination, hardware and software, radio frequencies, elements of communications system, communication techniques, transmitters, receivers, telemetry, conventional launch, rail launchers, hand launch, air launch, and recovery systems. Due to the limited length of this book, many topics are reviewed in brief, but more details are provided on the design process and flowchart. Unattributed figures are held in the public domain and are from either the US Government Departments or Wikipedia.

Manchester, USA
May 2024

Mohammad H. Sadraey

Contents

1 Design Fundamentals

1.1 Introduction

The Unmanned Aerial Vehicle (UAV) or pilotless or uninhabited/uncrewed aircraft is a remotely piloted vehicle (RPV) or self-piloted aircraft that can carry payloads such as cameras, sensors, and communications equipment. All flight operations (including take-off and landing) are performed without on-board human pilot. In some reports of DOD, Unmanned Aerial System (UAS) is preferred. In media reports, the term "drone", flying robot, or aerial robot are utilized. The UAV mission is to perform critical flight operations without risk to personnel and more cost effectively than comparable manned system. A civilian UAV is designed to perform a particular mission at a lower cost or impact than a manned aircraft equivalent.

UAV design is essentially a branch of engineering design. Design is primarily an analytical process which is usually accompanied by drawing/drafting. Design contains its own body of knowledge that is independent of the science-based analysis tools that is usually coupled with it. Design is a more advanced version of a problem-solving technique that many people use routinely.

Research in unmanned aerial vehicles (UAVs) has grown in interest over the past couple decades. There has been tremendous emphasis in unmanned aerial vehicles, both of fixed and rotary wing types over the past decades. Historically, UAVs were designed to maximize endurance and range, but demands for UAV designs have changed in recent years. Applications span both civilian and military domains, the latter being the more important at this stage. Early statements about performance, operation cost, and manufacturability are highly desirable already early during the design process. Individual technical requirements have been satisfied in various prototype, demonstrator and initial production programs like Reaper, Global Hawk and other international programs. The possible break-through of UAV technology requires support from the aforementioned

M. H. Sadraey, *Unmanned Aircraft Design*, Synthesis Lectures on Mechanical Engineering, https://doi.org/10.1007/978-3-031-67795-3_1

awareness of general UAV design requirements and their consequences on cost, operation and performance of UAV systems.

In June of 2016, the Department of Transportation's Federal Aviation Administration has finalized the first operational rules for routine commercial use of small unmanned aircraft systems [27], opening pathways towards fully integrating UAS into the nation's airspace. These new regulations aim to harness new innovations safely, to spur job growth, advance critical scientific research and save lives. Moreover, in June of 2017, European Commission has released a blueprint for UAV standards which will "unify laws across the EU" by creating a common low-level airspace called the U-space that covers altitudes of up to 150 m.

The design principles for UAV's are similar to the principles developed over the years and used successfully for the design of manned UAV. The size of UAV varies according to the purpose of their utility. In many cases the design and constructions of UAV's faces new challenges and, as a result of these new requirements, several recent works are concerned with the design of innovative UAV's. Autonomous vehicle technologies for small and large fixed-wing UAVs are being developed by various startups and established corporations such as Lockheed Martin. A number of conceptual design techniques, preliminary design methodologies, and optimization has been applied to the design of various UAVs including Medium Altitude Long Endurance (MALE) UAV using multi objective genetic algorithm.

The first UAV designs that appeared in the early nineties were based on the general design principles for full UAV and findings of experimental investigations. The main limitation of civil UAV's is often low cost. An important area of UAV technology is the design of autonomous systems. The tremendous increase of computing power in the last three decades and developments of general-purpose reliable software packages made possible the use of full configuration design software packages for the design, evaluation, and optimization of modern UAV.

The oldest US military UAV, the MQ-5 Hunter was retired [56] in 2015, following 22 years of service by the U.S. Army. It was replaced by General Atomics MQ-1C Gray Eagle, a larger UAV that can fly for up to 24 h, at altitudes of 29,000 feet, and with a maximum speed of 190 mph. In 2023, around 1,500 drones lit up the night sky over the Chinese city of Shenzhen with imagery of a flying dragon to mark the start of the country's Dragon Boat Festival.

UAVs are air vehicles; they fly like airplanes and operate in an airplane environment. They are designed like air vehicles. They have to meet flight critical air vehicle requirements. You need to know how to integrate complex, multi-disciplinary systems and understand the environment, the requirements and the design challenges.

A UAV system is much more than a reusable air vehicle or vehicles. The UAV system includes five basic elements: 1. The Environment in which the UAV(s) operates, 2. Aerial vehicle, 3. Control station, 4. Payload, and 5. Maintenance and support system.

The design of manned UAV and the design of UAVs have some similarities; and some differences such as: design process; constraints (e.g., g-load, pressurization); and UAV main components (Autopilot, ground station, communication system, sensors, payload). A UAV designer must be aware of 1. Latest UAV developments; 2. Current technologies; 3. Know lessons learned from past failures. Designer should appreciate breadth of UAV design options.

Every year, R&D in various aspects of UAS are attracting billions of dollars and generates new technologies and frontiers. The future sixth-generation fighter jets are expected to include new technologies ranging from AI and cutting-edge adaptive engines to more digital components and teaming with multiple autonomous UAVs flying alongside its wings.

In 2023, Amazon [56] has applied for a patent for a “collective” UAV, with multiple small UAVs teaming together to form a collective to carry and deliver larger and heavier packages. Moreover, the Osprey MK III, made its first autonomous test flight [56], to prove a capability to safely and quickly test novel autonomy and AI on small UAS that is safe enough to be in close proximity to other aircraft. This was a start and demonstration of a testbed by the Air Force research lab.

In this chapter, definitions; design process; UAV classifications; current UAVs; and challenges; will be covered. In addition, conceptual design, preliminary design and detail design of an UAV based on systems engineering approach are introduced. In each stage, application of this approach is described by presenting the design flow chart and practical steps of design.

1.2 Design Project Planning

In order for a design project schedule to be effective, it is necessary to have some procedures for monitoring progress; and in a broader sense for encouraging personnel to progress. An effective general form of project management control device is the Gantt chart is. It presents a project overview which is almost immediately understandable to non-systems personnel; hence it has great value as a means of informing management of project status. A Gantt chart has three main features:

1. It informs the manager and chief designer of what tasks are assigned and who has been assigned to them.
2. It indicated the estimated dates on which tasks are assumed to start and end, and it represents graphically the estimated ration of the task.
3. It indicates the actual dates on which tasks were started and completed and pictures this information.

Like many other planning/management tools, Gantt charts provide the manager/chief designer with an early warning if some jobs will not be completed on schedule and/

or if others are ahead of schedule. Gantt charts are also helpful in that they present graphically immediate feedback regarding estimates of personnel skill and job complexity. A Gantt chart provides the chief designer with a scheduling method and enables him/her to rapidly track and assess the design activities on a weekly/monthly basis. An aircraft project such as the Global Hawk will not be successful without a design project planning.

1.3 Decision Making

Not every design parameter is the outcome of a mathematical/technical calculations. There are UAV parameters which are determined through a selection process. In such cases, the designer should be aware of the decision-making procedures. The main challenge in decision making is that there are usually multiple criteria along with a risk associated with each one. Any engineering selection must be supported by logical and scientific reasoning and analysis. The main challenge in decision making is that there are usually multiple criteria along with a risk associated with each one. There are no straight forward governing equations to be solved mathematically.

A designer must recognize the importance of making the best decision and the adverse of consequence of making the poorest decision. In majority of the design cases, the best decision is the right decision, and the poorest decision is the wrong one. The right decision implies the design success, and the wrong decision results in a fail in the design. As the level of design problem complexity and sophistication increases in a particular situation, a more sophisticated approach is needed.

1.4 Design Criteria, Objectives and Priorities

One of the preliminary tasks in UAV configuration design is identifying system design considerations. The definition of a need at the system level is the starting point for determining customer requirements and developing design criteria. The requirements for the system as an entity are established by describing the functions that must be performed. Design criteria constitute a set of “design-to” requirements, which can be expressed in both qualitative and quantitative terms. Design criteria are customer specified or negotiated target values for technical performance measures. These requirements represent the bounds within which the designer must “operate” when engaged in the iterative process of synthesis, analysis, and evaluation. Both operational functions (i.e. those required to accomplish a specific mission scenario, or series of missions) and maintenance and support functions (i.e. those required to ensure that the UAV is operational when required) must be described at the top level.

Various UAV designer have different priorities in their design processes. These priorities are based on different objectives, requirements and mission. There are primarily three

Table 1.1 Design objectives

No	Objective	Basis for measurement	Criterion	Units
1	Inexpensive in market	Unit manufacturing cost	Manufacturing cost	Dollar
2	Inexpensive in operation	Fuel consumption per km	Operating cost	L/km
3	Light weight	Total weight	Weight	N
4	Small size	Geometry	Dimensions	m
5	Fast	Speed of operation	Performance	km/hr
6	Maintainable	Man-hour to maintain	Maintainability	Man-hour
7	Producible	Required technology for manufacturing	Manufacturability	–
8	Recyclable	Amount of hazardous or non-recyclable materials	Disposability	kg
9	Maneuverable	Turn radius; turn rate	Maneuverability	m
10	Detect and avoid	Navigation sensors	Guidance and control	–
11	Airworthiness	Safety standards	Safety	–
12	Autonomy	Autopilot complexity	Crashworthiness/ formation flight	–

groups of UAV designers, namely: 1. military UAV designer, 2. civil UAV designer, 3. homebuilt UAV designer. These three groups of designers have different interests, priorities, and design criteria. There are mainly ten figures of merit for every UAV configuration designer. They are production cost, UAV performance, flying qualities, design period, beauty (for civil UAV) or scariness (for military UAV), maintainability, producibility, UAV weight, disposability, and stealth requirement. Table 1.1 demonstrates objectives and priorities of each UAV designer against some figures of merit.

In design evaluation, an early step that fully recognizes design criteria is to establish a baseline against which a given alternative or design configuration may be evaluated. This baseline is determined through the iterative process of requirements analysis (i.e. identification of needs, analysis of feasibility, definition of UAV operational requirements, selection of a maintenance concept, and planning for phase-out and disposal). The mission that the UAV must perform to satisfy a specific customer should be described, along with expectations for cycle time, frequency, speed, cost, effectiveness, and other relevant factors. Functional requirements must be met by incorporating design characteristics within the UAV and its configuration components.

As an example, Table 1.2 illustrates three scenarios of priorities (in percent) for military UAV designers. Among ten figures of merit (or criteria), grade “1” is the highest priority and grade “10” is the lowest priority. The grade “0” in this table means that, this figure of merit is not a criterion for this designer. Number one priority for a military UAV

Table 1.2 Three scenarios of priorities (in percent) for a military UAV designer

No	Figure of Merit	Priority	Designer # 1	Designer # 2	Designer # 3
1	Cost	4	8	9	9
2	Performance	1	50	40	30
3	Autonomy	2	10	15	20
4	Period of design	5	7	7	8
5	Scariness	10	1	1	2
6	Maintainability	7	4	5	5
7	Producibility	6	6	6	7
8	Weight	8	3	4	4
9	Disposability	9	2	2	3
10	Stealth	3	9	11	12
		Total	100%	100%	100%

designer is UAV performance, while for a homebuilt UAV designer cost is the number one priority. It is also interesting that stealth capability is an important priority for a military UAV designer, while for other three groups of designers, it is not important at all. These priorities (later called weights) reflect the relative importance of the individual figure of merit in the mind of the designer.

Design criteria may be established for each level in the system hierarchical structure. The optimization objectives must be formulated in order to determine the optimum design. A selected UAV configuration would be optimum based on only one optimization function. Applicable criteria regarding the UAV should be expressed in terms of technical performance measures and should be prioritized at the UAV (system) level. Technical performance measures are measures for characteristics that are, or derive from, attributes inherent in the design itself. It is essential that the development of design criteria be based on an appropriate set of design considerations, considerations that lead to the identification of both design-dependent and design-independent parameters, and that support the derivation of technical performance measures.

The UAV cost is so important, that a high-cost design and production could end up with a broken UAV industry. For instance, in 2021, the Chinese UAV manufacturer DJI with introducing low-cost UAVs such as Phantom and Mini was able to capture 70% of the US market (by defeating mass-market American-produced multirotor manufacturer 3DR).

1.5 Feasibility Analysis

In the early stages of design and by employing brainstorming, a few promising concepts are suggested which seems consistent with the scheduling and available resources. Prior to committing resources and personnel to the detail design phase, an important design activity; feasibility analysis; must be performed. There are a number of phases through which the system design and development process must invariably pass. Foremost among them is the identification of the customer-related need and, from that need, the determination of what the system is to do. This is followed by a feasibility study to discover potential technical solution, and the determination of system requirements.

It is at this early stage in the life cycle that major decisions are made relative to adapting a specific design approach and technology application, which has a great impact on the life-cycle cost of a product. In this phase, the designer addresses the fundamental question of whether to proceed with the selected concept. It is evident that there is no benefit or future in spending any more time and resource attempting to achieve an unrealistic objective. Some revolutionary concepts initially seem attractable, but when it comes to the reality, it is found to be too imaginary. Feasibility study distinguishes between a creative design concept and an imaginary idea. Feasibility evaluation determines the degree to which each concept alternative satisfies design criteria.

In this phase, the designer addresses the fundamental question of whether to proceed with the selected concept. Feasibility study distinguishes between a creative design concept and an imaginary idea. Feasibility evaluation determines the degree to which each concept alternative satisfies design criteria.

In the feasibility analysis, the answers to the following two questions are sought: 1. Are the goals achievable?; or are the objectives realistic?; or are the design requirements meetable? 2. Is the current design concept feasible? If the answer to the first question is no, the design goal and objectives, and design requirements must be changed. Hence, no matter where is the source of design requirements; either direct customer order or market analysis; they must be changed.

1.6 Design Groups

An aircraft chief designer should be capable of covering and handling a broad spectrum of activities. Thus, an aircraft chief designer should have years of experiences, be knowledgeable of management techniques, and preferably have full expertise and background in the area of “flight dynamics”. The chief designer has a great responsibility in planning, coordination, and conducting formal design reviews. He/she must also monitor and review aircraft system test and evaluation activities, as well as coordinating all formal design changes and modifications for improvement. The organization must be such that facilitate the flow of information and technical data among various design departments. The design

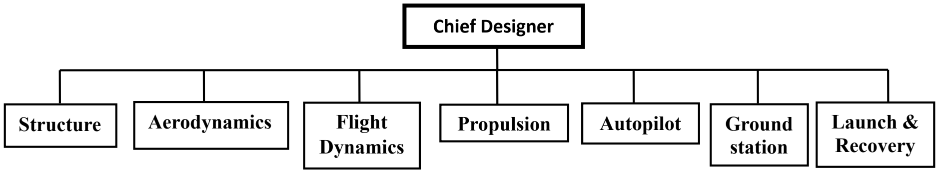

Fig. 1.1 UAV main design groups

organization must allow the chief designer to initiate and establish the necessary ongoing liaison activities throughout the design cycle.

A primary building block is organizational patterns is the functional approach, which involves the grouping of functional specialties or disciplines into separately identifiable entities. The intent is to perform similar work within one organizational group. Thus, the same organizational group will accomplish the same type of work for all ongoing projects on a concurrent basis. The ultimate objective is to establish a team approach, with the appropriate communications, enabling the application of concurrent engineering methods throughout.

There are mainly two approaches to handle the design activities and establishing design groups: 1. Design groups based on aircraft components, 2. Design groups based on expertise. If the approach of groups based on aircraft components is selected, the chief designer must establish the following teams: 1. Wing design team, 2. tail design team, 3. Fuselage design team, 4. Propulsion system design team, 5. Landing gear design team, 6. Autopilot design team, 7. Ground station design team, 8. Launch & recovery design team. The ninth team is established for documentation and drafting. There are various advantages and disadvantages for each of the two planning approaches in terms of ease of management, speed of communication, efficiency, and similarity of tasks. However, if the project is large such as the design of a large transport aircraft, both groupings (Fig. 1.1) could be applied simultaneously.

1.7 Design Process

UAV Design is an iterative process which involves synthesis, analysis, and evaluation. Figure 1.2 demonstrates the design process block diagram. Design (i.e., Synthesis) is the creative process of putting known things together into new and more useful combinations. Analysis refers to the process of predicting the performance or behavior of a design candidate. Evaluation is the process of performance calculation and comparing the predicted performance of each feasible design candidate to determine the deficiencies. A design process requires both integration and iteration. There is an interrelationship between synthesis, analysis, and evaluation. Two main groups of design activities are: 1.

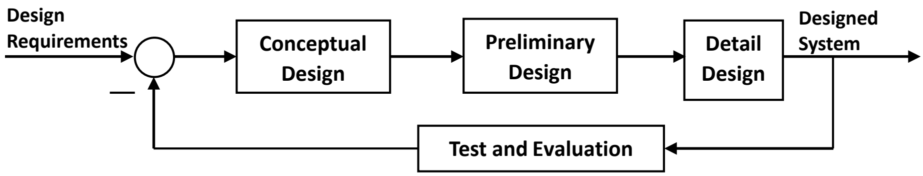

Fig. 1.2 UAV design process block diagram

Problem solving through mathematical calculations; 2. Choosing a preferred one among alternatives.

In general, design considerations are the full range of attributes and characteristics that could be exhibited by an engineered system, product, or structure. These interest both the producer and the customer. Design-dependent parameters are attributes and/or characteristics inherent in the design to be predicted or estimated (e.g., weight, design life, reliability, producibility, maintainability, and disposability). These are a subset of the design considerations for which the producer is primarily responsible. On the other hand, design-independent parameters are factors external to the design that must be estimated and forecasted for use in design evaluation (e.g., fuel cost per gallon, interest rates, labor rates, and material cost per pound). These depend upon the production and operating environment of the UAV.

A goal statement is a brief, general, and ideal response to the need statement. The objectives are quantifiable expectations of performance which identify those performance characteristics of a design that are of most interest to the customer. Restrictions of function of form are called constraints; they limit our freedom to design.

1.8 Systems Engineering Approach

Complex UAV systems, due to the high cost and the risks associated with their development become a prime candidate for the adoption of systems engineering methodologies. The UAV conceptual design process has been documented in many texts, and the interdisciplinary nature of the system is immediately apparent. A successful configuration designer needs not only a good understanding of design, but also systems engineering approach. A competitive configuration design manager must have a clear idea of the concepts, methodologies, models, and tools needed to understand and apply systems engineering to UAV systems.

The design of a UAV begins with the requirements definition and extends through functional analysis and allocation, design synthesis and evaluation, and finally validation. An optimized UAV, with a minimum of undesirable side effects, requires the application of an integrated life-cycle oriented “system” approach. The design of the configuration for