

1

Design Fundamentals

CONTENTS

Educational Outcomes,	1
1.1	Introduction, 2
1.2	UAV Classifications, 5
1.3	Review of a Few Successful UAVs, 8
1.3.1	Global Hawk, 8
1.3.2	RQ-1A Predator, 9
1.3.3	MQ-9 Predator B Reaper, 9
1.3.4	RQ-5A Hunter, 10
1.3.5	RQ-7 Shadow 200, 10
1.3.6	RQ-2A Pioneer, 11
1.3.7	RQ-170 Sentinel, 11
1.3.8	X-45A UCAV, 12
1.3.9	Epson Micro-flying Robot, 12
1.4	Design Project Planning, 12
1.5	Decision Making, 13
1.6	Design Criteria, Objectives and Priorities, 15
1.7	Feasibility Analysis, 17
1.8	Design Groups, 17
1.9	Design Process, 18
1.10	Systems Engineering Approach, 19
1.11	UAV Conceptual Design, 21
1.12	UAV Preliminary Design, 27
1.13	UAV Detail Design, 28
1.14	Design Review, Evaluation, Feedback, 30
1.15	UAV Design Steps, 30
	Questions, 32

Educational Outcomes

After study of this chapter, the reader will be able to:

- 1) Discuss features of current and modern Unmanned Aerial Vehicles UAVs
- 2) Manage a Unmanned Aerial System (UAS) design project
- 3) Develop UAV design requirements

- 4) Be familiar with the current UAS technologies
- 5) Be familiar with the current UAS design techniques
- 6) Describe UAV classifications
- 7) Explain design process
- 8) Conduct feasibility analysis
- 9) Organize a UAV design team
- 10) Describe systems engineering approach in designing UAVs
- 11) Conduct UAV conceptual, preliminary, and detail design phases
- 12) Know alternatives in a UAV configuration design
- 13) Analyze design reviews, evaluations, and feedbacks
- 14) Implement safety analysis
- 15) Demonstrate familiarity with contemporary issues and challenges related to UAVs
- 16) Learn from past UAV design lessons
- 17) Prepare and present a design report

1.1 Introduction

Unmanned Aerial Vehicles (UAVs) are remotely-piloted or self-piloted air vehicles that can carry payloads such as cameras, sensors, and communications equipment. All flight operations (including take-off and landing) are performed without an on-board human pilot. In some reports of Department of Defense (DOD), Unmanned Aerial System (UAS) is preferred. In media reports, the term “drone” is 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 UAVs has grown in interest over the past couple decades. There has been tremendous emphasis in UAVs, 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 Predator, Global Hawk and other international programs. The possible break-through of UAV technology requires support from the aforementioned awareness of general UAV design requirements and their consequences on cost, operation, and performance of UAV systems.

In June 2016, the Department of Transportation's Federal Aviation Administration finalized the first operational rules [2] for commercial use of small unmanned aircraft systems (sUAS), opening pathways toward fully integrating UAS into the USA's airspace. These new regulations aim to harness new innovations safely, to spur job growth,

advance critical scientific research and save lives. From FAR (Federal Aviation Regulations) Part 107, a small UAV is defined as the one with a weight of less than 55 lb (i.e., its mass is less than 25 kg). Please note that, Part 107 does not cover recreational applications or hobby use of small UAVs. Moreover, as given in Part 107.51(a)–(d), an sUAS can be operated only below 400 ft. Above Ground Level (i.e., local altitude), 500 ft below clouds, and must have at least three statute mile visibility.

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 the UAV varies according to the purpose of the utility. In many cases the design and construction of UAVs face new challenges and, as a result of these new requirements, several recent works are concerned with the design of innovative UAVs. 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 have been applied to the design of various UAVs including Medium-Altitude, Long-Endurance (MALE) UAV using a multi-objective genetic algorithm.

The first UAV designs that appeared in the early 1990s were based on the general design principles for full UAV and findings of experimental investigations. The main limitation of civil UAVs 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 two 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.

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. You need to 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) or the Systems Element operates (e.g., the airspace, the data links, relay UAV, etc.). 2. The air vehicle(s) or the Air Vehicle Element. 3. The control station(s) or the Mission Control Element. 4. The payload(s) or the Payload Element. 5. The maintenance and support system or the Support Element.

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: (a) the latest UAV developments; (b) current technologies; and (c) lessons learned from past failures. The designer should appreciate breadth of UAV design options.

The number of small RC model (hobbyist) airplanes registered in the US is projected to grow from 1.1 million units in 2017 to 2.4 million in 2022. Moreover, commercial (small non-model UAVs) registrations are totaled 110604 in 2017, and are projected to grow to 451800 in 2022. FAA (Federal Aviation Administration) has required owners of model and commercial UAVs weighing more than 0.55 and less than 55 pounds to register them, beginning December 2015. Large UAVs – those weighing over 55 pounds – must register with the FAA as traditional aircraft.

There are five primary military UAVs in service currently: The US Army's Hunter and Shadow, the US Navy's Pioneer, and the US Air Force's Predator and Global Hawk. The features and characteristics of these UAVs are presented in the next section.

By January 2019, at least 62 countries are using or developing over 1300 various UAVs. The contributions of unmanned UAV in sorties, hours, and expanded roles continue to increase. As of September 2004, some 20 types of coalition UAVs, large and small, have flown over 100 000 total flight hours in support of Operation Enduring Freedom and Operation Iraqi Freedom. Large numbers of UAVs presently exist, both domestically and internationally. Their payload weight carrying capability, their accommodations (volume, environment), their mission profile (altitude, range, duration) and their command, control and data acquisition capabilities vary significantly.

As of January 2019, the following countries developed and employed UAVs with civil payloads: Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Croatia, Czech Republic, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, India, Indonesia, International, Iran, Israel, Italy, Japan, Jordan, Latvia, Malaysia, Mexico, Netherlands, New Zealand, Nigeria, Norway, North Korea, Pakistan, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Serbia, Singapore, Slovenia, South Africa, South Korea, Spain, Switzerland, Sweden, Taiwan, Thailand, Tunisia, Turkey, United Arab Emirates, United Kingdom, United States, Vietnam.

Their once reconnaissance only role is now shared with strike, force protection, and signals collection. As of 2018, the following countries developed and employed UAVs with military payloads: Argentina, Australia, Brazil, Canada, China, France, Germany, Israel, Iran, Iraq, India, Italy, Nigeria, Pakistan, Russia, Somalia, Spain, South Africa, Turkey, United Kingdom, and the USA.

General Atomics Aeronautical Systems (as the General Atomic division of General Dynamics), on 9 April 2018 announced that its Predator-series family of Remotely Piloted Aircraft, encompassing MQ-1 Predator, Predator B, Gray Eagle, MQ-9 Reaper, MQ-9B SkyGuardian, and Predator C Avenger, has achieved a historic industry milestone: five million flight hours. The milestone was achieved on 4 April, with 360 311 total missions completed and more than 90% of all missions flown in combat.

UAVs can help companies in fields like energy, telecommunications, videography, sport, and construction to get new perspectives on their works. According to a 2013 report from the Aerospace Industries Association (AIA), the integration of UAS into civil airspace is projected to generate \$89 billion through 2023. In 2013, the US has more than one million unmanned flight hours annually, and the Department of Defense operates more than 7000 UAV operations.

Recently, United States Marine Corps procures the new InstantEye Mk-3 GEN5-D1 sUAS system to expand mission scope and to provide additional reconnaissance, surveillance, and target acquisition capability to the individual marine or sailor.

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

1.2 UAV Classifications

It is a must for a UAV designer to be aware of classifications and applications of UAVs, which are based on various parameters such as cost, size, weight, mission, and the user. For instance, UAVs range in weight from Micro Air Vehicles (MAV) weighing less than one pound to UAVs weighing over 40000 pounds. Moreover, these diverse systems range in cost from less than one hundred dollars (Amazon sells varieties) to tens of millions of dollars (e.g., Global Hawk). In addition, UAV missions range from: reconnaissance; combat; target acquisition; electronic warfare; surveillance; special purpose UAV; target and decoy; communication relay; logistics [3]; research and development; civil and commercial UAVs; to Environmental application (e.g., University of Kansas North Pole UAV for measuring ice thickness).

For instance, in humanitarian aid/disaster response, a communication relay UAV can be utilized to fill the gaps in the communications grid when cellphone towers are damaged, or to enhance existing communications past the normal quality, range, or security. Moreover, in a search and rescue mission, swarm technology allows multiple sUASs to work in tandem to cover larger areas and communicate back to a single ground control station.

UAVs are considered as a great force multiplier within military use, as they offer many advantages. Commonly these advantages are attained at a lower risk and a lower cost than if a corresponding manned aircraft would do the same mission. Typical applications for the Navy include [4, 5]: (a) shadowing enemy fleets; (b) decoying missiles by the emission of artificial signatures; (c) electronic intelligence; (d) relaying radio signals; (e) protection of ports from offshore attack; (f) placement and monitoring of sonar buoys and possibly other forms of anti-submarine warfare; (g) optical surveillance and reconnaissance; and (h) Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR).

For instance, sUASs can be considered as an effective way [5] to conduct aerial swarm raids to neutralize radar defenses by saturating the target acquisition area with a swarm of UAVs that either operate as decoys, or have weapons payloads to destroy designated targets. This tactic has the potential to be more cost effective than traditional stealth technology.

The early classification includes target drones, and remotely piloted vehicles (RPVs). The current classification ranges from Micro UAVs (less than 15 cm long, or 1 lb), to High-Altitude Long-Endurance (HALE), to tactical and combat UAVs. In this section, characteristics of various classifications are briefly presented.

The Micro Unmanned Aerial Vehicles (MUAV) was originally a DARPA (Defense Advanced Research Projects Agency) program to explore the military relevance of Micro Air Vehicles for future military operations, and to develop and demonstrate flight enabling technologies for very small UAV (less than 15 cm/6 in. in any dimension). The Tactical UAV (e.g., Outrider) is designed to support tactical commanders with near-real-time imagery intelligence at ranges up to 200 km. The Joint Tactical UAV (Hunter) were developed to provide ground and maritime forces with near-real-time imagery intelligence at ranges up to 200 km.

The MALE UAV (Predator) provides imagery intelligence to satisfy Joint Task Force and Theater Commanders at ranges out to 500 nautical miles. The High-Altitude Long-Endurance UAV (Global Hawk) are intended for missions requiring long-range deployment and wide-area surveillance or long sensor dwell over the target area.

Table 1.1 shows the UAV classifications from a few aspects including: (a) size (e.g., micro, mini, and small); (b) mass; and (c) mission (e.g., HALE, UCAV). In Table 1.1, the term “size” for fixed-wing UAVs, refers to the largest of the wing span and the fuselage length. However, for quadcopters, it refers to the outer distance between the tip of one propeller to the neighboring one. Moreover, the term weight refers to the maximum takeoff weight (MTOW) of the UAV.

The Boeing-Insitu Scan Eagle (Figure 3.3) is classified as a small UAV, RQ-4 Global Hawk is a HALE UAV, and MQ-1 Predator and MQ-9 Reaper are medium UAVs. X-45 is a tactical/ combat UAV or UCAV (Unmanned Combat Aerial Vehicle). Quadcopters may be in various classes including micro through medium.

In US military, the classification is mainly based on a tier system. For instance, in US Air Force the Tier I is for low altitude, long endurance missions, while Tier II is for MALE missions (e.g., Predator). Moreover, Tier II+ is for HALE missions, and Tier III- denotes HALE low observable. MALE UAVs usually have a continental operating scenario, while HALE UAVs usually have an intercontinental operating scenario.

For other military forces, the following is the classification: Marine Corp: Tier I: Mini UAV; (e.g., Wasp); Tier II: (e.g., Pioneer); and Tier III: Medium range, (e.g., Shadow). Army: Tier I: Small UAV, (e.g., Raven); Tier II: Short range, tactical UAV, (e.g., Shadow 200); and Tier III: Medium range, tactical UAV.

Micro, mini, very small, small, and HALE UAVs, and quadcopters are typically allowed to fly within the category G of international airspace. However, MALE UAVs are allowed to fly within the category A of airspace, and tactical UAVs can fly within the categories B, C, D, and E of airspace. It should be clear that flight within all categories must have a permission prior to the flight operation from the respective authorities. Large UAVs must always send radio signals (via equipment such as transponder) within the labeled airspace to declare their flight characteristics.

Table 1.1 Unmanned Aerial Vehicles (UAVs) classification.

No	UAV Class	Weight (lb)	Size	Normal operating altitude	Range (km)	Endurance
1	Micro	<0.55	≤ 10 cm	< 100 ft	0.1–0.5	≤ 1 hr
2	Mini	0.55–2	10–30 cm	< 500 ft	0.5–1	≤ 1 hr
3	Very small	2–5	30–50 cm	< 1000 ft	1–5	1–3 hr
4	Small	5–55	0.5–2 m	1000–5000 ft	10–100	0.5–2 hr
5	Medium	55–1000	5–10 m	10 000–15 000 ft	500–2000	3–10 hr
6	Large	10 000–30 000	20–50 m	20 000–40 000 ft	1000–5000	10–20 hr
7	Tactical/ combat	1000–20 000	10–30 m	10 000–30 000 ft	500–2000	5–12 hr
8	MALE	1000–10 000	15–40 m	15 000–30 000 ft	20 000–40 000	20–40 hr
9	HALE	> 5000	20–50 m	50 000–70 000 ft	20 000–40 000	30–50 hr
10	Quadcopter	0.5–100	0.1–1 m	< 500 ft	0.1–2	20 min–1 hr
11	Helicopter	0.001–200	13 mm–2 m	< 500 ft	0.2–5	10 min–2 hr

Another basis for classification for UAVs in the military is echelon: (a) Class 1 supports platoon echelon, (e.g., Raven), MUAV, and small UAV; (b) Class 2 supports company echelon, (e.g., Interim Class 1 and 2 UAV); (c) Class 3 supports battalion echelon, (e.g., Shadow 200 Tactical UAV); and (d) Class 4 supports unit of action (brigade), (e.g., Hunter), Extended Range/Multipurpose (ER/MP) UAV. In naming military UAVs in the USA, “R” stands for reconnaissance, and “Q” for unmanned aircraft system. As an example, Predator was the first UAV for a reconnaissance mission (Thus RQ-1).

In terms of wing, there are two groups of UAVs: (a) fixed-wing; and (b) rotary wing. A fixed-wing UAV often needs a runway or a launcher to take-off, while a rotary-wing UAV can take off and land vertically. Two popular groups of rotary-wing UAVs are: (a) unmanned helicopter; and (b) quadcopter. Figure 1.1 shows a Yamaha RMAX unmanned helicopter with a maximum mass of 94 kg that can have an endurance of one hour. This UAV has a main rotor diameter of 3.115 m, and a length of 3.63 m.

Some Current UAVs are listed here:

- **US Army UAV Systems:** RQ-1L I-GNAT Organization; RQ-5/MQ-5 Hunter Aerial Reconnaissance Company; RQ-7 Shadow Aerial Reconnaissance Platoon; RQ-11 Raven Team.
- **Air Force UAV Systems:** RQ-4 Global Hawk; RQ/MQ-1 Predator; MQ-9 Predator B; Force Protection Aerial Surveillance System–Desert Hawk.
- **Navy UAV Systems:** RQ-2 Pioneer; RQ-8B Fire Scout.
- **Marine Corps UAV Systems:** FQM-151 Pointer; Dragon Eye; Silver Fox; Scan Eagle.
- **Coast Guard UAV Systems:** Eagle Eye.
- **Special Operations Command UAV Systems:** CQ-10 SnowGoose; FQM-151 Pointer; RQ-11 Raven; Dragon Eye; RQ-170 Sentinel.

Any UAV must be registered under a particular part of FAR. Table 1.2 presents UAV registration coverage by FAA under three parts: Part 48, Part 47, and Part 107. The FAA has approved [6] the use of a new UAV weighing over 55 pounds for commercial crop-spraying operations.



Figure 1.1 Yamaha RMAX unmanned helicopter.

Table 1.2 Unmanned Aerial Vehicles (UAV) registration coverage.

No	UAV weight (mass)	FAR
1	> or = 0.55 lbs. (250 g)	Part 48
2	> or = 55 lbs. (25 kg)	Part 47
3	< 55 lbs. (25 kg)	Part 107

1.3 Review of a Few Successful UAVs

It is very helpful for a UAV designer to be familiar with the features of some old and current UAVs. The features of the ground control stations of these UAVs are presented in Chapter 11. Moreover, the payloads of these air vehicles are provided in Chapter 12. Furthermore, lessons learned in designing other UAVs are provided in Chapter 2. This covers success stories for some UAV design projects, as well as some lessons from crashes and cancelations of a few discontinued projects.

1.3.1 Global Hawk

The Global Hawk (Figure 1.2) is an advanced intelligence, surveillance, and reconnaissance unmanned air system composed of a HALE vehicle and a ground control segment for command, control, and data collection. Its primary mission is to provide overt, continuous, all-weather, day/night, and near-real-time, large geographic area reconnaissance and surveillance. The Global Hawk, designed and manufactured by Northrop Grumman, is the largest of the military unmanned aircraft systems.

This flew for the first time at Edwards Air Force Base, California, on Saturday, 28 February 1998. The first flight of the Global Hawk signified the first UAV to cross the Pacific Ocean in April 2001, when it flew from the United States to Australia. The entire mission, including the take-off and landing, was performed autonomously by the UAV based on its mission plan. The launch and recovery element of the system's ground segment continuously monitored the status of the flight.



Figure 1.2 Global Hawk.

Guinness World Records has recognized the flight as the longest (13840km) by a full-scale unmanned aircraft. The Global Hawks, monitored by shifts of pilots in a ground control station in California, fly 24-hour missions, and they are cheaper to operate than spy plane U-2.

Global Hawk is the largest active current UAVs with successful flights, and with a high altitude and long endurance. Some mass and geometry features are: wingspan: 39.9 m, length: 14.5 m, maximum takeoff mass: 14628 kg. This HALE UAV has a single Rolls Royce F137-RR-100 turbofan engine with a maximum thrust of 34 kN. The performance statistics of the UAV are: maximum speed: 340 knot, cruise speed: 310 knot, range: 22779 km, endurance: 32+ hours, and service ceiling: 60000 ft. Global Hawk has an aluminum fuselage and contains pressurized payload and avionics compartments.

1.3.2 RQ-1A Predator

The Predator UAV (Figure 8.5) – developed by General Atomics – is a relatively small aircraft (with a wing span of 48.4 ft) constructed of high strength composite materials. The Predator made its first flight in June 1994, and is considered as one of the most successful unmanned machines in the US Military.

Predator requires a full-time personnel of about 55 individuals to fly and operate. Predator can conduct an automatic flight along a path that has been programmed in advance. By using satellite communication and an encrypted data link, it can fly remotely anywhere in the world. The wings and tail surfaces are removable, and the entire vehicle fits into a purpose-built container, several of which can be transported in a C-130 along with the ground control trailer.

Predator has a relatively conventional configuration, a high aspect ratio (19) wing, Y-tail, single pusher piston engine, and retractable tricycle landing gear. Due to its MTOW of 2100 lb and a low engine power (115 hp), it has a relatively low performance (Cruise speed of 90 knot, and ceiling of 26000 ft). However, with a payload of 450 lb, its endurance of 25 hour is relatively long.

Since its first operational deployment in the mid-1990s, the Predator has evolved from a pure surveillance UAV to an armed flying weapon that has become a symbol of American military presence in Middle East countries (e.g., Afghanistan, Iraq, Pakistan, and Syria). The Predator can carry two Hellfire missiles, at a maximum speed of 135 mi/hr and has a range of 770 miles. The Hellfire missiles organizationally do not belong to Airforce; they are utilized, since they are light (14.2 kg), small (53 cm) enough to be attached and carried by Predator. The air force missiles are relatively heavy (86 kg) and large (2.89 m). In 2013, the cost per hour of Predator flight was at \$3679. The Predator fleet reached 500000 flight hours on 18 February 2009. The Predator is planned to retire from US Air Force service soon, its retirement has been pushed to 2018.

1.3.3 MQ-9 Predator B Reaper

There were originally two Predator variants, currently designated as MQ-1 Predator and MQ-9 Predator B Reaper. The MQ-9 Reaper is a larger, heavier, and more capable aircraft than the earlier version (i.e., Predator A). After more than 20 years of service, the US Air Force announced on 27 February 2017 that the MQ-1 Predator UAV would be phased out within a year. The retirement of the Predator does not mean that they will

not be present in the skies. Instead General Atomics Aeronautical Systems, the manufacturer, has redeveloped the UAV for civilian use, renamed it the Predator B Reaper, and is trying to sell it to police forces and firefighters.

General Atomics has examined four variants for the Predator B:

- Naval version, named Mariner
- US Customs and Border Protection variants, known as Guardians
- International version, Sky Guardian
- United Kingdom version Protector RG.1.

The Predator B (which first flew on 2001) is equipped with a Honeywell TPE-331-10T turboprop engine, flat-rated to 750hp and 1360kg of fuel. The greater engine power allows the Reaper to carry 15 times more ordnance payload and cruise at about three times the speed of the MQ-1 Predator A.

The UAV, with a take-off gross mass of 4500kg and a wingspan of 20 m, has a maximum speed 210knot, and ceiling of 50 000 ft. The Predator B has two types of payloads: (a) 340 kg of internal payload for sensors and cameras; and (b) 1360 kg of external payload, for 6 store stations/14 Hellfire missiles. An MQ-9 with two 1000-pound external fuel tanks and 1000 pounds of munitions has an endurance of 42 hours.

Avenger is the combat drone that has been developed by the General Atomics Aeronautical System Company. It is one of the latest unmanned aircrafts of the US Army. In 2012, the company improved the ground control station. A Predator variant, Avenger uses the same ground support infrastructure as the MQ-1 and MQ-9, including the ground control station and existing communications networks. By the end of 2018, variants of General Atomics' Predator (Predator A, Gray Eagle, SkyGuardian, and Reaper) have surpassed five million flight hours.

1.3.4 RQ-5A Hunter

The RQ-5A Hunter UAV is based on the MQ-5 Hunter, the first project that was canceled in January 1996 after some 20 air vehicle crashes. On 13 January 2014, Northrop Grumman's RQ-5A Hunter, in use with the US Army since 1996, surpassed 100 000 combat flight hours in service. This UAV with a wingspan of 10.57 m is powered by two Twin Mercedes HFE Diesel engines, each with a maximum power of 56hp. Hunter with a maximum TO mass of 885kg has a maximum speed of 90knot, a range of 125 km, an endurance of 21 hours and a service ceiling of 18 000 ft.

The UAV has two pilots, one in the Ground Control Station (GCS) to control the flight after takeoff, and one pilot on the runway to conduct takeoff and landing. A hook (a cable system) located below the aircraft is used to snag the aircraft on a set of arresting cables positioned across the runway. As of October 2012, the US Army had 20 MQ-5B Hunters in service, but retirement of the Hunter was expected to be completed in 2013.

1.3.5 RQ-7 Shadow 200

The RQ-7 Shadow 200 unmanned aircraft is of a high- rectangular wing, pusher engine, with a twin tail-boom and an inverted V-tail. The aircraft is powered by a 38 hp piston engine. Unlike the Hunter, the Shadow does not use an external pilot, depending instead

on a launcher for takeoffs, and an automated landing system for recovery. The landing system, called the tactical automated landing system controls the aircraft during approach and landing, usually without intervention from the GCS pilot.

A cable system, similar to the one used for the Hunter, is used to stop the aircraft after landing. Aircraft control during flight is accomplished by the GCS pilot through a computer menu interface that allows selection of altitude, heading, and airspeed. During landing, GCS personnel have no visual contact with the aircraft, nor do they have any sensor input from onboard sensors. A command to stop the aircraft engine is given by the GCS pilot, who must rely on an external observer to communicate that the plane has touched down.

1.3.6 RQ-2A Pioneer

Like the US Army's Hunter UAV, the Pioneer (First flight: 1985) requires an external pilot for takeoff and landing. After takeoff, the aircraft can be controlled from a GCS in one of three modes. In the first mode the air vehicle is operated autonomously, and the autopilot uses global positioning system preprogrammed coordinates to fly the air vehicle to each waypoint. In the second mode, the internal pilot commands the autopilot to command airspeed, altitude, and heading or bank angle. In the third mode, the internal pilot flies the aircraft using a joystick. The Pioneer can be landed at a runway using arresting cables, but because it is a US Navy/Marine operated aircraft, it is also landed on board a ship by flying into a net.

This vehicle with a wing span of 16.9ft, and a length of 14ft has a Max TO Weight: 450lbs. The maximum speed is only 110knots.

Since 1994, it has flown over a number of countries including Bosnia, Haiti, and Somalia. It was also used extensively in Falujeh, Iraq, 2006. During Operation Desert Shield, the US deployed 43 Pioneers that flew 330 sorties, completing over 1000 flight hours. In 10 years, the Pioneer system has flown nearly 14 000 flight hours.

1.3.7 RQ-170 Sentinel

The RQ-170 Sentinel (Figure 1.3) was developed by Lockheed Martin as a stealth UAV, operated by the US Air Force for the Central Intelligence Agency. It has a tail-less

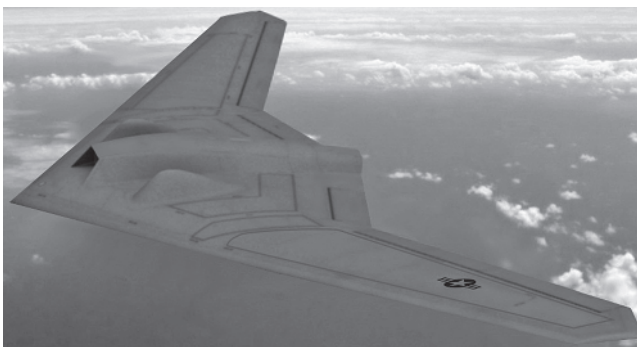


Figure 1.3 Lockheed Martin RQ-170 Sentinel.

configuration, and is fitted with aerial reconnaissance equipment; about 20 of this UAV were built. The wingspan is approximately 20 m, length about 4.5 m, takeoff mass is estimated as being greater than 3900 kg. The UAV is equipped with a single turbofan engine (GE TF34) with a thrust of 40.3 kN. The UAV which was introduced in 2007 has a service ceiling which is estimated to be 50 000 ft. The RQ-170 has three crew members in the GCS to remotely control the UAV; one for launch and recovery, one for mission control, and one as the sensor operator.

1.3.8 X-45A UCAV

The X-45A UCVA (Figure 4.10) – developed by Boeing [7] – is a concept demonstrator for the next generation of completely autonomous military fighter. It is of a swept-wing, stealthy design, no vertical tail, and composite construction. The fuselage is blended into a swept wing, with a small exhaust outlet. The air vehicle can carry advanced precision guided munitions, bombs, or other weapons systems. This vehicle with a wing span of 10.3 m, and a length of 8.08 m has a turbofan engine with a maximum thrust of 28 kN. The maximum speed is Mach 0.75, the range is 2405 km, and the service ceiling is 13 200 m.

In 2003, DARPA announced the cancelation of the X-45B, and the approval for the development of an improved UCAV, called the X-45C. Hence, after the completion of the flight test program, both X-45As were delivered to two national museums.

1.3.9 Epson Micro-flying Robot

In 2004, Epson announced that it has successfully developed one of the world's smallest and lightest micro-flying robots (Figure 1.4) with a mass of (with battery) 12.3 g.

The UAV is equipped with an image sensor unit that can capture and transmit aerial images via a Bluetooth wireless connection to a monitor on ground, and two LED lamps that can be controlled as a means of signaling. General specifications are: Power: 4.2 V, power consumption: 3.5 W, diameter: 136 mm, height: 85 mm, Flight time: about 3 minutes, and mass of the structure: 3 g.

Table 1.3 exhibits characteristics of a number of UAVs, including maximum takeoff mass, wing area, wing span, engine power or thrust. It also demonstrates a few performance features such as service ceiling, maximum speed, range, endurance.

1.4 Design Project Planning

The development and certification of a new UAS project is not cheap and easy, and usually takes several years to conduct. 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. 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.

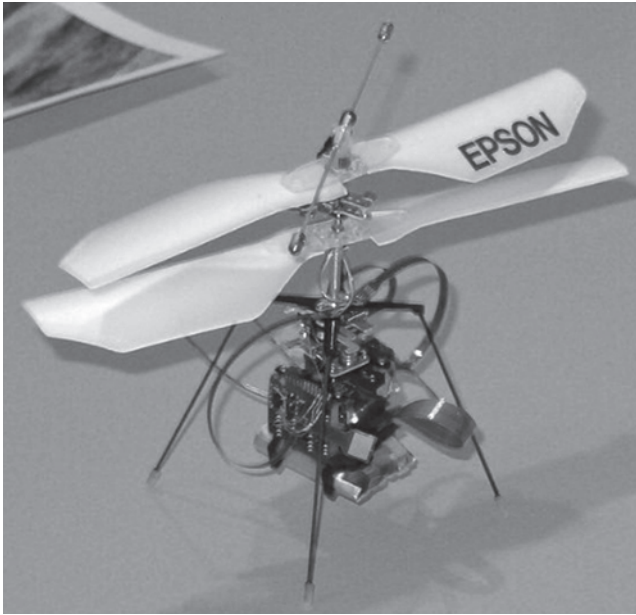


Figure 1.4 Epson micro flying robot.

- 2) It indicates the estimated dates on which tasks are assumed to start and end, and it represents graphically the estimated duration 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 Global Hawk (Figure 1.2) will not be successful without a design project planning.

1.5 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 straightforward governing equations to be solved mathematically.

Table 1.3 Characteristics of a number of Unmanned Aerial Vehicles (UAVs).

No	UAV name	m _{ro} (kg)	m _{pl} (kg)	S (m ²)	b (m)	P or T	Service ceiling	Max speed	Range	Endurance (hr)
1	Predator B Reaper	4760	1700	20.2	20.1	712kW Turboprop	50000 ft	260 knot	5926 km	14–28
2	Global Hawk	14628	2000 lb	69	39.9	31.4 kN Turbofan	65 000 ft	V _C 345 knot	14 000 nm	41
3	Predator A	1020	–	11.5	14.8	86 kW Piston	25 000 ft	117 knot	726 km	24
4	Yamaha R-MAX	94	30 kg	Rotor diameter: 3.115 m	–	15.4 kW Piston	–	–	1 hour	–
5	ScanEagle	18	–	–	3.1	1.5 hp Piston	16 000 ft	70 knot	–	20+
6	X-45A UCAV	6804	–	–	10.23	31.4 kN Turbofan	–	Mach 0.75	–	–
7	X-45C UCAV	16 555	–	–	14.9	50.03 kN Turbofan	12.19 km	Mach 1	2220 km	–
8	RQ-5A Hunter	885	90 kg	14.28	10.57	2 × 64 hp Piston	18 000 ft	89 knot	125 km	12
9	RQ-7 Shadow 200	170	–	4.5	4.3	28 kW Piston	15 000 ft	110 knot	400 km	6
10	Raven	1.9	0.4	0.32	1.37	250 W Electric	–	30 km/hr	10 km	1

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.

1.6 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 groups of UAV designers, namely: (a) military UAV designer; (b) civil UAV designer; and (c) homebuilt UAV designer. These three groups of designers have different interests, priorities, and design criteria. There are mainly 10 figures of merit for every UAV configuration designer. They are: (a) production cost; (b) AV performance; (c) flying qualities; (d) design period; (e) beauty (for civil UAV) or scariness (for military UAV); (f) maintainability; (g) producibility; (h) UAV weight; (i) disposability; and (j) stealth requirement. Table 1.4 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 1.5 illustrates three scenarios of priorities (in percent) for military UAV designers. Among 10 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 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

Table 1.4 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	Liter/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	Producibile	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	–

Table 1.5 Three scenarios of priorities (in percent) for a military Unmanned Aerial Vehicle (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%

for a military UAV designer, while for three other 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.

1.7 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 attractive, but when it comes to the reality, they are found to be too imaginary.

In this phase, the designer addresses the fundamental question of whether to proceed with the selected concept. A 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 the source of design requirements is, either through direct customer order or market analysis, they must be changed.

1.8 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 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 as the functional approach, which involves the grouping of functional specialties or disciplines into separately identifiable entities. The intention 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 for handling the design activities and establishing design groups: (a) design groups based on aircraft components; and (b) design groups based on expertise. If the approach of groups based on aircraft components is selected, the chief designer must establish the following teams: (a) structural design group; (b) aerodynamic design group; (c) payloads selection; (d) propulsion system design team; (e) landing gear design team; (f) autopilot design team; (g) ground control station design team; (h) launch and recovery design team; (i) communications system group; (j) landing gear; and (k) mission design and trajectory planning. The aerodynamic design group includes a number of teams such as: (a) wing design team; (b) tail design team; and (c) fuselage design team.

The last 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 HALE aircraft, both groupings (Figure 1.5) could be applied simultaneously. In Chapter 14, design groups based on expertise are presented. This approach is mainly structured and employed for design analysis.

1.9 Design Process

UAV Design is an iterative process which involves synthesis, analysis, and evaluation. 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

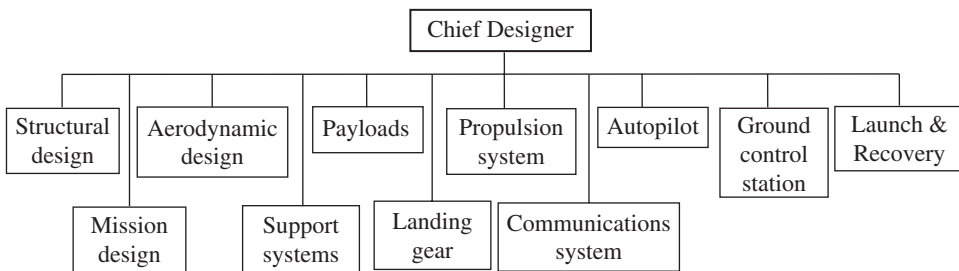


Figure 1.5 Unmanned Aerial Vehicle (UAV) main design groups.

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: (a) problem solving through mathematical calculations; and (b) 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 are of interest to 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 or form are called constraints; they limit our freedom to design.

1.10 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 the configuration for the 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. Operations and support needs must be accounted for in this process. 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 UAV subsystems plays a crucial role in the configuration design and their operation. These subsystems turn an aerodynamically shaped structure into a living, breathing, unmanned flying machine. These subsystems include the: flight control subsystem, power transmission subsystem, fuel subsystem, structures, propulsion, aerodynamics, and landing gear. In the early stages of a conceptual or a preliminary design these subsystems must initially be defined, and their impact must be incorporated into the design layout, weight analysis, performance calculations and cost benefits analysis.

A UAV is a system composed of a set of interrelated components working together toward some common objective or purpose. Primary objectives include safe flight achieved at a low cost. Every system is made up of components or subsystems, and any subsystem can be broken down into smaller components. For example, in an air transportation system, the UAV, terminal, ground support equipment, and controls are all subsystems. The UAV life-cycle is illustrated in Figure 1.6.

A UAV must feature product competitiveness, otherwise the producer and designer may not survive in the world marketplace. Product competitiveness is desired by UAV producers worldwide. Accordingly, the systems engineering challenge is to bring products and systems into being that meet the mission expectations cost-effectively. Because of intensifying international competition, UAV producers are seeking ways to gain sustainable competitive advantages in the marketplace.

It is essential that UAV designers be sensitive to utilization outcomes during the early stages of UAV design and development. They also need to conduct life-cycle engineering as early as possible in the design process. Fundamental to the application of systems engineering is an understanding of the system life-cycle process illustrated in Figure 1.6. It must simultaneously embrace the life cycle of the manufacturing process, the life cycle of the maintenance and support capability, and the life cycle of the phase-out and disposal process.

The requirements need for a specific new UAV first comes into focus during the conceptual design process. It is this recognition that initiates the UAV conceptual design process to meet these needs. Then, during the conceptual design of the UAV, consideration should simultaneously be given to its production and support. This gives rise to a parallel life cycle for bringing a manufacturing capability into being.

Traditional UAV configuration design attempts to achieve improved performance and reduced operating costs by minimizing MTOW. From the point of view of an UAV customer, however, this method does not guarantee the optimality of an UAV program. Multidisciplinary design optimization (MDO) is an important part of the UAV configuration design process. It first discusses the design parameters, constraints, objectives functions and criteria and then UAV configuration classifications. Then the relationship between each major design option and the design requirements are evaluated. Then the systems engineering principals are presented. At the end, the systems engineering approach is applied in the optimization of the UAV configuration design and a new configuration design optimization methodology is introduced.

The design of a UAV within the system life-cycle context is different from the design just to meet a set of performance or stability requirements. Life-cycle focused design is simultaneously responsive to customer needs and to life-cycle outcomes. The design of

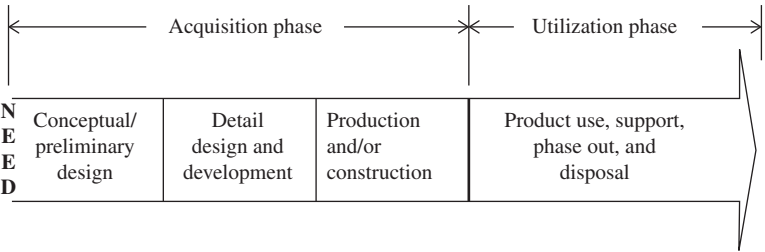


Figure 1.6 The Unmanned Aerial Vehicle (UAV) life-cycle.

the UAV should not only transform a need into a UAV/system configuration, but should also ensure the UAV's compatibility with related physical and functional requirements. Further, it should consider operational outcomes expressed as safety, producibility, affordability, reliability, maintainability, usability, supportability, serviceability, disposability, and others, as well as the requirements on performance, stability, control, and effectiveness.

An essential technical activity within this process is that of evaluation. Evaluation must be inherent within the systems engineering process and must be invoked regularly as the system design activity progresses. However, systems evaluation should not proceed without guidance from customer requirements and specific system design criteria. When conducted with full recognition of design criteria, evaluation is the assurance of continuous design improvement. 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 analysis to discover potential technical solutions, the determination of system requirements, the design and development of system components, the construction of a prototype, and/or engineering model, and the validation of system design through test and evaluation. The system (e.g., UAV) design process includes four major phases: (a) conceptual design; (b) preliminary design; (c) detail design; and (d) test and evaluation. The four phases of the integrated design of an UAV are summarized in Figure 1.7. Sections 1.10 through 1.13 present the details of these design phases.

In the conceptual design phase, the UAV will be designed in concept without precise calculations. In other words, almost all parameters are determined based on a decision-making process and a selection technique. On the other hand, the preliminary design phase tends to employ the outcomes of a calculation procedure. As the name implies, in the preliminary design phase, the parameters that are determined are not final and will be altered later. In addition, in this phase, parameters are essential and will directly influence the entire detail design phase. Therefore, the ultimate care must be taken to ensure the accuracy of the results of the preliminary design phase. In the detail design phase, the technical parameters of all components (e.g., wing, fuselage, tail, landing gear [LG], and engine) including geometry are calculated and finalized.

1.11 UAV Conceptual Design

Throughout the conceptual system design phase (commencing with the need analysis), one of the major objectives is to develop and define the specific design-to requirements for the system as an entry. The results from these activities are combined, integrated, and included in a system specification. This specification constitutes the top “technical-requirements” document that provides overall guidance for system design from the beginning. Conceptual design is the first and most important phase of the UAV system design and development process. It is an early and high-level life cycle activity with potential to establish, commit, and otherwise predetermine the function, form, cost, and development schedule of the desired UAV system. The identification of a problem and associated definition of need provides a valid and appropriate starting point for design at the conceptual level.

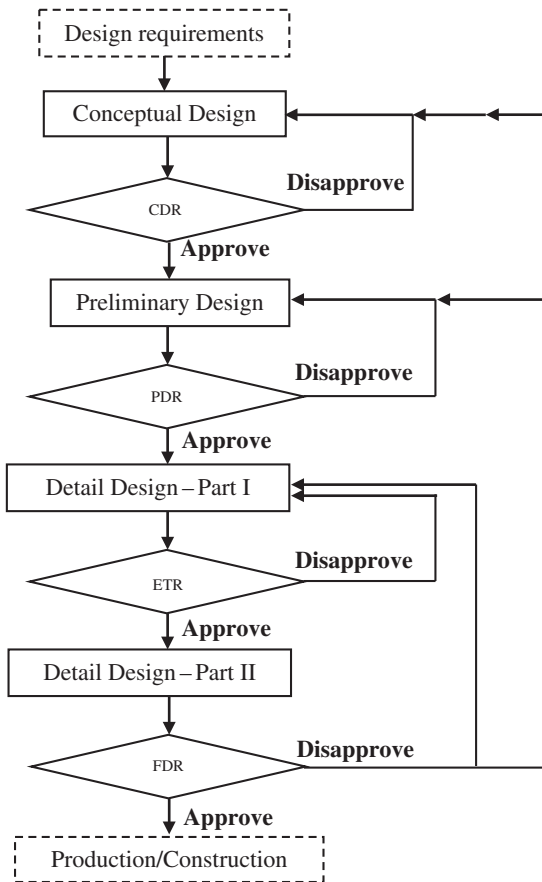


Figure 1.7 Design process and formal design reviews.

Selection of a path forward for the design and development of a preferred system configuration, which will ultimately be responsive to the identified customer requirement, is a major responsibility of conceptual design. Establishing this early foundation, as well as requiring the initial planning and evaluation of a spectrum of technologies, is a critical first step in the implementation of the systems engineering process. Systems engineering, from an organizational perspective, should take the lead in the definition of system requirements from the beginning and address them from a total integrated life-cycle perspective.

As the name implies, the UAV conceptual design phase is the UAV design at the concept level. At this stage, the general design requirements are entered in a process to generate a satisfactory configuration. The primary tool in this stage of design is the “*selection*.” Although there is a variety of evaluation and analysis, but there are not many calculations. The past design experience plays a crucial role in the success of this phase. Hence, the members of the conceptual design team must be the most experienced engineers of the corporation. Figure 1.8 illustrates the major activities which are practiced in the UAV conceptual design phase. The fundamental output of this phase is the configuration, with an approximate three-view of the UAV that represents the UAV configuration.

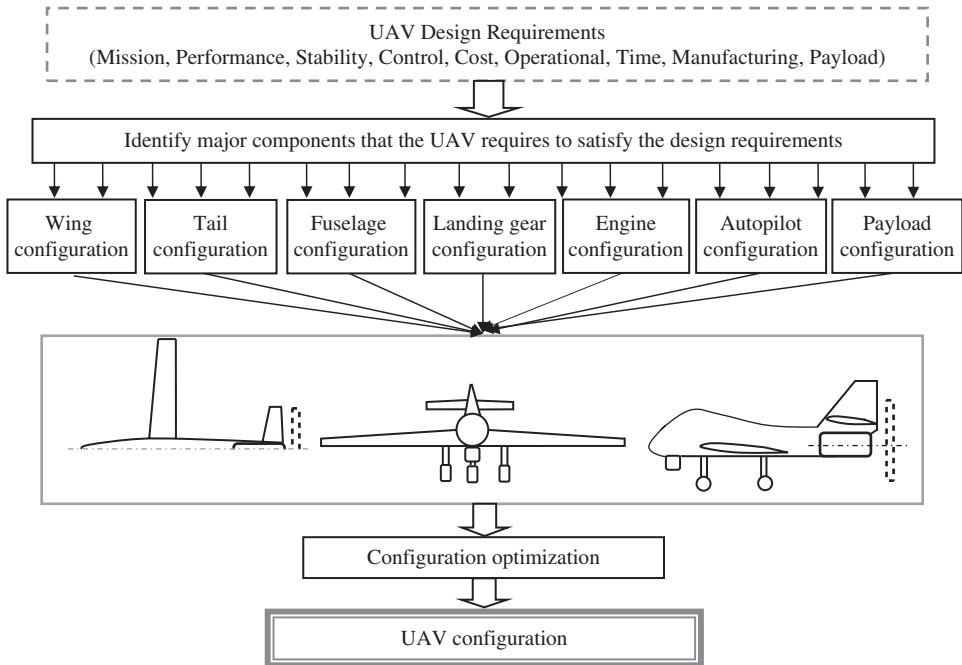


Figure 1.8 Unmanned Aerial Vehicle (UAV) conceptual design.

An UAV comprised of several major components. It mainly includes wing, horizontal tail, vertical tail, fuselage, propulsion system, landing gear, control surfaces, payloads, and autopilot. In order to make a decision about the configuration of each UAV component, the designer must be fully aware of the function of each component. Each UAV component has inter-relationships with other components and interferes with the functions of other components. The above six components are assumed to be the fundamental components of an air vehicle. However, there are other components in an UAV that are not assumed here as a major one. The roles of those components are described in the later sections whenever they are mentioned. Table 1.6 illustrates a summary of UAV major components and their functions. This table also shows the secondary roles and the major areas of influence of each UAV component. The table also specifies the design requirements that are affected by each component.

Table 1.7 illustrates a summary of configuration alternatives for UAV major components. In this table, various alternatives for wing, horizontal tail, vertical tail, fuselage, engine, landing gear, control surfaces, and automatic control system or autopilot are counted. An autopilot tends to function in three areas of guidance, navigation and control. More details are given in the detail design phase Section. For each component, the UAV designer must select one alternative which satisfies the design requirements at an optimal condition. The selection process is based on a trade-off analysis with comparing all pros and cons in conjunction with other components.

In order to facilitate the conceptual design process, Table 1.8 shows the relationship between UAV major components and the design requirements. The third column in this table clarifies the UAV component which affected most; or major design parameter

Table 1.6 Unmanned Aerial Vehicle (UAV) major components and their functions.

No	Component	Primary function	Major areas of influence
1	Fuselage	Payload accommodations	UAV performance, longitudinal stability, lateral stability, cost
2	Wing	Generation of lift	UAV performance, lateral stability
3	Horizontal tail	Longitudinal stability	Longitudinal trim and control
4	Vertical tail	Directional stability	Directional trim and control, stealth,
5	Engine	Generation of thrust	UAV performance, stealth, cost, control
6	Landing gear	Facilitate take-off and landing	UAV performance, stealth, cost
7	Control surfaces	Control	Maneuverability, cost
8	Autopilot	Control, guidance, and navigation	Maneuverability, stability, cost, flight safety
9	Ground station	Control and guide the UAV from the ground	Autonomy, flight safety
10	Launch and recovery	Launching and recovering the UAV	Propulsion, structure, launcher, recovery system

Table 1.7 Unmanned Aerial Vehicle (UAV) major components with design alternatives.

No	Component	Configuration alternatives
1	Fuselage	● Geometry: lofting, cross section ● Internal arrangement ● What to accommodate (e.g., payload, fuel, engine, and landing gear)?
2	Wing	● Type: Swept, tapered, dihedral ● Location: Low-wing, mid-wing, high wing, parasol ● High lift device: flap, slot, slat ● Attachment: cantilever, strut-braced
3	Horizontal tail	● Type: conventional, T-tail, H-tail, V-tail, inverted V ● Installation: fixed, moving, adjustable ● Location: aft tail, canard, three surfaces
4	Vertical tail	Single, twin VT, three VT, V-tail
5	Engine	● Type: turbofan, turbojet, turboprop, piston-prop, rocket ● Location: (e.g., under fuselage, under wing, beside fuselage) ● Number of engines
6	Landing gear	● Type: fixed, retractable, partially retractable ● Location: (e.g., nose, tail, multi)
7	Control surfaces	Separate vs. all moving tail, reversible vs. irreversible, conventional vs. non-conventional (e.g., elevon, ruddervator)
8	Autopilot	● UAV: Linear model, nonlinear model ● Controller: PID, gain scheduling, optimal, QFT, robust, adaptive, intelligent ● Guidance subsystem: Proportional Navigation Guidance, Line Of Sight, Command Guidance, three point, Lead, waypoint ● Navigation subsystem: Inertial navigation (Strap down, stable platform), GPS
9	Launch and Recovery	HTOL (Horizontal Take Off and Landing), ground launcher, net recovery, belly landing

Table 1.8 Relationship between Unmanned Aerial Vehicle (UAV) major components and design requirements.

No	Design requirements	UAV component that affected most, or major design parameter
1	Payload (weight) requirements	Maximum take-off weight (MTOW)
	Payload (volume) requirements	Fuselage
2	Performance Requirements (Range and Endurance)	MTOW
3	Performance requirements (maximum speed, Rate of climb, take-off run, stall speed, ceiling, and turn performance)	Engine; landing gear; and wing
4	Stability requirements	Horizontal tail and vertical tail
5	Controllability requirements	Control surfaces (elevator, aileron, rudder), Autopilot
6	Autonomy requirements	Center of gravity, Autopilot, ground station
7	Airworthiness requirements	Minimum requirements, Autopilot
8	Cost requirements	Materials; engine; weight, ...
9	Timing requirements	Configuration optimality
10	Trajectory requirements	Autopilot

by a design requirement. Every design requirement will normally affect more than one component, but we only consider the component that is influenced most. For example, the payload requirement, range and endurance will affect MTOW, engine selection, fuselage design, and flight cost. The influence of payload weight is different than payload volume. Thus, for optimization purpose, the designer must know exactly payload weight and its volume. On the other hand, if the payload can be divided into smaller pieces, the design constraints by the payload are easier to handle. Furthermore, the other performance parameters (e.g., maximum speed, stall speed, rate of climb, take-off run, ceiling) will affect, the wing area and engine power (or thrust).

In order to select the best UAV configuration, a trade-off analysis (Figure 1.9) must be established. Many different trade-offs are possible as the UAV design progresses. Decisions must be made regarding the evaluation and selection of appropriate components, subsystems, possible degree of automation, commercial off-the-shelf parts, various maintenance and support policies, and so on. Later in the design cycle, there may be alternative engineering materials, alternative manufacturing processes, alternative factory maintenance plans, alternative logistic support structures, and alternative methods of material phase-out, recycling, and/or disposal.

The UAV designer must first define the problem statement, identify the design criteria or measures against which the various alternative configurations will be evaluated, the evaluation process, acquire the necessary input data, evaluate each of the candidate under consideration, perform a sensitivity analysis to identify potential areas of risk, and finally recommend a preferred approach. Only the depth of the analysis and evaluation effort will vary, depending on the nature of the component.

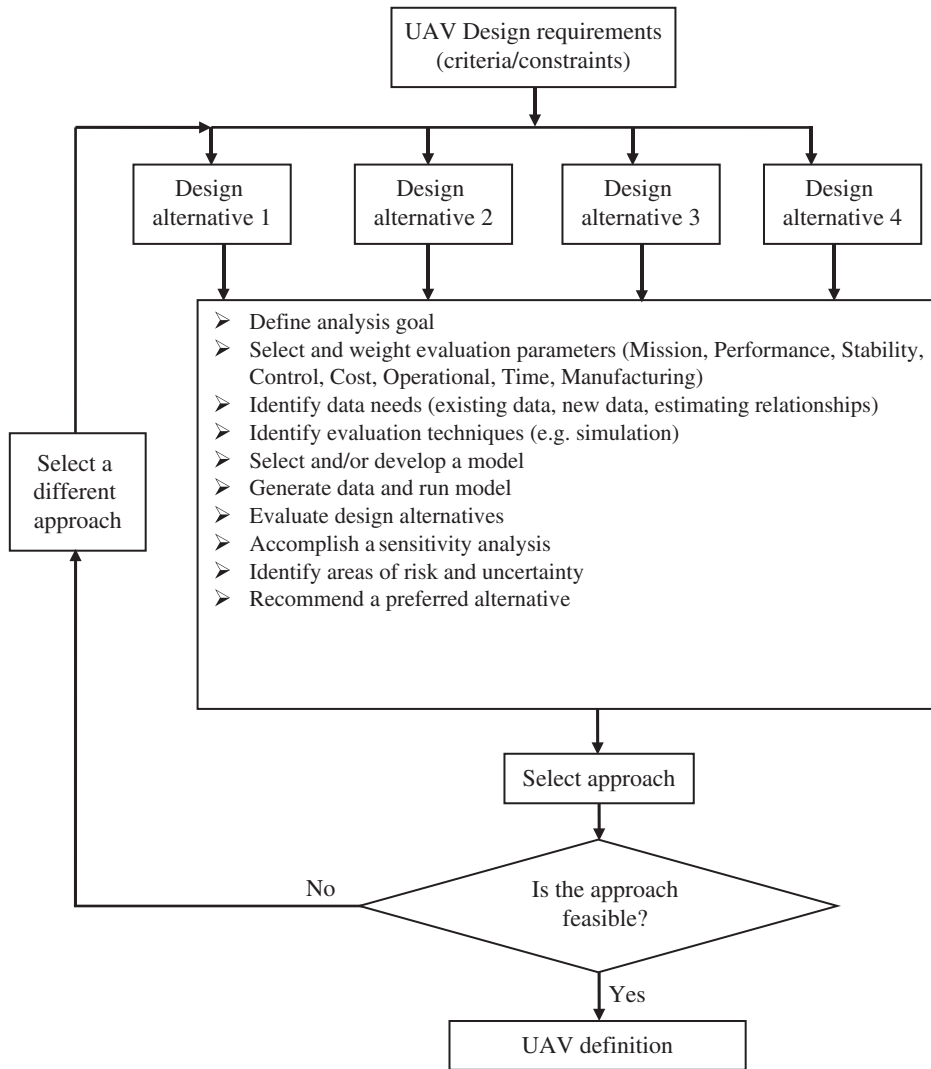


Figure 1.9 Trade-off analysis process.

Trade-off analysis involves synthesis which refers to the combining and structuring of components to create an UAV system configuration. Synthesis is design. Initially, synthesis is used in the development of preliminary concepts and to establish relationships among various components of the UAV. Later, when sufficient functional definition and decomposition have occurred, synthesis is used to further define the “*hows*” at a lower level. Synthesis involves the creation of a configuration that could be representative of the form that the UAV will ultimately take (although a final configuration should not be assumed at this early point in the design process).

One of the most effective techniques in trade-off studies is MDO. Researchers in academia, industry, and government continue to advance MDO and its application to practical problems of industry relevance. MDO is a field of engineering that uses

optimization methods to solve design problems incorporating a number of disciplines. MDO allows designers to incorporate all relevant disciplines simultaneously. The optimum solution of a simultaneous problem is superior to the design found by optimizing each discipline sequentially, since it can exploit the interactions between the disciplines. However, including all disciplines simultaneously significantly increases the complexity of the design problem.

Chapter 3 of Reference [8] presents various fixed-wing configuration options, and the technique to conceptually design the air vehicle. Section 2.10 of Chapter 2 of this present book provides the features of the most popular rotary-wing configuration (i.e., quadcopter).

1.12 UAV Preliminary Design

Four fundamental UAV parameters are determined during the preliminary design phase: (a) UAV MTOW (W_{TO}); (b) wing reference area (S); (c) engine thrust (T) or engine power (P); and (d) autopilot preliminary calculations. Hence, four primary UAV parameters of W_{TO} , S , T (or P), and several autopilot data are the output of the preliminary design phase. These four parameters will govern the UAV size, the manufacturing cost, and the complexity of calculation. If during the conceptual design phase, a jet engine is selected, the engine thrust is calculated during this phase. But, if during the conceptual design phase, a prop-driven engine is selected, the engine power is calculated during this phase. A few other non-important UAV parameters such as UAV zero-lift drag coefficient and UAV maximum lift coefficient are also estimated in this phase.

Figure 1.10 illustrates a summary of the preliminary design process. The preliminary design phase is performed in three steps: (a) estimate UAV MTOW; (b) determine wing area and engine thrust (or power) simultaneously; and (c) autopilot preliminary calculations.

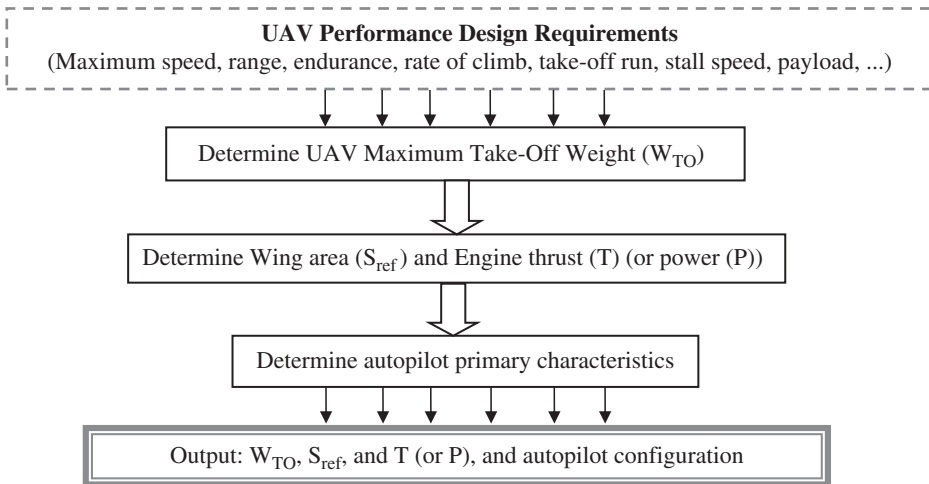


Figure 1.10 Preliminary design procedure.

In this design phase, two design techniques are employed. First a technique based on the statistics is used to determine UAV MTOW. The design requirements which are used in this technique are flight mission, payload weight, range, and endurance.

Second, another technique is employed based on the UAV performance requirements (such as stall speed, maximum speed, range, rate of climb, and take-off run) to determine the wing area and the engine thrust (or engine power). This technique is sometime referred to as the matching plot or matching chart, due to its graphical nature and initial sizing. The principles of the matching plot technique are originally introduced in a NASA technical report and they were later developed by Ref. [8]. The technique is further developed by the author in his new book on UAV design that is under publication.

In general, the first technique is not accurate (in fact, it is an estimation) and the approach may carry some inaccuracies, while the second technique is very accurate, and the results are reliable. Due to the length of the book, the details of these three techniques have not been discussed in detail here in this section. It is assumed that the reader is aware of these techniques which are practiced in many institutions.

1.13 UAV Detail Design

The design of the UAV subsystems and components plays a crucial role in the success of the flight operations. These subsystems turn an aerodynamically shaped structure into a living, breathing, unmanned flying machine. These subsystems include the: wing, tail, fuselage, flight control subsystem, power transmission subsystem, fuel subsystem, structures, propulsion, landing gear, and autopilot. In the early stages of a conceptual or a preliminary design phase, these subsystems must initially be defined, and their impact must be incorporated into the design layout, weight analysis, performance/stability calculations and cost benefits analysis. In this section, the detail design phase of an UAV is presented.

As the name implies, in the detail design phase, the details of parameters of all major components (Figure 1.8) of a UAV is determined. This phase is established based on the results of conceptual design phase and preliminary design phase. Recall that the UAV configuration has been determined in the conceptual design phase and wing area, engine thrust, and autopilot major features have been set in preliminary design phase. The parameters of wing, horizontal tail, vertical tail, fuselage, landing gear, engine, subsystems, and autopilot must be determined in this last design phase. To compare three design phases, the detail design phase contains a huge amount of calculations and a large mathematical operation compared with other two design phases. If the total length of an UAV design is considered to be one year, of that about 10 months is spent on the detail design phase.

This phase is an iterative operation in its nature. In general, there are four design feedbacks in the detail design phase. Figure 1.11 illustrates the relationships between detail design and design feedbacks. Four feedbacks in the detail design phase are: (a) performance evaluation; (b) stability analysis; (c) controllability analysis; and (d) flight simulation. The UAV performance evaluation includes the determination of UAV zero-lift drag coefficient. The stability analysis requires the component weight estimation plus the determination of UAV center of gravity (cg). In the controllability analysis operation, the control surfaces (e.g., elevator, aileron, and rudder) must be designed. When the autopilot is designed, the UAV flight needs to be simulated to assure the success of the flight.

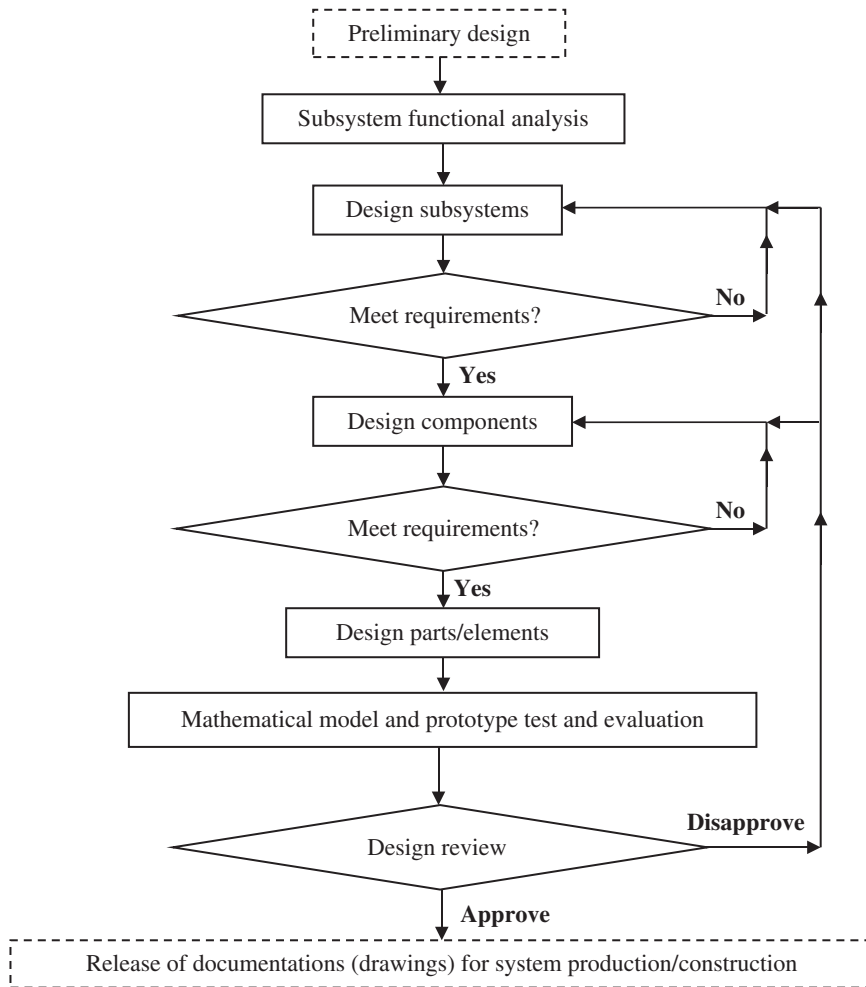


Figure 1.11 Detail design sequence.

As the name implies, each feedback is performed to compare the output with the input and correct the design to reach the design goal. If the performance requirements are not achieved, the design of several components, such as engine and wing, might be changed. If the stability requirements are not met, the design of several components, such as wing, horizontal tail, and vertical tail could be changed. If the controllability evaluation indicates that the UAV does not meet controllability requirements, control surfaces and even the engine must be redesigned. In the case where both stability requirements and controllability requirements were not met, then several components must be moved to change the cg location.

In some instances, this deficiency may lead to a major variation in the UAV configuration, which means the designer needs to return to the conceptual design phase and begin the correction from the beginning. The deviation of the UAV from trajectory during flight simulation necessitates a change in autopilot design.

1.14 Design Review, Evaluation, Feedback

In each major design phase (conceptual, preliminary, and detail), an evaluation should be conducted to review the design and to ensure that the design is acceptable at that point before proceeding with the next stage. There is a series of formal design reviews conducted at specific times in the overall system development process. An essential technical activity within the design process is that of evaluation. Evaluation must be inherent within the systems engineering process and must be invoked regularly as the system design activity progresses. When conducted with full recognition of design criteria, evaluation is the assurance of continuous design improvement. The evaluation process includes both the informal day-to-day project coordination and data review, and the formal design review.

The purpose of conducting any type of review is to assess if (and how well) the design configuration, as envisioned at the time, is in compliance with the initially specified quantitative and qualitative requirements. A design review provides a formalized check of the proposed system design with respect to specification requirements. In principle, the specific types, titles, and scheduling of these formal reviews vary from one design project to the next. The following main four formal design reviews are recommended for a design project:

- 1) Conceptual Design Review (CDR)
- 2) Preliminary Design Review (PDR)
- 3) Evaluation and Test Review (ETR)
- 4) Critical (Final) Design Review (FDR)

Figure 1.7 shows the position of each design review in the overall design process. Design reviews are usually scheduled before each major design phase. The CDR is usually scheduled toward the end of the conceptual design phase and prior to entering the preliminary design phase of the program. The purpose of CDR is to formally and logically cover the proposed design from the system standpoint. The PDR is usually scheduled toward the end of the preliminary design phase and prior to entering the detail design phase. The FDR is usually scheduled after the completion of the detail design phase and prior to entering the production phase.

The ETR is usually scheduled somewhere in the middle of the detail design phase and prior to the production phase. The ETR accomplishes two major tasks:

- 1) Finding and fixing any design problems and the subsystem/component level, and then
- 2) Verifying and documenting the system capabilities for government certification or customer acceptance.

The ETR can range from the test of a single new system for an existing system to the complete development and certification of a new system.

1.15 UAV Design Steps

In a UAV design process, some UAV parameters must be minimized (e.g., weight), while some other variables must be maximized within constraints (e.g., range, endurance, maximum speed, and ceiling), and some others must be evaluated to ensure that they

are acceptable. The optimization process must be accomplished through a systems engineering approach. In some cases, the design of the UAV may impose slight to considerable changes to the UAV mission during the conceptual design process. The strong relationship between the analysis and the influencing parameters allow definite, traceable relationships to be constructed. In the case of a UAV design, the major parameters are derived almost completely from operational and performance requirements.

The integration of system engineering principles with the analysis-driven UAV design process demonstrates that a higher level of integrated vehicle can be attained; identifying the requirements/functional/physical interfaces and the complimentary technical interactions which are promoted by this design process. The details of conceptual design phase, preliminary design phase, and detail design phase were introduced earlier.

The following is a suggestion for the UAS major design steps that summarizes the above-mentioned three design phases into steps:

- 1) Derive UAV design technical requirements, objectives and specifications from the customer order and problem statement.
- 2) Design program and management planning (e.g., Gantt chart and checklists).
- 3) Perform feasibility studies.
- 4) Perform risk analysis.
- 5) Functional analysis and allocation.
- 6) Design team allocation.
- 7) UAV Configuration design.
- 8) First estimation of UAV MTOW.
- 9) Estimation of UAV zero-lift drag coefficient (C_{D0}).
- 10) Calculation of wing reference area (S).
- 11) Calculation of engine thrust (T) or engine power (P).
- 12) Wing design.
- 13) Fuselage design.
- 14) Horizontal tail design.
- 15) Vertical tail design.
- 16) Landing gear design.
- 17) Propulsion system design.
- 18) Communication system design.
- 19) Payload selection/design.
- 20) First estimate of weight of UAV components.
- 21) Second estimate of UAV MTOW.
- 22) First calculation of UAV center of gravity limits.
- 23) Relocation of components to satisfy stability and controllability requirements.
- 24) Redesign of horizontal tail and vertical tail design.
- 25) Design of control surfaces.
- 26) Autopilot design.
- 27) Launch/recovery system design.
- 28) GCS design.
- 29) Calculation of UAV C_{D0} .
- 30) Re-selection of engine.
- 31) Calculation of interferences between UAV components (e.g., wing, fuselage, engine, and tails).

- 32) Incorporation of design changes.
- 33) First modifications of UAV components.
- 34) First calculation of UAV performance.
- 35) Second modification of UAV to satisfy performance requirements.
- 36) First stability and control analysis.
- 37) Third UAV modification to satisfy stability and control requirements.
- 38) Manufacturing of UAV model.
- 39) Wind tunnel test.
- 40) Fourth UAV modification to include aerodynamic considerations.
- 41) UAV structural design.
- 42) Design ground station.
- 43) Design launch and recovery system.
- 44) Calculation of weight of UAV components.
- 45) Second calculation of UAV center of gravity limits.
- 46) Fifth UAV modification to include weight and cg considerations.
- 47) Second performance, stability and control analysis and design review.
- 48) Sixth UAV modification.
- 49) UAV systems design (e.g., electric, mechanical, hydraulic, pressure, and power transmission).
- 50) Manufacturing of the UAV prototype.
- 51) Flight tests.
- 52) Seventh UAV modification to include flight test results.
- 53) Trade-off studies.
- 54) Optimization.
- 55) Certification, validation, or customer approval tests.
- 56) Eighth modification to satisfy certification requirements.

It is clear that some steps may be moved along with regard to the UAV mission, design team members, past design experiences, design facility, and manufacturing technologies. As it is observed, the design process is truly an iterative process and there are several modification steps to satisfy all design requirements.

Questions

- 1 What are the five expressions which are currently used for unmanned aircraft?
- 2 What are the primary design requirements for a UAV?
- 3 Describe features of a Tier II UAV in the Air Forces.
- 4 Describe the features of a micro UAV.
- 5 What is the main objective for the feasibility study?
- 6 What is the size range for mini UAVs?

- 7 What do MALE and HALE stand for?
- 8 What are the operating altitudes for HALE UAVs?
- 9 What is the endurance range for MALE UAVs?
- 10 What are the wingspan and MTOW of Global Hawk?
- 11 What are the cruise speed and endurance for Predator (RQ-1A)?
- 12 What was the major setback during Phase II flight testing of the Global Hawk on March 29, 1999? What was the reason behind that?
- 13 Describe the fundamentals of systems engineering approach in UAV design.
- 14 What are the main four formal design reviews?
- 15 What are the UAV main design groups based on components?
- 16 Describe the conceptual design phase.
- 17 Describe the main outputs of the preliminary design.
- 18 Describe the process of detail design.
- 19 Describe the trade-off analysis process.
- 20 From a systems engineering approach, what are the main design phases?
- 21 Describe Murphy's Law.
- 22 Briefly describe the features of Global Hawk.
- 23 Briefly describe the features of RQ-1A Predator.
- 24 Briefly describe the features of RQ-9 Predator B Reaper.
- 25 Briefly describe the features of RQ-5A Hunter.
- 26 Briefly describe the features of RQ-17 Shadow 200.
- 27 Briefly describe the features of RQ-170 Sentinel.
- 28 Briefly describe the features of RQ-2A Pioneer.
- 29 Briefly describe the features of X-45A UCAV.

- 30 What is the engine power of Predator A?
- 31 What is the wing area of Global Hawk?
- 32 What is the MTOW of Yamaha RMAX?
- 33 What is the maximum speed of ScanEagle?
- 34 What is the range of Reaper UAV?
- 35 What is the maximum speed of X-45A?
- 36 What is the endurance of RQ-5A Hunter?
- 37 What is the wingspan of X-45C UCAV?