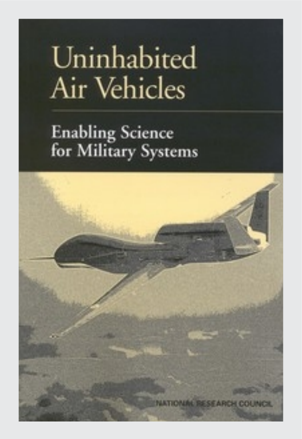

Uninhabited Air Vehicles: Enabling Science for Military Systems

DETAILS

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Uninhabited Air Vehicles

Enabling Science for Military Systems

Committee on Materials, Structures, and Aeronautics for
Advanced Uninhabited Air Vehicles

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Aeronautics and Space Engineering Board
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Preface

The development of effective and affordable uninhabited air vehicles (UAVs) has become a priority for the U.S. Air Force because UAVs have the potential to perform autonomously under conditions that are not conducive to inhabited aircraft. UAVs will either save human operators from long or monotonous tasks or, more importantly, will preclude risking human pilots in dangerous situations. To be accepted by the military services, UAVs must provide these advantages at significantly lower life-cycle costs than current costs.

The development of optimal UAVs is a complex systems engineering problem. Complicated trade-offs must be made among performance, survivability, autonomy, range, payload, and, perhaps most important, cost. The fundamental driving force behind the development of military UAVs is to reduce substantially the cost of weapon system acquisition and sustainment.

The objectives of this joint study of the National Research Council National Materials Advisory Board and the Aeronautics and Space Engineering Board were (1) to identify needs and opportunities for technology development that have the potential to meet the Air Force's performance and reliability requirements and reduce costs for "generation-after-next" UAVs and (2) to recommend areas of fundamental research in materials, structures, and aeronautical technologies. The committee focused on technological innovations likely to be ready for development and scale-up in the post-2010 time frame (i.e., ready for use in 2020–2025). The intent is to "leapfrog" current technology development.

To complete its task, the committee reviewed proposed missions and design concepts for advanced UAVs that are anticipated to be operating in the long term and then reviewed key requirements for vehicle structures, flight control systems, propulsion systems, and power systems, based on a range of potential mission scenarios. Finally, the committee identified the underlying technological advancements required to meet the performance targets. This report recommends fundamental and applied research for developing a tool box of UAV-unique or UAV-critical technologies that could provide the required performance and reliability while reducing costs.

Comments and suggestions can be sent via electronic mail to nmab@nas.edu or by fax to NMAB at (202) 334-3718.

Gordon Smith, chair
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This report has been reviewed (in draft form) by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Robert Crowe, Virginia Polytechnic and State University; James B. Day, Belcan Engineering Group; Earl Dowell, Duke University; Michael Francis, Aurora Flight Systems; George J. Gleghorn, TRW Space and Technology Corporation (retired); James Mattice, Universal

Technology Corporation; and Leland Nicolai, Lockheed Martin Skunk Works. While the individuals listed above have provided constructive comments and suggestions, it must be emphasized that responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Finally, the committee gratefully acknowledges the support of the staff of the National Research Council: Thomas Munns, study director, Teri Thorowgood, research associate, Arul Mozhi, senior program officer, and Jan Prisco, administrative assistant, National Materials Advisory Board; Alan Angleman, senior staff officer, Aeronautics and Space Engineering Board; and Carol R. Arenberg, editor, Commission on Engineering and Technical Systems.

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Executive Summary

U.S. Air Force (USAF) planners have envisioned that uninhabited air vehicles (UAVs), working in concert with inhabited vehicles, will become an integral part of the future force structure. Current plans are based on the premise that UAVs have the potential to augment, or even replace, inhabited aircraft in a variety of missions. However, UAV technologies must be better understood before they will be accepted as an alternative to inhabited aircraft on the battlefield. The U.S. Air Force Office of Scientific Research (AFOSR) requested that the National Research Council, through the National Materials Advisory Board and the Aeronautics and Space Engineering Board, identify long-term research opportunities for supporting the development of technologies for UAVs. The objectives of the study were to identify technological developments that would improve the performance and reliability of "generation-after-next" UAVs at lower cost and to recommend areas of fundamental research in materials, structures, and aeronautical technologies. The study focused on innovations in technology that would "leapfrog" current technology development and would be ready for scaling-up in the post-2010 time frame (i.e., ready for use on aircraft by 2025).

To date, UAVs have been considered advanced-concept technology demonstrations, with an emphasis on mission payloads. Therefore, the design of the systems has been outside of the U.S. Department of Defense's procurement process for weapon systems, which has enabled developers to aggressively use available advanced technologies. Although this approach has been effective for meeting near-term goals, it will provide only limited opportunities for fundamental technology development because it favors the adaptation of available technologies.

The committee recommends that the USAF establish a research and development program to develop technologies that will advance the use of UAVs either by enabling unique missions or by providing significant cost savings. The following steps are recommended for establishing a research program for UAV technologies:

- the establishment of requirements for a range of missions and system attributes, with a focus on key air vehicle concepts
- the identification of technologies that could meet requirements
- the development of technology forecasts and trends for relevant technology areas
- the initiation of research that could provide the necessary technologies

Both fundamental research and technology development will be required to improve available technologies and develop military UAVs with significantly lower system development costs.

Because of the wide variety of possible configurations and missions, the committee used "notional vehicle types" to identify technical areas of need. Three notional vehicle types were identified as indicative of the range of technologies that would improve the USAF's capability of designing, producing, and fielding generation-after-next UAVs. The notional vehicle types represent classes of vehicles, not conceptual aircraft designs suited to any particular mission. The three vehicle types were:

- high-altitude, long-endurance (HALE) vehicles, to provide a focus on long-term technical advances for reconnaissance and surveillance aircraft
- high-speed, maneuverable (HSM) vehicles, to emphasize the potential for a highly survivable, second-generation combat UAV
- very low-cost vehicles, to highlight performance-cost trade-offs

Based on analyses of the notional vehicle types, the committee identified technical needs and opportunities in research and development for major UAV subsystem technologies. The committee considered the following five technology areas: aerodynamics (and vehicle configuration); airframes (especially materials and structures); propulsion systems; power and related technologies; and controls.

VEHICLE DESIGN ISSUES

Two issues related to system design—(1) human-machine science and (2) manufacturing and design processes—will strongly influence the design of future UAVs. Both issues should be considered in the selection and prioritization of research opportunities. *Human-machine science* includes (1) integration of human-machine systems (e.g., allocation of functions and tasks and the determination of the effects of automation on situational awareness), (2) human performance (e.g., human decision-making processes and methods for defining and applying human performance measures in system design), and (3) information technologies (e.g., effects of human factors on requirements for information content and display). *Manufacturing and design processes* include (1) designing for low-cost fabrication (e.g., reducing vehicle size and modular design and construction) and (2) low-cost product realization (e.g., new approaches to product design, low-cost manufacturing processes, and consideration of cost as an independent variable).

GENERAL RESEARCH OPPORTUNITIES

The committee identified opportunities for research on crosscutting vehicle subsystem technologies that could benefit all types of UAVs. The committee recommends that the USAF long-term research program focus on four areas: (1) computational modeling and simulation; (2) propulsion technologies for small engines; (3) integrated sensing, actuation, and control devices; and (4) controls and mission management technology.

Computational Modeling and Simulation

The low cost and short design cycles that will be necessary for UAVs will require changes in design practice, especially an increased reliance on computational modeling, simulation, verification, testing, and training. The committee recommends that the following research opportunities in this area be pursued:

- development, validation, and application of computational tools for major subsystem design, including unsteady, nonlinear, three-dimensional aerodynamics models; structural analysis and aeroelasticity models; aerodynamic modeling concepts for designing vehicle control systems; propulsion system models; and simulation models for assessing control laws
- validation of manufacturing process models for UAV components
- clarification of the role of uncertainty in computational analysis
- integration of models and simulations to provide a “virtual mockup” for testing and evaluation of the total system

Propulsion Technologies for Small Engines

In the past, development costs have been a major factor in the development of UAV propulsion technologies. To meet program budget constraints, the practice has been to adapt existing devices, usually at the expense of both performance and reliability. To address this concern, the committee recommends that research be focused on technologies that could enable the development of small, low-cost turbine engines. The following topics should be considered:

- low-cost, high-temperature materials and coatings
- cooling schemes to reduce the need for costly air-cooled parts
- technology and approaches to reduce leakage through clearances between stationary and rotating parts
- bearing and lubrication systems that would be more reliable after long-term storage
- small, low-cost accessories (e.g., fuel pumps, engine controls, and electrical generators)

Integrated Sensing, Actuation, and Control Devices

Minimizing the weight and volume of sensors, actuators, and other subsystems will be critical for UAVs, which will have stringent size and payload limitations. Emerging microelectromechanical system (MEMS) technology can provide transducers as small as tens of microns. Potential MEMS-based sensors include inertial sensors, aerodynamic sensors, structural sensors, and surveillance sensors. Innovative uses for MEMS-based transducers include: structures that respond to load variations, controls of aerodynamic flow, and improvements in situational awareness (e.g., collision avoidance and detection of biological and chemical agents).

Controls and Mission-Management Technology

The optimal utility and effectiveness of UAVs will require exploiting the capabilities, and recognizing the limitations, of controls and mission-management technologies. The committee envisions that UAVs will operate in integrated scenarios with the following features: several vehicles with specified missions; communication links among vehicles and between vehicles and remote human-operated control sites; and the capability to use sensors and information-processing systems located on the vehicle, on other vehicles, and at ground sites. Important areas for research in controls for UAVs include: rapid (automated) design and implementation of high-performance control laws, robust vehicle management functions (e.g., to carry out mission sequence), and mission-management technologies, including real-time path planning and control of dynamic networks.

RESEARCH OPPORTUNITIES FOR SPECIFIC VEHICLE TYPES

In addition to the general research just described, the committee identified research opportunities that would support the development of each notional vehicle type. As the long-range plans and priorities for UAVs emerge, the USAF should include the applicable opportunities in its long-range research program.

Key subsystem technologies that will enable the development of HALE UAVs are listed below:

- vortex drag reduction (e.g., lifting systems and tip turbines)
- laminar-to-turbulent transition for low Reynolds numbers
- aeroelastic controls
- high-compression operation of gas turbines or piston engines
- alternative propulsion systems (e.g., fuel cells, solar cells, and energy storage systems)
- materials and designs for aeroelastic tailoring
- low-rate manufacturing technologies for ultra-lightweight airframe structures

The following key subsystem technologies will enable the development of HSM UAVs:

- nonlinear, unsteady aerodynamics
- simulation of flow fields for complex configurations
- modeling tools for propulsion-airframe integration
- stiff, lightweight structures for highly-loaded propulsion systems
- fluid seals
- high-load, long-life bearings
- probabilistic structural design methods for a high-speed, high-*g* environment
- automated manufacturing processes for high-performance structural materials
- high-temperature composite materials[1]

Finally, the following key subsystem technologies will enable the development of very low-cost UAVs:

- very low Reynolds number aerodynamics
- bearings for long-term storage
- low-cost accessories for propulsion systems (e.g., fuel pumps, engine controls, and electrical generators)
- structural design criteria for expendable, low-use systems
- expanded suite of structural materials (including low-cost, commodity-grade materials)
- modular designs for low-cost manufacture

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[1] Some important research and development programs in composite materials and structures, such as the National Aeronautics and Space Administration's High Speed Research Program, have recently been discontinued.

Part I

Integrated Air Vehicles

1

Introduction

Uninhabited air vehicles (UAVs) are vehicles "specifically designed to operate without an onboard operator or aircraft intended to be manned that have been converted to unmanned operation" (USAFSAB, 1996). UAVs range in size from a few inches to hundreds of feet, can be fixed or rotary wing aircraft, can be remotely piloted or autonomous, and can be jet or piston powered. Despite technological shortcomings that have slowed their rate of acceptance (e.g., inability to provide adequate control "feel" for remote pilots; inability to meet both cost and performance targets), the momentum is increasing to consider using UAVs in a wide range of applications including the following:

- weather and atmospheric research (Niewoehner, 1998)
- reconnaissance and surveillance (Francis, 1998)
- conventional combat roles (SAB, 1996)
- innovative roles that were not previously possible (e.g., "dull, dirty, and dangerous" missions, such as operations in chemical and biological weapons environments [Air University, 1996; SAB, 1996] and operations that require micro air vehicles [McMichael, 1998])

The U.S. Air Force (USAF) has included UAVs in its long-term plans for difficult or risky military missions. In a report by the USAF Scientific Advisory Board (USAFSAB), *New World Vistas: Air and Space Power for the Twenty-First Century* (USAFSAB, 1995), it was suggested that UAVs, working in concert with inhabited vehicles, could become an integral part of the force structure. The report recommended that the USAF support technology development for cost-effective UAVs that can perform a wide range of combat tasks. In 1996, the

USAFSAB conducted a study to assess technology development for changing UAVs from their current reconnaissance role to much broader combat and noncombat roles (USAFSAB, 1996). The SAB recommended that the USAF (1) exploit the capabilities of reconnaissance UAVs (Predator, Darkstar, and Global Hawk) in the near term, (2) consider the suppression of enemy air defenses (SEAD) mission as a near-term combat objective, and (3) develop advanced penetrating uninhabited combat air vehicles (UCAVs) for midterm and long-term use. The SAB reports focused on technological and operational issues related to UAVs, the communications and combat systems in which they would operate, and the context in which they would be used. This report focuses on just one aspect of UAV systems, air vehicle technologies.

Air Force operation scenarios envision multiple vehicle types and multiple vehicles of the same type acting in "coordinated clusters" (USAFSAB, 1996). This approach would provide broader capabilities than UAVs operating independently as reconnaissance, survelliance, countermeasures, or attack vehicles. UAVs operating in coordinated clusters would also have the potential to cover a larger area in a complicated battle zone and would protect valuable assets (e.g., high-performance sensors).

RECONNAISSANCE PROGRAMS

The U.S. Department of Defense (DOD) has been developing UAVs with a wide range of characteristics to meet a variety of mission requirements. UAV programs that have been undertaken by the U.S. military and intelligence communities are summarized in Table 1-1. Of the recent programs, Pioneer has been deployed, Hunter was cancelled after initial production, Predator is in low-rate initial production, Darkstar was terminated prior to initial production, and Global Hawk and Outrider are still being developed (CBO, 1998). Historically, UAVs have been considered advanced-concept technology demonstrations, which are intended to be low-cost, low-risk technology demonstrations.

Pioneer

Pioneer (Figure 1-1) was developed by Pioneer UAV, Inc., to provide targeting support for Navy ships (Pioneer UAV, Inc., 1997). Since Pioneer was first deployed in 1986, it has been used for reconnaissance, surveillance, target acquisition, battle-damage assessment, and battle management. Pioneer is 14 feet long and is driven by a pusher-propeller powered by a 26 hp, two-stroke, twin-cylinder, rear-mounted engine. Pioneer is equipped with electro-optical and infrared video sensors. It can carry a 75-pound payload, has a maximum altitude of 15,000 feet, a range of 185 kilometers, and an endurance of five hours at that radius. Although Pioneer is expected to be retired from service in 2003, sustainment programs are being contemplated to extend the life of Pioneer to 2005–2008.

TABLE 1-1 Major UAV Programs

Program	Period	Description	Status
Lightning Bug	1964–1979	Reconnaissance drone first used by the Air Force during the Vietnam War	Retired
Aquila	1979–1987	Tactical UAV for Army commanders	Canceled
Amber	1984–1990	Classified endurance UAV	Canceled
Pioneer	1986–present	UAV originally acquired to assess battle damage by naval gunfire	Deployed
Medium Range	1987–1993	Tactical UAV for the Air Force and Navy	Canceled
Hunter	1988–1996	Joint tactical UAV	Canceled after low-rate initial production
Gnat-750	1988–present	Long-endurance UAV developed with CIA funding; exported commercially	Used for training and intelligence missions
Darkstar	1994–1999	Stealthy endurance UAV for high-threat environments	Canceled
Predator	1994–present	Long-endurance UAV for theater commanders; based on the Gnat-750	In low-rate initial production
Global Hawk	1994–present	High-altitude, long-endurance (HALE) UAV	In development
Outrider	1996–present	Joint tactical UAV	In development

Source: CBO, 1998.

Hunter

Hunter (Figure 1-2) was developed by Israeli Aircraft Industries to perform short-range surveillance for ground forces. Hunter is equipped with electro-optical and infrared video sensors. It was designed to carry a 200-pound payload and has a maximum altitude of 15,000 feet, a range of 267 kilometers, and endurance of 11 hours at that radius. Hunter was cancelled after low-rate initial production of seven systems, with eight aircraft each. The aircraft are currently being used by the U.S. Army and U.S. Navy for training and mission development.

Predator

Predator (Figure 1-3) is a derivative of the Central Intelligence Agency’s Gnat-750. Also known as Tier II, Predator is a medium-range, medium-altitude vehicle capable of all-weather reconnaissance, surveillance, targeting, and battle-damage assessment. Manufactured by General Atomics, Predator carries a payload of 450 pounds, has a maximum altitude of 25,000 feet, a range of 926 kilometers, and endurance at that radius of more than 20 hours. Unlike Pioneer or

FIGURE 1-1 Pioneer UAV taking off from the deck of the *USS Iowa*. Source: Pioneer UAV, Inc.

Hunter, Predator's satellite communication system enables it to operate beyond line-of-sight from the control station. Predator has been successfully demonstrated in reconnaissance missions during peacekeeping operations in Bosnia. The Air Force plans to purchase 12 systems with four vehicles each.

Global Hawk

Global Hawk (Figure 1-4) is a developmental high-altitude, long-endurance (HALE) reconnaissance vehicle designed to complement the Darkstar UAV. Also known as Tier II$^+$, Global Hawk has been designed as a "highly capable, moderately survivable" system capable of reconnaissance, surveillance, and providing targeting information. The prime contractor of Global Hawk is Teledyne Ryan. Global Hawk will carry a 2,000-pound payload, have a maximum altitude of 65,000 feet, a range of 5,556 kilometers, and endurance at that radius of 22 hours.

FIGURE 1-2 Hunter reconnaissance and surveillance UAV. Source: Director, Operational Test and Evaluation, U.S. Department of Defense.

FIGURE 1-3 Predator airborne surveillance, reconnaissance, and target acquisition vehicle. Source: Air Combat Command, U.S. Air Force.

FIGURE 1-4 Global Hawk during sixth test flight. Source: Ryan Aeronautical Center.

FIGURE 1-5 Darkstar high-altitude, long-endurance UAV. Source: Lockheed Martin Aeronautics Company.

Darkstar

Like Global Hawk, Darkstar (Figure 1-5) was a developmental HALE reconnaissance vehicle. Also known as Tier III^{-}, Darkstar was intended to be the “moderately capable, highly survivable” complement to Global Hawk. It was designed to be stealthy, so that it could penetrate air defenses to perform reconnaissance, surveillance, and targeting missions. The prime contractors were Lockheed Martin and Boeing. Darkstar was designed to carry a 1,000-pound payload, have a maximum altitude of 45,000 feet, a range of 926 kilometers, and endurance at that radius of eight hours. Together, Global Hawk and Darkstar were intended to fulfill the near-term and midterm needs of the Defense Airborne Reconnaissance Office. In late January 1999, the DOD terminated the Darkstar program.

Outrider

Outrider (Figure 1-6) is a tactical UAV developed for the Army, Navy, and Marine Corps for reconnaissance and surveillance missions for brigade and task force commanders. The prime contractor is Alliant Systems. Outrider, a small aircraft with a wingspan of only 13 feet, was designed to carry a 65-pound

FIGURE 1-6 Outrider tactical UAV. Source: Aliant Techsystems, Inc.

payload, have a maximum altitude of 15,000 feet, a range of 200 kilometers, and an endurance of three to four hours at that radius.

COMBAT PROGRAM

The Defense Advanced Research Projects Agency (DARPA) and the USAF are collaborating on a program to develop a UCAV. The purpose of this program is to demonstrate the technical feasibility of a UCAV that can effectively and affordably perform lethal missions, including SEAD and strike missions, as an integral part of a mixed inhabited/uninhabited force structure (Birckelbaw and Leahy, 1998). As operational concepts and vehicle technologies mature and

UCAV affordability goals are achieved, UCAVs will be able to perform a broader range of combat missions.

The vision for the UCAV is of an affordable system that increases mission options and tactical deterrence, requires minimal maintenance, can be stored for extended periods of time, and, with its dynamic mission control, can engage multiple targets in a single mission with minimal human supervision (DARPA, 1998). UCAVs will perform combat missions that do not currently exist; high-risk missions that do not warrant the risk to human life; or current missions that UCAVs can perform more cost effectively than current platforms.

The affordability of UCAVs will be a result of reduced acquisition costs (e.g., air vehicle unit cost that will be about one-half the cost of a Joint Strike Fighter) and operation and support costs (50 percent to 80 percent lower than the costs of current tactical aircraft). Operation and support costs will be reduced through the introduction of condition-based maintenance, simplified onboard systems, and the ability to keep vehicles in flight-ready storage.

STUDY SCOPE AND OBJECTIVES

The recommendations of foregoing studies and the results of design and demonstration programs all indicate that UAVs have the potential to augment, and even replace, inhabited aircraft in a variety of missions. However, UAV technologies must be better understood before they will be accepted as an alternative to inhabited aircraft on the battlefield.

To augment these studies, the Aerospace and Materials Sciences Directorate of the USAF Office of Scientific Research (AFOSR) requested that the National Research Council, through the National Materials Advisory Board and the Aeronautics and Space Engineering Board, identify long-term research opportunities in materials, structures, and aeronautical technologies to support the USAF's plans to develop UAV systems. The objectives of the study were: (1) to identify technology developments that would improve the performance and reliability of low-cost, "generation-after-next" UAVs, and (2) to recommend areas of fundamental research in materials, structures, and aeronautical technologies.

Specific committee tasks included the following:

- Review proposed missions and design concepts for advanced large UAVs that are anticipated to be operating in the long term.
- Review key requirements for vehicle structures, flight control systems, propulsion, and power, based on a range of potential mission scenarios. For at least one mission scenario, identify the underlying technology advancements needed to achieve performance targets. Consider approaches that could lead to less costly air vehicles.
- Identify critical technologies and suggest research opportunities that could provide required performance and reliability at lower cost. Research

> opportunities should address the following vehicle subsystems: air vehicle structures, including structural concepts, structural materials, structural integrity, and health monitoring; air vehicle propulsion systems, including materials and structures, engine control, and fluid mechanics; onboard power systems, including power generation and power management; and vehicle control concepts, including control laws that relate to automatic landing and extremely high-*g* maneuvers, vehicle aerodynamics, and man-machine interfaces.

The design and manufacture of the UAV is just one critical factor in the development of an integrated battlefield. Although topics such as total battlefield management, command and control, and communications are compelling engineering problems—critical for the introduction of UAVs to the battle space of the future—they are not the subject of this report. Instead, the study focuses on innovations in vehicle technologies that would leapfrog current technology development and would be ready for development and scaling-up in the post-2010 time frame (i.e., ready for use by 2025).

The committee limited the scope of the study to make the best use of available time and resources and to focus on USAF needs. The committee focused primarily on combat and reconnaissance missions, especially the integrated air vehicle and key vehicle subsystems: air vehicle structures, air vehicle propulsion, onboard power, and vehicle control. Cost, reliability, and manufacturability were considered in all deliberations.

Only fixed-wing aircraft were considered. Although rotorcraft and "flapping-wing" aircraft could be used by other services, they are not emphasized in the long-term plans (DSRC, 1997; Williamson, 1998). The committee also focused on reusable aircraft with advanced communications and control capabilities that could be operated with some degree of autonomy, de-emphasizing drones, cruise missiles, and remotely piloted aircraft. Finally, the committee focused on aircraft platform and subsystem technologies. Therefore, some important aspects of UAV operation are not addressed in depth in this report. For example, previous reports have recognized that the effective deployment of UAVs will require that individual UAVs operate as part of communications network (i.e., as one of a "family of systems") and suggested that near-term and midterm research focus on communications and controls technology, human factors, and human-machine interfaces (DSRC, 1997; SAB, 1996). As a result of these studies, substantial research has already been initiated in these areas.

STUDY APPROACH

The committee considered five areas in the analysis of air vehicle technologies: aerodynamics (and vehicle configuration), airframe (with a focus on materials and structures), propulsion systems; power and related technologies, and controls. Because of the wide variety of possible configurations and missions for UAVs, the committee decided to use notional UAV classifications based on general attributes to identify technical needs for the broad range of potential applications. The committee identified three notional vehicle types indicative of the range of technologies that would support general advances in the USAF's capability of designing, producing, and fielding generation-after-next UAVs. The notional vehicle types were:

- high-speed, maneuverable (HSM) vehicles
- HALE vehicles
- very low-cost vehicles

Chapter 2 describes the technology needs of the integrated vehicle for each notional UAV classification based on a "systems engineering" approach to air vehicle development. Chapters 3 through 7 identify critical technologies and long-term research opportunities for each major UAV platform subsystem. Chapter 8 summarizes these research opportunities.

2

The Uninhabited Air Vehicle as a System

To identify key technologies for future UAVs, the air vehicle system design should be considered as a whole. Although UAVs in operational environments will be part of a larger family of systems that could include multiple UAV types, manned combat and surveillance aircraft, communications satellites, and remote command and control centers, the focus of this chapter is on the UAV as a system capable of working within the future environment. Up to now, UAVs have generally been developed as advanced concepts technical demonstrators (ACTDs), with an emphasis on mission payloads. This practice has placed the design of UAVs beyond the DOD procurement process for weapon systems and enabled developers to apply available advanced technologies aggressively (CBO, 1998). The ACTD approach to technology development includes the following steps:

- creating a point design for a system that satisfies mission requirements
- defining the differences between currently available technology and the point design
- establishing a development program to address the differences

This approach has been effective in the near term but has provided only limited opportunities for fundamental technology development and has favored adaptations of available technologies. In effect, the short design-cycle times and limited budgets for fundamental research and technology development has inhibited the development of technologies optimized for UAVs.

Recommendation. The U.S. Air Force should establish a research and development program to develop fundamental technologies that will advance the use of

UAVs by enabling them to carry out unique missions or by providing significant cost savings.

The committtee's recommended approach is shown schematically in Figure 2-1. First, requirements for a range of missions and system attributes should be established with a focus on key air-vehicle concepts. Next, technologies that can address the requirements should be identified and technology forecasts and trends for applicable technology areas developed. Finally, the research on the required technologies should be initiated. Fundamental research and technology development will be required to make advanced technologies generally available so that military UAVs can be developed with significantly lower system development costs. The goal should be to develop enabling technologies for a range of UAVs.

This approach has two principal advantages. First, the development of advanced technology is separated from the development of the UAV system so that basic research and technology development can be undertaken in a more realistic time frame. Second, the recommended approach allows revolutionary advances to be pursued for implementation in future systems. The balance of this report demonstrates the value of the recommended approach for developing technological needs and suggested research and technology development for a range of UAV systems.

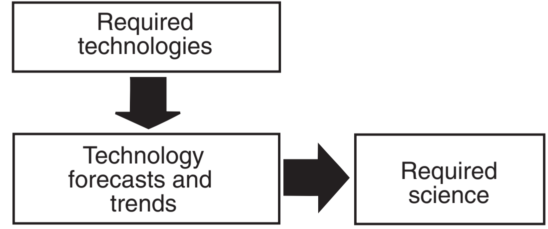

FIGURE 2-1 Recommended approach to technology prioritization. Source: Adapted from Lang, 1998.

DESIGN DRIVERS

The committee identified several general characteristics or trends that would drive all aspects of the UAV system design. Most of these characteristics have to do with the competing motivations for developing UAVs for defense applications—unique mission capabilities and significantly reduced life-cycle costs (including acquisition, operation, and sustainment costs). In general, the development of UAVs is being driven by a combination of "mission pull" (e.g., risk avoidance and cost avoidance), which requires that systems be developed for certain missions, and "technology push," which is fueled by advances in particular technologies (e.g., microelectromechanical systems [MEMS], electronics, and composites). The committee feels that the following considerations will drive the development of future UAVs:

- UAVs will be smaller, easier to maintain, and have lower peacetime operational costs than inhabited military aircraft.
- To maintain low peacetime operational costs (e.g., maintenance and field support costs), UAVs may be stored for long periods of time, with little use except during combat.
- Continued development of small precision weapons, higher levels of automatic control, and improved human-machine interactions will enable UAVs to carry out limited combat missions that are not yet envisioned.
- With the continued development of software, miniaturized electronics (including information systems), specialized actuators and sensors, and innovative component design and manufacturing processes, UAVs could be produced at significantly lower cost than similar inhabited systems.
- The continued development of human-machine interfaces, software, computer hardware, and miniature components will have a substantial effect on next-generation UAVs.
- The feasibility of advanced UAVs and combat UAVs will require a highly capable and secure communications network.

MISSIONS

A wide range of potential missions—from surveillance through combat strikes—were described in the USAF SAB report (SAB, 1996). The objective of the SAB's analysis was to identify technological needs in terms of threat environment, altitude, range, level of autonomy, and maneuverability. Twenty-two missions were identified to support five fundamental USAF capabilities: deterrence (conventional and nuclear), power projection, global mobility, situational awareness, and information domination. The missions and the time frames for operational demonstrations are shown in Figure 2-2. Of these missions, the SAB selected nine that would address USAF needs and requirements; would be operationally useful for joint military forces; would be technically feasible in a defined time

Air Force Capabilities	*Near Term (1995 – 2005)*	*Mid Term (2005 –2015)*	*Long Term (2015 –2025)*
Sustain nuclear and conventional deterrence		Strategic Attack	
		Space control	
Project long-range, sustainable, lethal combat power	FIXED TARGET ATTACK		
	Base defense		
	SEAD		
	THEATER/CRUISE MISSLE DEFENSE		
	MOVING TARGET ATTACK		
		Special operations	
		Area denial	
		Decontamination and defoliant dispensing	
		AIR-TO-AIR COMBAT	
			Counter weapons of mass destruction
			Combat search and rescue
			During the initiation of nuclear warfare and afterwards per Single Integrated Operational Plan
Support rapid global mobility		Tanker	
			Cargo transport
Provide global situational awareness	Intelligence, surveillance, and reconnaissance		
		Humanitarian assistance	
Dominate the information spectrum	Unmanned communications network		
	JAMMING		
		Information warfare	
		GPS augmentor	
Assumptions	• Complement to manned vehicles • Current tier platforms, mission systems, and weapons • Use of unmanned tactical aircraft	• New UAV platforms • New mission systems and weapons • New UAV command and control systems	• Autonomous or complementary • Robust command, control, and communications • Out-of-box platforms, mission systems, and weapons

FIGURE 2-2 Missions and time frames for operational demonstration recommended by the USAFSAB. Source: USAFSAB, 1996.

frame; and would be representative of the design, development, and enabling technologies for all 22 missions. The nine missions selected are listed below:

- countering weapons of mass destruction
- theater missile defense (ballistic missiles/cruise missiles)
- attacking fixed targets
- attacking moving targets
- jamming enemy communications
- SEAD
- intelligence, surveillance, and reconnaissance (ISR)
- communications and navigation
- air-to-air combat

The SAB report identified three vehicle types the USAF would require in the near term to provide the size, configuration, observability, loiter altitude, endurance, and payload capacity and power to support the nine priority missions. The vehicle types were (1) penetrating HALE vehicles; (2) stand-off HALE vehicles; and (3) combat, medium-altitude, medium-endurance vehicles. The report recommended that the existing programs on HALE vehicles (Predator, Global Hawk, and Darkstar) be completed and that the USAF pursue the SEAD mission as the initial combat role for UAVs.

Finding. The USAFSAB has provided a comprehensive analysis of the USAF's needs and potential missions for UAVs. This analysis of short-term and midterm needs was the basis for the committee's assessment of the long-term technical and operational requirements.

VEHICLE ATTRIBUTES

The committee identified vehicle attributes to determine some of the technology trade-offs that will be required to develop a UAV system design. On the basis of vehicle attributes, design trade-offs, and technology trends, the committee was able to identify the technologies that would enable the development of potential UAV systems. Vehicle attributes in the general areas of configuration, performance, operation, and control (see Figure 2-3) ranged from conventional capabilities (i.e., capabilities that are commonly used or are readily available) to special capabilities (i.e., capabilities that will require research and development).

Configuration

Conventional, manned aircraft configurations are dominated by the need to accommodate human operators. If the considerations of pilot comfort and safety

Configuration

Size: midsized to very small
Configuration Drivers: flight configured to payload configured
Takeoff/Landing: conventional to vertical

Performance

Threat Environment: low threat to hostile environment
Observability: untreated to extremely low observability
Range: short-range/midrange to very long range
Maneuverability: flight capable to highly maneuverable

Operations

Reusability: long lived to expendable
Logistics: crew maintained to canister shot
Life-Cycle Costs: competitive to extremely low cost

Control

Communications and Controls Environment: stand-alone to system-embedded
Autonomy: remotely piloted to autonomous
Redirection: programmable to responsive

FIGURE 2-3 Range of vehicle attributes (from conventional missions to special applications).

are eliminated, the configuration of the vehicle can be determined by other considerations, such as mission requirements, operating environment, and size and configuration of major subsystems or payloads (e.g., aperture area required for sensors). The principal attributes the committee considered were vehicle size, configuration drivers, and mode of takeoff/landing. *Vehicle size* was assumed to range from conventional midsized to very small (e.g., micro air vehicles [MAVs] less than six inches in their largest dimension). Air vehicle *configuration drivers* ranged from conventional flight-configured vehicles, in which the operating regime or survivability determine configuration, to advanced payload-configured vehicles, in which factors such as aperture size and orientation and payload volume determine the configuration. Finally, although the more advanced vertical takeoff and landing systems were considered, the committee concluded that future USAF requirements could be met without advances in the *mode of takeoff/landing*.

Performance

Performance attributes include the capabilities required to perform the missions described earlier in this chapter. The principal attributes of UAVs considered by the committee include threat environment, observability, range, and maneuverability. The *threat environment* was considered to range from low threat (for which no extraordinary measures are needed for survival) to hostile environments (for which potentially extreme measures are necessary to ensure survival). Depending on the threat environment, *observability* can range from conventional untreated vehicles to vehicles with extremely low observability, either as a result of design or surface treatments. *Range* involves two related factors—distance from station and endurance. Range capabilities were considered to vary from conventional short-range/midrange capabilities (i.e., the aircraft is not required to travel more than hundreds of miles from base or loiter for more than a few hours) to very long-range capabilities (i.e., where the vehicle is required to travel thousands of miles or loiter for as long as several days). Finally, *maneuverability* was considered to range from flight capable to advanced, highly maneuverable capabilities, free of pilot's inability to withstand high accelerations.

Operations

The principal design trade-offs between mission capability and cost are most evident in the operational attributes. The operational attributes the committee considered included reusability, logistics, and life-cycle costs. *Reusability*, a reflection of the design trade-off between cost and durability or survivability, ranged from long-lived vehicles like conventional inhabited vehicles, (i.e., designed for indefinite life) to expendable, low-cost vehicles suited to high-threat environments. Vehicle *logistics*, which include transportability and maintainability, was considered to vary from crew-maintained vehicles (i.e., the conventional attribute for vehicles flown periodically and serviced by a maintenance crew between combat operations) to canister-shot vehicles (i.e., vehicles kept in storage until they are needed). Finally, *life-cycle costs* were considered to range from competitive costs, for vehicles with productivity and support requirements similar to those of inhabited aircraft, to extremely low costs, for which design and operational issues have been optimized for extremely low acquisition and support costs.

Control

Control attributes considered by the committee included the communications and control environment, the level of autonomy, and the ability to provide redirection. The *communication and control environment* ranges from stand-alone capability (i.e., individual vehicles operate independently) to system-embedded capability (i.e., individual vehicles operate in concert with other vehicles, both inhabited and uninhabited). *Autonomy*, the degree of self-reliance and independence the system is given, ranges from remotely piloted vehicles (i.e., the operator retains control throughout the mission) to autonomous vehicles (i.e., vehicles perform assigned missions without human intervention). Finally, *redirection*, an attribute related to autonomy, varies from programmable vehicles (i.e., vehicles perform preprogrammed missions and have limited ability to be redirected) to responsive vehicles (i.e., vehicles that can be easily directed to change the mission during flight).

SYSTEM DESIGN

A number of system technologies, through their influence on air vehicle design, affect the basic vehicle subsystem technologies that are the focus of this report. The crosscutting technologies include communications and human-machine science, which are fundamental to the development of vehicle controls, as well as low-cost manufacturing. These technologies are discussed in the following sections.

Communications

The communications systems associated with a UAV can be divided into three categories: (1) external communications used to communicate commands to the UAV or extract data from the UAV; (2) internal communications to interconnect the payload, the flight and engine control systems, and other mission-management subsystems; and (3) relayed communications, in which a UAV communications payload is used to extend the horizon of ground-based communications systems or to relay command data to and from other UAVs. Communications technology is neither an enabling nor a limiting factor in UAV design, except in the case of MAVs, for which external and internal communications would be a challenge because of their small size.

The arrangement of internal communications to support the operation of a UAV is shown in Figure 2-4. A wideband (on the order of tens of megahertz) onboard bus interconnects all of the subsystems in the UAV. For current designs, the standard MIL-STD-1553B avionics bus would suffice. Many of the current avionics management systems used with the 1553 bus could be adapted for UAVs. Integrated weapons control systems have been configured to integrate communications, navigation, identification (CNI), and both internal and external sensor systems. These integrated systems are available for aircraft ranging from high-performance fighters to helicopters and can be preprogrammed for routine sorties or configured to be programmed during flight through external communications systems. Systems are available from U.S., Canadian, and European avionics suppliers (Johnson, 1998). The representative system shown in Figure 2-4 includes individual sensors, data conditioners, processors, and interfaces that do not exceed the bandwidths available in current hardware.

Development programs for future systems are under way, such as the USAF Pave Pace program for a totally integrated avionics architecture that will use a modular, digital approach to integrate CNI and sensor functions (Carmichael et

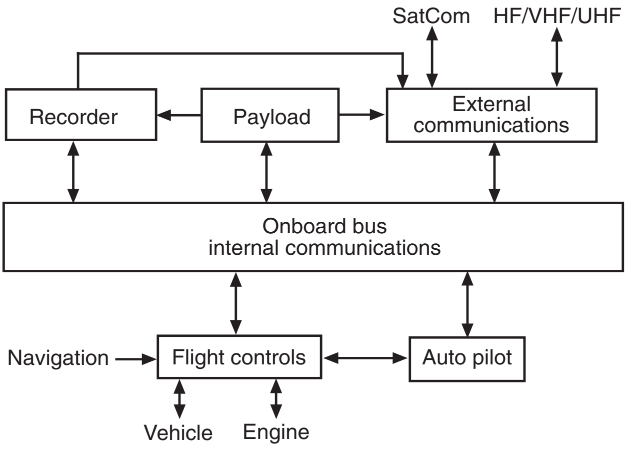

FIGURE 2-4 UAV internal communications system.

al., 1996). A high-speed optical network with crossbar switches operating at 1 to 2 Gbytes per second will interconnect the sensors, processors, and CNI functions and distribute the data using a fault tolerant approach. Similar processing will integrate the radio-frequency system of synthesizers, receivers, transmitters, and antennas. Millimeter and microwave integrated circuits will be used along with ceramic packaging. Multi-arm, spiral, coplaner antennas will span the frequency spectrum from about 200 Mhz to 6 Ghz. There will also be broadband active arrays for radar and electronic warfare functions.

The Pave Pace program started in 1994, and laboratory demonstrations were conducted in 1998 and 1999. The development is being managed by the Air Force Research Laboratory, and virtually all major airframe companies and electronics/avionics houses are participating in the program. The availability of this integrated avionics architecture would substantially reduce the number of external sensors, as well as the size and weight of the data processing and distribution system. These reductions in payload and control-system weight and volume would enable improvements in mission performance and/or vehicle range.

Figure 2-5 shows external communications for several potential military missions in which UAVs would act independently. The data-gathering, processing, and relaying functions could be accommodated by communications systems currently available. The deployment of many of these vehicles simultaneously, either as combat or surveillance units, might appear to create an excessive bandwidth requirement. However, data compression techniques will be available to reduce the required bandwidth by as much as a factor of 10. The housekeeping data from each vehicle will be minimal and can be handled on a narrowband

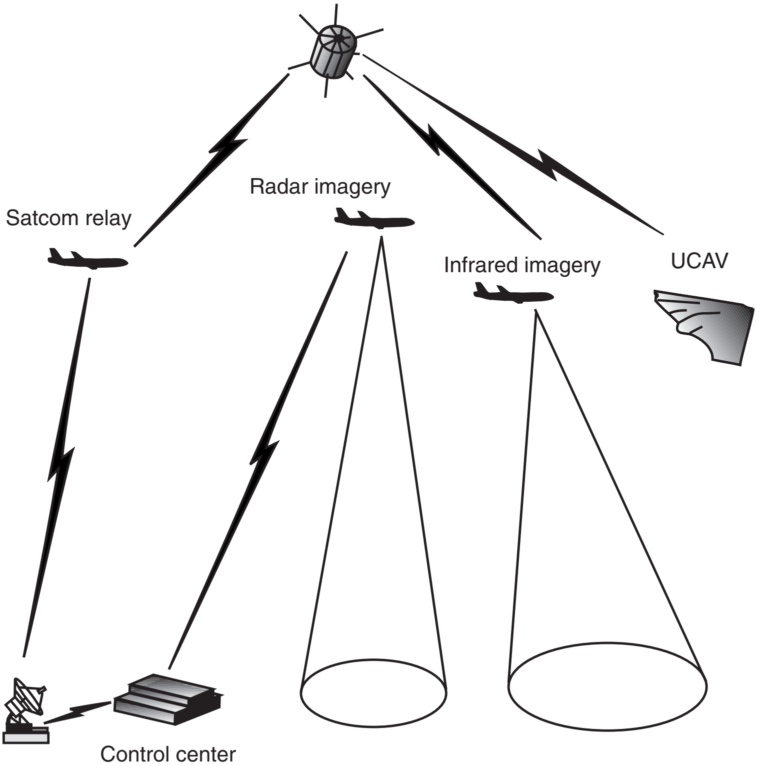

FIGURE 2-5 Notional UAV external communications system.

channel. Time division multiple access (TDMA) techniques can easily accommodate the multiple data streams. For vehicle control from the ground or reprogramming of payloads, telecommunications bandwidths of about 50 kHz should suffice. The approach used by the Internet's Worldwide Web has demonstrated the simultaneous service of many users at telecommunications bandwidths, albeit in an unstressed, benign environment.

In a wartime environment, the MILSTAR satellite could be used for control. Although the operating bandwidth is narrow (2.4 Kbits per sec), superb anti-jamming protection is provided. The number of channels available would be determined on a mission priority basis. The MILSTAR medium data rate channels could be used for relaying essential communications in a wartime environment or delivering volatile, high-priority surveillance data to the ground. MILSTAR would be a factor to be considered in the mission-planning phase of a wartime operation; the procedures for implementation would be an operational issue.

State-of-the-art throughput, storage capacity, processing speed, input/output bandwidth, and other basic parameters of signal processing and data processing has been doubling every two to three years (SAB, 1996). At that rate, within a few years, processors capable of 100 giga-operations per second (GOPS) will be available, along with gigabytes of memory. Current multimode signal processors require 5 to 10 GOPS, indicating that digital processing is not likely to be a limiting factor for UAV performance in the near term.

Finding. Communications and data processing are not limiting technologies for the development and operation of military UAVs. Available technologies can accommodate the needs of currently conceived missions, and developments under way in the telecommunications community will be able to satisfy the needs of expanded military missions for UAVs.

The DOD, through DARPA, has developed a program to apply advances in high-speed computation, signal processing, and miniaturization to mobile, wireless, multimedia information systems. This program, called Global Mobile Information Systems, recognizes that commercial advances will not meet all defense needs for security, interoperability, and other capabilities. A previous NRC study recommended ways for the military to "ride the wave of commercial technology advances while retaining technical capabilities that exceed those of any potential adversary" (NRC, 1997a). The study recommended component and systems development for modeling and simulation of military information networks, integrating commercial components into network architectures, upgrading network security, reducing co-site interference, fielding software radio technology, adapting smart antennas, developing transmission techniques that can adapt to a wide range of operating conditions, improving current filter technology for use in military software radios and high-density platforms, and enhancing the flexibility of software radios.

Human-Machine Science

The goal of human-machine science, also known as "human factors" or "human-system integration," is to take advantage of human capabilities and compensate for human limitations in the design, manufacture, and operation of systems of all kinds. Human-machine science includes not only the primary system, but also all ancillary activities, such as logistics, operational procedures, maintainability, and training. The field is supported by, and draws on, several other disciplines, including psychology, physiology, medicine, engineering, sociology, anthropology, mathematics, and computer science.

Finding. The design decision that has the most profound effect on the human-machine sciences is degree of autonomy.

The degrees of autonomy for UAVs are listed below:

- completely autonomous (once programmed)
- quasi-independent (highly autonomous)
- semi-autonomous
- remotely piloted

The level of autonomy for some UAVs will vary depending on mission segment and/or unforseen events, such as system failures or enemy action.

A great deal of automation has already been implemented in current systems, including modern aircraft systems. Generally, decision making and override of automated systems have been retained for human operators, although UAV designs may change this. Experience with current operational and developmental systems (or concepts) has shown, however, that the integration of the human and machine components of the system is a much greater challenge than many anticipated (Munson, 1998).

Like most design alternatives, automation has both positive and negative aspects. Potential advantages of automation are greater operator safety, fewer human errors, more precise control, the capability to perform functions beyond the environmental or physical limitations of human operators, the capability to perform functions that humans do not want to do, and greater human comfort (Gabriel, 1992). The disadvantages of highly automated systems include boredom and a resulting loss of vigilance and situational awareness; interruptions or lags in communication links; more complex training because of the increase in operational modes, both normal and abnormal; higher costs for defining, coding, and checking automated functions; reduced ability to deal with unanticipated situations; and fewer cues available to the operator assigned to intervene. To remain effective, human operators must have meaningful tasks that are challenging but achievable and significant feedback on their performance.

A more comprehensive use of automation might increase, rather than diminish, the importance of human considerations in system design, development, and operation (Figure 2-6). Success will depend on the effective allocation of functions to humans and machines. For instance, humans will be able to intervene only if provisions have been made for intervention and only if the human is attentive.

Even though the methods and tasks involved in interacting with any system may vary significantly in terms of frequency and specific actions, the fundamental human functions to support future UAV operations will be similar to

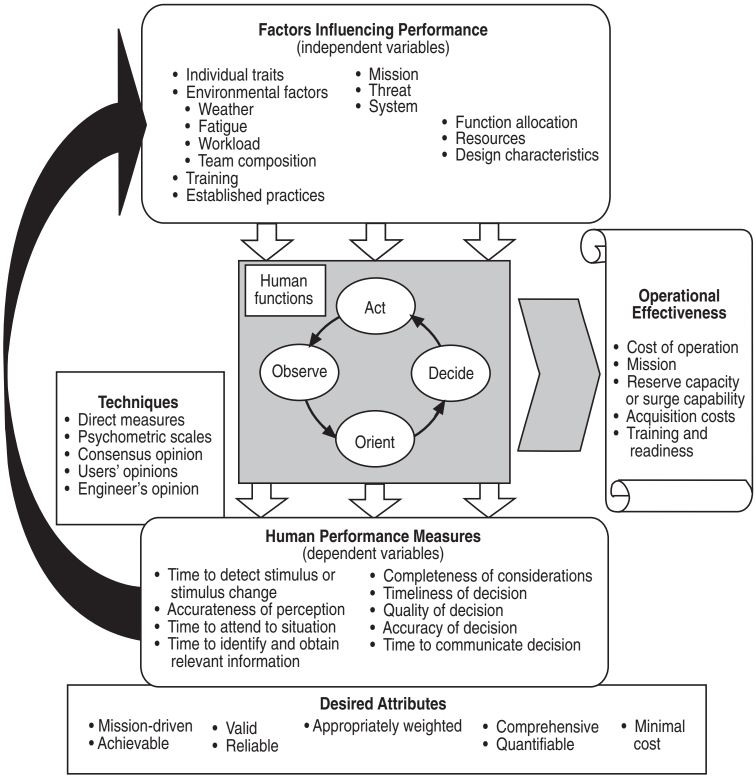

FIGURE 2-6 Human performance measures. Source: USAFSAB, 1998.

the ones carried out by humans today (i.e., observe, orient, decide, and act). Examples include:

- logistics support, including planning, air vehicle breakout, mission programming, system checkout, systems management, service, and maintenance
- execution of control and/or monitoring system performance, including mission redirection/reprogramming, direct control of systems or vehicle (e.g., sensors, weapons, and various other subsystems), communication with other operators, and coordination with other vehicles

The degree of independence of the automated system from human intervention is a vital design decision that will be influenced by many factors for a specific vehicle. The following operational considerations must be considered in determining the degree of automation:

- status of related technology (i.e., can the functions be automated effectively)
- mission type and importance (e.g., ISR, SEAD)
- control of multiple UAVs
- deconfliction requirements
- environmental factors (e.g., visibility, terrain)
- enemy activities, threats, and/or countermeasures
- stores, including weapons, sensors, and communications
- size of vehicle
- range of vehicle
- launch and recovery method
- mission complexity
- system reliability requirements
- cost of total loss (e.g., system costs, availability of replacements, potential for mission failure, potential for collateral damage, potential for enemy capture of part, or all, of system)
- user characteristics (e.g., aptitude, training, strength, fatigue)
- cost of training
- logistics requirements
- duration of the mission
- other friendly forces involved on ground near target or over flight path
- number of other aircraft involved in the mission

Recommendation. The U.S. Air Force should continue to strengthen its activities on human-machine science related to the design and development of UAVs. Research should be pursued in the following key areas:

- *integration of human-machine systems into the design process*, including (1) the optimal and dynamic allocation of functions and tasks and (2) determination of the effects of various levels of automation on situational awareness
- *human performance*, including (1) the investigation of human decision-making processes, (2) the development of methods to define and apply human-performance measures in system design, and (3) the enhancement of force structure through improved methods of team interaction and training
- *information technologies*, including (1) the determination of the effects of human factors on information requirements and presentation and (2) the development of enhanced display technologies to improve the human operator's ability to make effective decisions

Low-Cost Manufacturing

Substantially reducing the total life-cycle costs of UAVs compared to the costs of conventional, inhabited air vehicles will be vital to the successful introduction and deployment of UAV technologies. Reducing the life-cycle costs to acceptable levels will necessarily entail reducing all system acquisition costs, including design costs, personnel costs, and manufacturing costs. This section focuses on low-cost manufacturing, specifically (1) designing for low-cost fabrication and (2) low-cost product realization. These considerations will influence the way that UAVs are designed and how technologies are prioritized.

Designing for Low-Cost Fabrication

Overall air-vehicle concepts, as well as specific subsystem concepts described in subsequent chapters, will have to be designed for low-cost fabrication. The following steps have the potential to reduce the overall cost of air-vehicle fabrication:

- Reduce vehicle size and weight.
- Reduce the part count for major assemblies.
- Sacrifice weight (e.g., constant thickness, resin transfer molded composites instead of weight-optimized hand-layup constructions).
- Maximize the use of room temperature processes.

Reductions in vehicle size and weight will generally result in reductions in fabrication costs and total life-cycle costs. Fabrication costs will be reduced simply because less raw and processed material will be required to produce components. Cost reductions through size and weight reduction will be realized as long as the manufactured cost per pound remains stable as size is reduced. Limits on the size of vehicle payloads (including weapons) and major subsystems (especially sensor apertures and propulsion systems) will determine the lower limit of vehicle size.

Modular vehicle designs could significantly reduce both design and manufacturing costs. One concept for a modular design would use a common centerbody module for a range of vehicle configurations (Lang, 1998). With a modular design, design and tooling costs could be amortized over multiple systems. Modular design could also be used for major subsystems by including common components (e.g., propulsion systems, avionics, communications systems, and sensors) for a range of air vehicles.

Low-Cost Product Realization

Substantial advances in commercial manufacturing have reduced the time and cost of getting product innovations to market. Although not all of these advances are applicable, some of them could be adapted for defense applications (NRC, 1999). Rapid (and flexible) product realization requires low-volume production at a reasonable cost. Future UAVs could be developed and manufactured more rapidly and at lower cost if cycle times and nonrecurring costs can be significantly reduced through new approaches to product design, manufacturing processing, and the consideration of cost as an independent variable (CAIV) (NRC, 1999).

Practices that have been proven effective include integrated product and process development, the standardization of parts, and reduction in parts count. Three-dimensional digital product models, modeling and simulation of manufacturing processes, and virtual prototyping can also reduce cycle time and the need for late redesigns by predicting problems before resources have been committed for physical prototypes. Assembly modeling can complement simulations to optimize the assembly of complex systems.

Two new approaches to manufacturing processes could be explored. First, innovative processes that use low-cost tooling, including soft tooling (e.g., wood or composite tools for out-of-autoclave composite molding), flexible tooling that can be used for multiple parts or configurations, and toolless assembly could enable cost-effective, low-rate production. Second, generative numerical control (GNC), the automatic creation of process control data sets as the designer creates the three-dimensional product description, can be coupled on the factory floor with other knowledge bases to reduce flow times and can be configured to generate the manufacturing plan or process automatically from the three-dimensional data set.

CAIV is a means of treating cost as the principal input variable in the program structure, development, design, and support of a product. In past acquisition programs, the buyer and seller either accepted high costs as unavoidable or waited until late in the system development process to attempt to reduce manufacturing costs. In a general guidance document for implementing CAIV, the undersecretary of defense for acquisition and technology called for the early establishment of unit-cost goals based on performance-cost trade-offs. The document also stresses that strong incentives should be provided for program managers and contractors to implement CAIV objectives.

Development programs for UAVs must be structured from the outset to take full advantage of CAIV. Trade-offs of mission requirements and performance against cost and the establishment of unit-cost production goals should be done during the preliminary design and development phases. UAV designers, for example, may be willing to sacrifice “that last 100 miles of range” if it would drive up the unit cost by 20 percent. CAIV concepts can also be used for designing subsystems. For example, the avionics system, which accounts for 30 to 40 percent of the air vehicle cost, could (and should) be treated in a similar fashion to arrive at the best, low-cost solution. CAIV methods were successfully used to optimize product design and materials and process selection in the development of DARPA’s Miniature Air-Launched Decoy (MALD) (Price, 1998).

Part II

Vehicle Technologies

Part II identifies technical needs and opportunities for research and development for major UAV subsystem technologies. The committee considered five areas in its analysis of air vehicle technologies: aerodynamics (and vehicle configuration), airframe (with a focus on materials and structures), propulsion systems, power and related technologies, and controls.

The committee used "notional vehicle types" as a way of identifying technical needs for applications ranging from replacing manned aircraft to performing unique missions. The committee identified three notional vehicle types as indicative of the range of technologies that would support general advances in the USAF's capability of designing, producing, and fielding generation-after-next UAVs. The notional vehicle types were: (1) HALE (high-altitude, long-endurance) vehicles; (2) HSM (high-speed, maneuverable) vehicles; and (3) very low-cost vehicles.

Each notional vehicle type represents a class of vehicles, not a conceptual aircraft design suited to a particular mission. For example, the HALE class could include a reconnaissance air vehicle with an endurance of several days, as well as a very different vehicle with indefinite endurance.

HIGH-ALTITUDE, LONG-ENDURANCE VEHICLES

The HALE vehicle type provided a focus on long-term technical advances for generation-after-next reconnaissance and surveillance aircraft. The key attributes of HALE vehicles will be operation at very high altitudes (> 65,000 feet) and long endurance (from days to "indefinite" duration). The committee believes that future aircraft intended to operate at altitudes above 65,000 feet will be uninhabited, so the issues associated with the design and operation of these aircraft should be considered UAV-unique. The committee focused on high-altitude technologies, especially aerodynamics/vehicle configuration and propulsion systems. HALE vehicles would generally be flight configured, with an emphasis on structural efficiency (light weight) to provide endurance. Because of the lightweight structures and large wingspans typical of HALE vehicles, aeroelasticity is an important factor. HALE vehicles would be generally autonomous and programmable because a key reason for using UAVs for long-duration missions is to avoid operator fatigue and reduced vigilance due to monotony.

HIGH-SPEED, MANEUVERABLE VEHICLES

The HSM vehicle type provided a focus on potential second-generation UCAVs. The goal for HSM vehicles will be to conduct high-risk combat operations at a significantly lower cost than inhabited systems. Because the key consideration for HSM vehicles will be survivability, design trade-offs will include stealth and maneuverability versus speed, maximum altitude, and damage tolerance. HSM vehicles will generally operate in concert with other vehicles (inhabited and uninhabited) and will be responsive to changes in mission at the direction of a remote human operator. The cost of operations and logistics will be critical for the HSM vehicle type.

VERY LOW-COST VEHICLES

The very low-cost vehicle type was chosen to focus attention on trade-offs between cost and performance. Low-cost vehicles will be small, autonomous, and inexpensive. Operating in concert with other vehicles as a single distributed system, individual low-cost vehicles will not carry high-value payloads, and the loss of an individual vehicle would present a small threat of mission failure or collateral damage. Important attributes of low-cost vehicles will be vehicle configuration, which will depend on payload, structural design criteria, reliability after long-term storage, and low-cost manufacturing.

3

Aerodynamics

In many ways, the aerodynamic issues important to UAVs are similar to those for manned aircraft. However, certain classes of UAVs operate quite differently from manned aircraft and present different aerodynamic design problems.

In most cases the particular demands on UAVs are reflected in changes in the relative importance of aerodynamic performance parameters. Sometimes these differences can lead to novel UAV configurations. Some technologies that have little payoff for commercial aircraft (e.g., lift augmentation in unsteady maneuvers) can be crucial for certain UAVs.

Aerodynamic development for UAVs relies strongly on linearized aerodynamics, especially for aeroelasticity and control. The presence of mixed laminar and turbulent flows, the importance of transition, the appearance of significant aeroelastic effects, and in some cases the presence of vortex-dominated flow fields make it difficult to conduct complete vehicle aerodynamic studies using available computational tools. The low Reynolds numbers of many UAVs makes the use of wind tunnel models very attractive, and most UAV development involves the creation of substantial experimental databases for performance and control studies. However, very few facilities are suitable for dynamic testing of very maneuverable UAVs (such as UCAVs and HSM vehicles).

Several aspects of UAV aerodynamics, from configuration design to aerodynamic modeling for stability and control, require more development. The rest of this chapter describes some of the basic aerodynamics-related research areas and promising technologies associated with the three notional vehicle types. Aeroelastic controls, propulsion/airframe integration, and improved multidisciplinary design approaches, which are critical to UAV development, cut accross traditional disciplinary boundaries.

BASIC RESEARCH

Each class of UAVs is driven by aerodynamic considerations that are either unique or very important for the future development of UAVs. This section describes some of these issues.

High-Altitude, Long-Endurance UAVs

HALE UAVs developed in the past 30 years represent a wide range of flow conditions. From the low-speed Predator (Ernst, 1996) and Condor (Johnstone and Arntz, 1990) to Global Hawk (Heber, 1996) and Darkstar (Berman, 1997), these aircraft share several aerodynamic challenges, but also illustrate the differences among UAVs in this class. This section deals with some of the common aerodynamic challenges.

Induced Drag

Although HALE UAVs may be required to operate at speeds higher than those for maximum aerodynamic efficiency for reasons of cost or mission effectiveness, the requirement for long endurance leads to lower speed operation, with a subsequent increase in vortex drag. Low-speed, high-altitude operations could also require that dynamic pressure be less than ideal. The standard approach to reducing induced drag is to increase wingspan (e.g., the wingspan of the 26,000-pound, jet-powered Global Hawk is 116 feet, the propeller-driven Boeing Condor of the 1980s 210 feet, and the solar-powered AeroVironment Centurion 240 feet). Large span, high-aspect-ratio wings pose difficulties, ranging from storage and transport to aeroelastic control, in addition to the performance penalties associated with the high unit-weights of the wings. Vortex drag can also be reduced by nonplanar lifting systems, including winglets, joined wings, C-wings, and other geometries (Kroo et al., 1996). Although these configurations reduce induced drag, their overall advantages over larger-span planar wings are small and mission specific. More radical approaches to drag reduction, such as tip turbines, may be more practical for UAVs than for commercial aircraft, but the potential for savings is uncertain at best.

Boundary-Layer Issues

Boundary-layer characteristics are among the most important issues for future UAV research and development. These issues are related to low Reynolds number, predicting and modifying boundary-layer transition, boundary-layer sensing and control, and airfoil section design.

Because HALE UAVs have high-aspect-ratio wings and fly in low-density conditions, often at low speeds, airflow is characterized by low Reynolds numbers (see Figure 3-1). Typical Reynolds numbers for the wings of HALE UAVs are

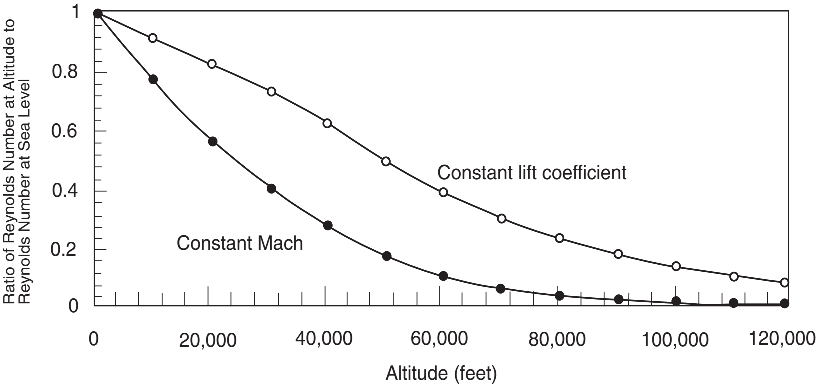

FIGURE 3-1 Variation of Reynolds number with altitude.

closer to those of sailplanes than commercial jets or fighters. This leads to challenges (e.g., attaining high lift coefficient and avoiding laminar separation) as well as opportunities (e.g., extensive laminar flow) in a flow domain that has not been studied thoroughly (Figure 3-2). A basic understanding of laminar-to-turbulent transition is promising for research critical to high-performance aircraft with lift-to-drag ratios approaching 40. Current Reynolds-averaged Navier-Stokes

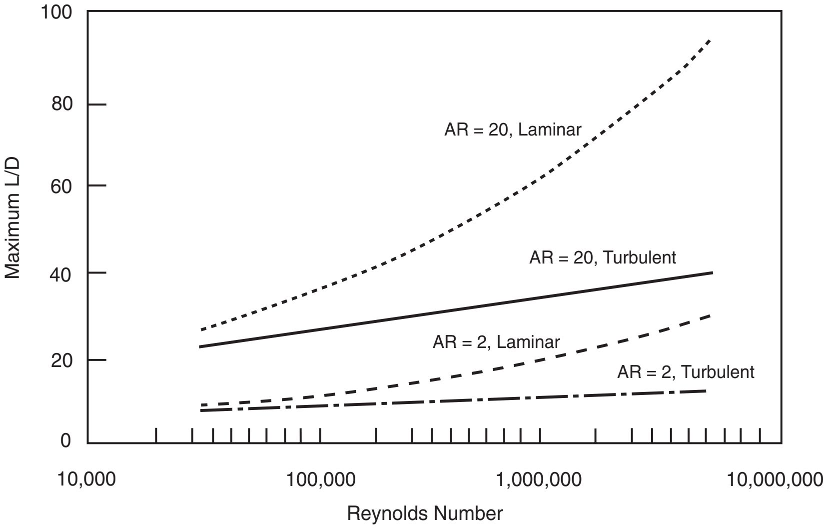

FIGURE 3-2 Maximum lift-to-drag ratio vs. Reynolds number showing influence of aspect ratio (AR) and laminar flow. Lift coefficient (C_L) is limited to 1.0, parasite drag coefficient (C_{Dp}) = 1.5 coefficient of skin friction (C_f).

simulations with modern turbulence models cannot predict transition and do a poor job of modeling the combined laminar and turbulent flows, even when the transition location is known. The effect of surface roughness caused by rain or bugs is not well modeled in this Reynolds number regime, and heuristic methods are generally used in design. Even for smooth surfaces, transition predictions (including Tollmein-Schlichting, cross-flow, and attachment line instabilities) on swept wings in compressible flow are difficult to make. The behavior of laminar separation bubbles can also be important, especially in off-design conditions, and substantial work remains to be done to understand this phenomenon before it can be considered in design (O’Meara and Mueller, 1986). In addition to understanding and predicting boundary-layer phenomena, technologies for the design of efficient wings in this flight regime are required. Design approaches, including the incorporation of active boundary-layer sensing and control, are discussed in the section below on promising technologies for UAV aerodynamics.

Very High Altitude UAVs

Aerodynamic design issues become even more significant for UAVs designed to operate at extremely high altitudes. Much lower Reynolds numbers may dictate substantial departures from traditional design philosophies and may benefit more from both active and passive techniques for boundary-layer manipulation. Low-speed HALE UAVs that incorporate large propellers for efficient propulsion introduce several additional aerodynamic issues, including those associated with interactions between propeller and control on aircraft with high Mach and low Reynolds numbers.

Higher Speed HALE UAVs

The requirements for surveying large areas could also be met by higher speed UAVs, which could cover the same area as long endurance UAVs in a much shorter time. For certain types of vehicles, survivability considerations could dictate operation at very high altitudes and high speeds. Higher speed UAVs, including supersonic designs, that can gather data efficiently is an intriguing area for future research (Tracy et al., 1999).

Aeroelasticity and Controls

Wing flexibility resulting from the requirement for high aspect ratio and low structural weight fraction could cause aeroelastic instability for long endurance UAVs. These very flexible vehicles could use stability augmentation systems to combat aeroelastic instability. These aircraft may also feature unconventional configurations, such as flying wings or low-observable designs, and often exhibit significant nonlinear aerodynamic characteristics. Although dynamic aeroelasticity is not a new field, the requirements for aeroelastic control will be difficult to meet with current analysis and design approaches (Weisshaar et al., 1998).

High-Speed, Maneuverable UAVs

HSM vehicles raise an unconventional aerodynamic design problem. Configurations are based on considerations of radar cross section, efficient propulsion integration, requirements for a wide range of speeds, and maneuvering capability. Configurations vary widely, but many involve the following aerodynamics-related design challenges.

Nonlinear Unsteady Aerodynamics

With significant maneuvering requirements, the dimensionless pitch rate can become large.[1] This suggests that unsteady aerodynamics may play a greater role in the performance of HSM UAVs than in the performance of conventional aircraft and might be exploited to improve vehicle capabilities (Lang, 1998). However, the three-dimensional unsteady aerodynamics of this type of vehicle (i.e., vehicles with high sweep, low aspect ratio, and transonic Mach number) at high angle of attack are very poorly understood. Even the prediction of steady-state characteristics for vehicles that rely on nonlinear vortex lift is difficult, especially at critical conditions such as vortex burst (Ashley et al., 1991). New experiments and computational methods to study and predict three-dimensional separated flows or vortex-dominated flows are needed before such flows can be effectively controlled.

Unique Configurations and Control Concepts

HSM mission requirements lead to a wide range of design possibilities, including many that are not feasible for manned aircraft. Meeting the demands for high maneuverability and low observability can lead to unconventional arrangements that may involve flight in nonlinear regimes that would normally be avoided by conventional aircraft. Although specific aerodynamic features are likely to depend on the configuration, good simulations of complete vehicle flows, including vortex shedding and separation, will be important.

Propulsion-Airframe Integration

HSM UAVs will probably require highly integrated designs, which will require better modeling of inlet and exhaust flows over a wide operating range.

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[1] The dimensionless pitch rate is defined as $k = \frac{da}{dt}\frac{c}{2U}$, where a is the angle of attack, t is time, c is the mean geometric reference chord, and U is freestream velocity.

The effects of boundary-layer ingestion on inlet performance and distortion are difficult to model and are even more difficult to incorporate into the initial vehicle design. Size reduction and observability requirements have led to the use of serpentine inlets for advanced fighters, creating large adverse internal pressure gradients, increased distortion, and risk of separation. Preliminary results suggest that passive or active flow-control measures could be used to reduce these problems (Anderson and Miller, 1999).

Small UAVs

The design of small UAVs is dominated by problems associated with very low Reynolds number flows. From poor lift-to-drag ratios to low values for the maximum lift coefficient and related control problems, the design of efficient, small vehicles represents a significant aerodynamic challenge. Fundamental research may not be necessary to develop a 10 to 15 centimeter MAV (micro air vehicle) that can fly successfully (McMichael and Francis, 1998). However, smaller vehicles may employ fully laminar sections or, like insects, may require the use of novel unsteady aerodynamic mechanisms to generate sufficient lift for efficient flight.

Other Concepts

Some potential UAV applications fall outside the three classes of UAVs described above. Novel aerodynamic problems are likely to arise in the development of UAVs with vertical takeoff and landing (VTOL) capabilities, ultra-long endurance, supersonic or hypersonic speeds, or lighter-than-air structures. The resulting aerodynamic problems are difficult to anticipate, although research on analysis and design capabilities for complex, nonlinear flows over complete configurations would greatly accelerate the development of these devices.

PROMISING TECHNOLOGIES

This section suggests specific aerodynamics-related technologies and the associated research areas that appear to be promising for the development of UAVs.

High-Altitude, Long-Endurance UAVs

Section Design Concepts

Many current HALE UAVs employ airfoils based on sailplane sections that have been modified for higher Mach number requirements. New sections based on multipoint optimization may improve performance at the high lift coefficient, transonic, low Reynolds number conditions of interest here (Selig and Giglielmo, 1994). The direct integration of vehicle trim and off-design performance constraints should be incorporated into a design approach that recognizes the important role of section geometry in drag, structures, and control. Innovative section concepts include very high lift sections; divergent trailing edge concepts (Henne and Gregg, 1989); continuous-mold-line, variable-camber sections; and slotted sections.

Multidisciplinary Design

Although some UAVs, such as Global Hawk and Condor, use rather conventional configuration concepts, future HALE UAVs may have very unconventional configurations, including tailless designs, varying degrees of sweep, joined wings, multiple body concepts, oblique wings, formations of cooperating aircraft, and others. Unique aerodynamic issues are associated with each of these concepts (e.g., swept-wing transition at low Reynolds number), and aerodynamics research must be conducted in the context of system configuration to identify the most important topics. Highly integrated design concepts, such as very flexible span-loaded vehicles, aircraft with distributed propulsion systems, or integrated payloads, require high-fidelity multidisciplinary analyses early in the design cycle (Wakayama et al., 1996). Figure 3-3 illustrates two unconventional configuration concepts.

Boundary-Layer Sensing and Control

Boundary-layer sensing can be useful for HALE UAVs for determining transition location and adjusting control gains, mission planning, or wing geometry based on the inferred vehicle state. Passive techniques for boundary-layer modification (such as riblets for reducing turbulent skin friction or vortex generators for boundary-layer modification) have been used with some success (Bechert and Bartenwefer, 1989). In some cases, unsteady flow perturbations and even active feedback control can be used to modify boundary layers or free shear layers (Ho and Huerre, 1984). These include synthetic jets for fluidic thrust vectoring or enhanced mixing (Smith and Glezer, 1998), and piezoelectric systems for separation control (Seifert et al., 1998).

Modification of transition location and redesign of sections for extended laminar flow with more aggressive pressure recoveries is possible with boundary-layer suction, although the cost of such systems (in terms of weight, power, and manufacturing) makes their application to HALE aircraft less compelling. Emerging MEMS technology makes micron-scale sensors and actuators possible (see Chapter 7). A variety of very lightweight microflow sensors (e.g., sensors for shear stress, pressure, velocity, temperature, and heat flux) and many microactuators have been designed and fabricated. MEMS transducers may provide a

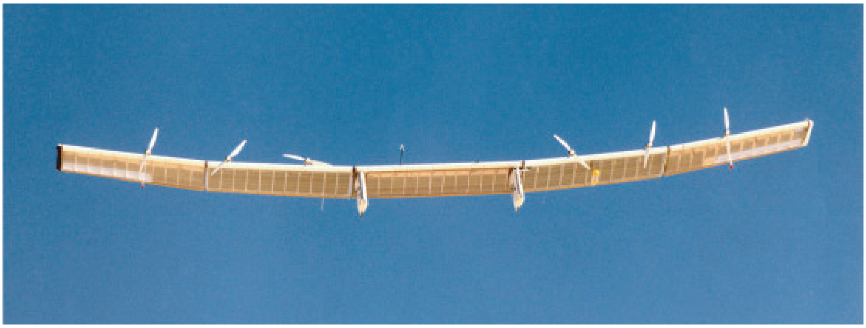


FIGURE 3-3 Unconventional designs with challenging configuration aerodynamics. Top: Aurora Flight Science Corporation's Theseus. Bottom: AeroVironment Pathfinder. Source: NASA.

means for much more efficient flow control by applying actuation at the place and time that is most effective. Separation control to enhance maximum lift could improve the loiter performance of HALE vehicles, and modifying the pressure distribution with miniature actuators could extend the region of extensive laminar flow.

Aeroelastics

The construction application of aeroelasticity to improve performance has been studied for many years, but it has seen little application. Aeroelasticity is generally regarded as a problem that should be avoided, especially with HALE UAVs. Research on active aeroelastic wings (Zillmer, 1997), however, looks promising and could be feasible for this class of UAVs. Current research on very flexible wings may lead to interesting design possibilities, although the practical advantages in this domain will have to be quantified.

Radical Concepts

Many new technologies that could dramatically improve aerodynamic performance have been suggested. A variety of proposals for reducing induced drag, such as vortex diffusers, tip turbines, and special wing-tip geometry, may be relevant to HALE UAVs. In the committee's opinion, however, the results to date on each of these concepts does not justify substantial additional research emphasis.

High-Speed, Maneuverable UAVs

Configuration Concepts

HSM mission requirements may dictate highly integrated and/or unconventional designs strongly influenced by aerodynamic characteristics. The need for high maneuverability may lead to configurations that lend themselves especially well to control at high angles of attack or that generate large nonlinear lift increments. Computational and experimental work will be required to identify planform geometries that produce desirable aerodynamic characteristics at high angles of attack.

Dynamic Lift

Design concepts that exploit dynamic lift are of great interest for vehicle design of HSM UAVs. These concepts include configurations and control devices that delay or control vortex bursting. Shed circulation strength and location can be influenced in a number of ways, including strakes, boundary-layer modification through blowing or local geometry changes, and more conventional controls.

Active Flow Control

In addition to the potential role of flow control in exploiting dynamic lift, more general applications of flow control are also of interest for HSM vehicles. The manipulation of separated flow fields may be accomplished efficiently by various flow-control technologies, and active manipulation could permit operation of HSM vehicles in nonlinear flow regimes that would otherwise be avoided, with the goal of increasing mission performance. Because the vortex-dominated flow field arises from separation near the leading edge, subtle changes in boundary-layer properties (due to blowing, suction, or small shape changes) can be used to manipulate leading edge vortices and produce large changes in vehicle forces and moments. Leading-edge flow control using blowing has been demonstrated in wind tunnel and computational simulations, providing control in flight regimes where conventional surfaces are ineffective. The use of these alternative control concepts is especially promising in applications, such as UCAVs, where radar cross section is of critical concern, because they would eliminate the easily detected wing-flap interface (Ho and Tai, 1998).

Aerodynamic Modeling for Control Systems

Along with technologies that exploit unsteady aerodynamics and nonlinear, high angle-of-attack flows, improved techniques for assimilating these unconventional aerodynamic properties into vehicle simulation and control system design will be necessary. The concept of stability derivatives, which have proven to be very useful for linear design, should be augmented with the idea that aerodynamic properties are history dependent and highly nonlinear. Various modeling concepts, including indicial response models and neural networks (Faller et al., 1995), are currently being studied, but alternative concepts are required.

Small UAVs

Very small UAVs may benefit from a better understanding and enhanced modeling capabilities for very low Reynolds number flows and may also require unique aerodynamics technologies. In this viscous-dominated domain, boundary-layer control is especially important, although accomplishing this practically at the small scales envisioned here may be difficult. New propulsion technologies will also be critical for these small UAVs (see Chapter 5). Integrated propulsion systems, including flapping wings, become more attractive at smaller scales. Very small devices with centimeter-level dimensions would create unique challenges for aerodynamic design. Novel all-laminar sections have been developed, and techniques for introducing unsteady motions to increase maximum lift capability may be critical in this application (and may also be of interest for larger UAVs).

OPPORTUNITIES AND RECOMMENDATIONS

Recommendation. The U.S. Air Force should focus aerodynamic research on the following areas to maximize the benefit to future UAVs:

- boundary-layer research focused on issues important to UAVs, including (1) transition prediction with (three-dimensional) pressure gradients, Reynolds numbers, and Mach numbers typical of UAV flight conditions and (2) improved flow modeling with part-chord natural laminar flow
- techniques for real-time flow sensing and actuation
- design architectures for complex multidisciplinary problems, including highly integrated systems

- aeroelastic analysis and design approaches, especially for very flexible, unrestrained, actively-controlled aircraft
- novel vehicle control concepts, including flow control
- exploitation and modeling of unsteady, nonlinear, three-dimensional aerodynamics
- design concepts for very low Reynolds numbers, including steady and unsteady systems
- aerodynamic modeling concepts for designing vehicle control systems

4

Airframe Materials and Structures

The most notable developments in UAV airframe structures will be reductions in size (miniaturization) and the use of multifunctional materials. Even though many advances in materials, manufacturing, health monitoring, durability, and smart structures are already enabling technologies for affordable UAVs, not all of the benefits are unique to UAVs. This chapter identifies structures and materials research areas that will have a significant effect on the development of cost-effective UAVs. Like most other next-generation aircraft, UAVs will require low-cost, lightweight materials. The design and construction of any air vehicle is driven by consideration of a range of failure modes, such as excessive elastic deformation, yielding, buckling, fracture, fatigue, corrosion, creep, and impact damage. However, some mission-specific features of UAVs are especially dependent on advances in airframe materials and structures.

The committee identified four areas that will be essential to the further development and evolution of UAVs. All four areas will require research and development ranging from basic science to prototype testing. The four areas (in arbitrary order) are as follows:

- defining the design environment in which future UAVs will operate, including loads definition, reliability requirements, and aeroelasticity
- reducing manufacturing costs for airframe structural components, including advanced composite materials and multifunctional materials (i.e., structural materials that also serve another primary purpose)
- improving design processes to support reduced cycle time, rapid prototyping, and low-cost fabrication

- health monitoring, health management, and novel control and sensing technologies, including MEMS, smart materials, new sensors, and actuators

Each of these areas will require a better understanding of the processes and phenomena involved and more reliable prediction of interactions among the elements of the process or device.

STRUCTURAL DESIGN

Probabilistic Methods

The design of aircraft structure considers interactions among many complex processes, including material selection, fabrication, assembly, operations, and maintenance. The primary material parameters that affect a structural design are strength and stiffness, which are traditionally characterized by deterministically derived design property values, or "allowables." Allowables are statistically reduced values based on experimental data and on assumed statistical models or distributions. Historically, structural design criteria are established by reducing design limits and ultimate conditions by a "safety factor" of 1.5, based on the ratio of ultimate strength to yield strength of common structural metals. In addition to engineering simplicity, the most important reason for using deterministic approaches is that design criteria expressed in terms of a margin of safety are more readily accepted by regulators and customers.

In the deterministic approach, a structure is designed to operate with the simultaneous occurrence of poorest allowable material quality and the most severe operating environment, level of damage, and service load conditions. That is, uncertainties are handled using conservative safety factors, a safe approach when most of the data describing the uncertainties are incomplete. As a result, current structural designs are very conservative and very heavy.

Probabilistic structural design/analysis is based on the principles of structural mechanics and uses conventional structural analysis tools, such as closed-form solution of mathematical equations and finite element methods, to solve structural problems involving the variables. In the probabilistic approach, the actual strength or stiffness distributions are developed using analysis models that account for the probability of material defects, dimensional tolerances in structural component fabrication and assembly, variations in operational loads, and the probability of in-service and maintenance damage. Using probabilistic models, the safety and reliability of structures can be assessed over their entire lifetimes. Probabilistic structural design/analysis has been used to solve a variety of engineering problems, including spacecraft engines, durability analyses, and risk assessment of existing structures.

The committee believes that the use of probabilistic design criteria for UAV structural design could result in a lower cost, more efficient structure and could accelerate the maturation and acceptance of probabilistic design approaches for other systems. The probabilistic approach is more suitable for UAV structural design criteria than for inhabited systems for two reasons. First, the uncertainties and difficulties in accurately characterizing the operational environment for UAVs could require an overly conservative statistical safety factor for structural design when using deterministic design criteria. Probabilistic design and analysis would reveal more of the information about a structure to allow for a more realistic assessment of performance and operating life. Second, the design criteria for UAV structures are not well defined, even in the traditional deterministic approach. Thus, in terms of safety or risk of structural failure, there may be fewer objections to a deviation from the conventional arbitrary margin of safety. Customers and designers are reluctant to accept any structure with a level of reliability less than 100 percent or a risk of failure higher than 0 percent for inhabited systems. Risk is more acceptable when human life is not involved.

The highest payoff from using the probabilistic design/analysis approach will be the potential to meet required safety goals with an optimized structural design that reduces both weight and cost. Based on operational experience with a range of aircraft, industry has obtained a substantial amount of data to simulate the probabilistic occurrence of individual events. Probabilistic design and analysis can use this information to design more efficient structures. In addition, because structures will be designed to meet a discrete safety goal, new approaches for planning structural testing will be necessary to generate experimental data to characterize materials and structures. Once basic statistical relationships between key structural parameters have been determined, simulations could replace many materials and structures tests. Thus, less expensive and more accurate assessments of structural performance could be obtained with less testing.

Analytical Tools

Research should be initiated to integrate design and analysis models and methods into a versatile engineering tool. Current analytical models, such as the finite element codes developed by the National Aeronautics and Space Administration (NASA) and structural evaluation codes developed by industry, will have to be modified and improved for structural design and analysis in a production environment. The development of analytical tools should also include the development of procedures for assessing the accuracy and reliability of model predictions.

Several probabilistic approximation methods are available, the most reliable of which is the Monte Carlo simulation method. However, faster and more efficient methods are needed.

Characterization and Testing

Fundamental research should be undertaken to establish potential failure modes and performance levels for materials and structures to support probabilistic analysis methods. Current approaches for testing materials are based on deterministic design methods and rely on extensive testing at the subelement, element, subcomponent, component, and full-scale levels, using a "building block" approach (NRC, 1996). The development of basic property relationships and potential failure modes are needed for implementing probabilistic design approaches and reducing the amount of large-scale verification testing required.

Simulation Methods

Techniques and software codes should be developed for computational simulations of structural responses to operational environments throughout the structure's lifetime at both the material and structural levels. Effective analytical simulations would enable designers to model design alternatives without developing and testing expensive prototypes, resulting in potentially significant reductions in developmental costs.

Design Criteria

Fundamental research on critical failure modes and property relationships to establish meaningful design criteria for probabilistic methods should be undertaken. Criteria could be established based on the results of studies on the relationship between the conventional safety factor and the probabilistic reliability of a structure, along with an in-depth survey of existing structures.

Recommendation. To support the development and introduction of probabilistic methods for UAVs, the U.S. Air Force should sponsor research on (1) analytical tools, (2) characterization and testing, (3) simulation methods, and (4) design criteria.

Aeroelastic Tailoring

Aeroelasticity is the interaction between mechanical and aerodynamic forces. Unstable aeroelastic interactions can lead to flutter, buffeting, and ultimately catastrophic failure. As described in Chapter 3, high aspect ratios and low structural weight fractions for HALE UAVs can lead to structural flexibility and potential problems with aeroelastic stability. The large displacements inherent in flexible structures can result in nonlinear aeroelasticity, which substantially complicates structural analysis and design.

Aeroelastic tailoring of composite structures could significantly reduce aeroelastic instability. Aeroelastic tailoring is accomplished using directional structural stiffness. Structural laminate tailoring has many potential benefits, including the potential to increase flutter speed and improve effectiveness. The location of the primary stiffness direction (i.e., the locus of points where the structure exhibits the greatest resistance to bending deformation) can be tailored by laying out stiffeners, ribs, or skin structures in a way that shifts the axis fore or aft of the conventional elastic axis. Although structures optimized for aeroelastic interactions may not represent the lightest weight or lowest cost configuration, the benefits to dynamic stability and control often outweigh these penalties.

Recommendation. As part of an integrated approach to vehicle configuration and structural design, the U.S. Air Force should conduct research to develop a fundamental understanding of design and analysis methods for aeroelastic tailoring of composite structures. This capability will be especially important for high-altitude, long-endurance configurations.

LOW-COST COMPONENTS

For more than 25 years, structural materials for military aircraft were selected and structural components were designed and fabricated to provide maximum performance with relatively little concern for the manufactured cost of the structures. Reductions in weapon acquisition budgets in the past decade have focused attention on the life-cycle costs (including acquisition, operational, maintenance, and disposal costs) of structural components. The need for low-cost aircraft and the differences in structural configurations and design criteria for UAVs should encourage the introduction of new structural concepts and innovative manufacturing processes. In addition to modular structural designs and reduced size and weight discussed in Chapter 2, advances in low-cost materials and processes will provide opportunities for reducing the cost of airframe structural components.

The implementation of innovative, low-cost manufacturing processes, along with consideration of manufacturing costs and sustainment throughout the design process, will be key to the development of cost-effective UAV airframes. Processes that reduce the number of parts, simplify tooling, reduce energy requirements, and minimize waste will be preferred. Complicating the need for low-cost processes is that production quantities for UAVs will be small. Therefore, primary criterion for the expanded use of polymeric composites in structural applications is the potential for low-cost manufacturing processes (NRC, 1996).

An important program is already under way to reduce the processing costs of high-performance composites for aircraft. The Composite Affordability Initiative (CAI) is jointly funded by the Air Force, the Navy, and industry (Boeing, Lockheed Martin, and Northrop Grumman). The objective of CAI is to "develop the tools, methodologies, and technologies necessary to design and manufacture a composite airframe utilizing revolutionary design and manufacturing practices to enable breakthrough reductions in cost, schedule, and weight" (DOD, 1999). CAI benefits government and industry by developing technology applicable to a variety of aircraft. The program includes (1) design integration, (2) design and manufacturing concepts, (3) fabrication technologies for unitized structures, (4) assembly processes for unitized structures, (5) development of performance standards for analysis methods, (6) element and subcomponent design and testing, (7) cost data, modeling, and analysis, (8) development of quality methods, (9) component scale-up and process validation, and (10) long-term technology development.

Analysis tools and design methodologies are being developed to automate and improve predictions of the characteristics of composite components so that designs can be less conservative and the excess weight associated with overdesign can be avoided. The CAI is investigating a range of innovative composite processes, including the following:

- fiber placement
- resin transfer molding (and vacuum-assisted resin transfer molding)
- low-temperature/vacuum bag curing
- through-thickness reinforcement (e.g., stitching/3-D weaving/Z pinning)
- electron beam curing

The low-cost, high-performance structures developed for CAI would be of particular interest for HSM-type vehicles.

Recommendation. The U.S. Air Force should monitor the progress of the Composites Affordability Initiative and conduct research to develop a fundamental understanding of processes with promise for UAV structures.

Although polymeric composite structures will dominate future UAVs, significant advances in the processing of high-performance metallic alloys will also be required. Although metallic structures will continue to be driven by traditional weight and durability considerations, cost is expected to become an even greater issue. Net-shape processing and integrated manufacturing techniques have the potential to reduce costs (Theibert and Semiatin, 1998). Promising processes for producing metal airframe structures in small quantities at reduced cost include the following:

- solid free-form fabrication
- superplastic extrusion
- spray forming

- electron-beam physical vapor deposition
- advanced sheet metal processes

Reducing the number of parts and lowering cost may also be aided by more common materials, processes, and design features.

Recommendation. The U.S. Air Force should conduct research to develop a fundamental understanding of metals processes applicable to UAV structures, such as research on low-cost processing of UAV airframe components.

Finally, for the low-cost vehicle type, the suite of airframe materials should be expanded beyond those used for conventional aircraft. For example, the MALD Program took a CAIV approach to design by trading off performance for cost reduction (Price, 1998). MALD is a small, inexpensive, modular vehicle that will replicate a jet aircraft kinematically and in terms of radar cross section on the battlefield. In addition to modular design and extensive use of existing commercial-off-the-shelf components, the MALD program used very low-cost materials and processes to meet its cost targets. A key manufacturing technology used by the MALD program was compression molding of sheet-molding compounds to produce discontinuously reinforced composite components. These materials and processes are similar to those widely used in the automotive industry.

The committee believes that very low-cost materials and processing can also be used for small, expendable UAVs, especially for components substructures, such as ribs and bulkheads, because of the shorter service life and lower reliability requirements of these UAVs. Materials and processes, such as aluminum casting, high-speed machining of integral metal structures, and compression molding of low-cost materials (e.g., automotive sheet molding compounds), should be considered.

Recommendation. The U.S. Air Force should expand the suite of materials and processes for use in small, low-cost vehicles to include very low-cost, commodity-grade materials that are not used in conventional aircraft constructions.

COMPUTATIONAL DESIGN PROCESSES

A number of analytic tools have been developed to model and simulate environments and reduce the amount of testing required to qualify structures for aerospace applications. These tools have shortened the design process and permitted more iteration during product development. However, extensive empirical testing and data reduction are still required to establish mechanical, chemical, and thermal properties and the effects of process variations. Basic research is still required to develop the fundamental effects of alloy composition and heat treatment for metals; and resin behavior, interface properties, and fiber chemistry for composites.

Modeling so far has been of little use for identifying new compositions. Although modeling at the first-principles level can provide useful information on thermodynamic stability and structure, many key aspects of materials cannot be adequately simulated. Modeling has had a significant impact on materials processing, however, where macroscopic predictions and trends have been useful for optimizing processes. Key barriers to implementation of computational tools include the following (Srolovitz, 1998):

- complexity of bridging between atomistic models and engineering components (which involves a variation of 22 orders of magnitude in time scales and 9 orders of magnitude in spatial scales)
- basis in principles versus experimental knowledge (i.e., heuristic materials models)
- model verification (because models will only be trusted if they have been verified)

The objective of process design is for a small team to be able to design and produce a quality product quickly and efficiently. Process design will enable teams to simulate processes and conduct cost trade-offs for materials and processes.

Recommendation. The U.S. Air Force should develop computational models for new materials and processes and apply them to UAVs.

HEALTH MONITORING AND HEALTH MANAGEMENT

Prognostics and health monitoring are being used today to assess air vehicle systems. Systems such as engines, auxiliary power units (APUs), computers, and avionics packages contain sensors and self-diagnostic software to evaluate their performance in real time. Onboard computing has increased significantly, and shared networks are technically feasible. For UAVs, diagnostic capabilities will have to be extended to the airframe structure to evaluate load cycles, damage conditions, corrosion, and fatigue.

UAVs that operate with minimal human intervention will require self-monitoring. UAVs that must function reliably after long-term storage will require a nervous system integral to the airplane, which will add both complexity and cost.

Sensors developed for one purpose can often be adapted to serve other sensory functions. In some cases, they can also serve as actuators. Low-cost UAVs will require materials and devices that can control smaller vehicles without using hydraulic systems. Smart structures technologies, such as piezoelectrics and neural networks, can improve load and health monitoring capabilities, as well as alleviate dynamic loads (Geng et al., 1994; Kim and Stubbs, 1995). Neural networks can potentially monitor many locations on an aircraft and reduce the number of sensors required. Piezoelectric-based health monitoring systems have been demonstrated in the laboratory for integrated damage detection of both metallic and composite structures (Lichtenwalner et al., 1997).

Along with a mix of sensors (e.g., accelerometers; pressure transducers; or piezoelectric sensors, actuators, or strain gages) that can sense the environment and determine desired vehicle response, an ideal system would be able to locate and assess damage rapidly on the ground or in the air.

Recommendation. The U.S. Air Force should develop improved health monitoring technologies that take advantage of recent advances in sensors, controls, and computational capabilities. Specific opportunities include the following:

- MEMS and mesoscale technologies for integrated sensor-actuation-control devices
- improved load and condition-monitoring capabilities that use piezoelectric sensors and neural networks for data analysis
- active flutter suppression and buffet load suppression systems that link condition-monitoring capabilities with piezoelectric transducers/actuators and intelligent controls

5

Propulsion Technologies

If the performance required of a UAV is similar to the performance of conventional aircraft, the propulsion system may also be similar. Many UAVs will weigh more than 1,000 pounds, fly at subsonic and supersonic velocities at altitudes below 60,000 feet, maneuver at 9*g*'s or less, and will be maintained in ways similar to current military or commercial aircraft. These UAVs will not require unique propulsion technology. Indeed, many new aircraft of all types are designed to use existing engines to avoid the time and expense of developing new engines. This chapter discusses UAV concepts that require new propulsion technology.

Some classes of UAV require new engine technology, new designs, or even new fundamental research and propulsion concepts. For example, a UCAV may require a gas turbine engine that can operate at much more than the 9*g* forces that limit manned vehicles. For high *g* loadings, the entire engine structure, especially the rotor support, will have to be reevaluated. An engine capable of maneuvering at 30*g*, for example, would require new design concepts that could require considerable engineering development but not new basic research. Nevertheless, for some UAVs, the propulsion system is a critical limiting technology. These include subsonic HALE aircraft that must operate above the altitude limits of current engine technologies; MAVs; and very low-cost, high-performance vehicles.

BACKGROUND

In addition to thrust, propulsion systems for modern aircraft must provide high fuel economy, low weight, small size (to limit drag), and extremely high reliability. The primary engine performance metrics are minimum total fuel burn (while meeting aircraft performance requirements) and reliability levels commensurate with permissible aircraft loss rate (1 per 10^8 departures for commercial aircraft). Many military missions also require stealth, which greatly affects engine design and installation. For all types of aircraft (including UAVs), engines and fuel typically account for 40 percent to 60 percent of gross takeoff weight, and the performance of the propulsion system has an enormous effect on air vehicle performance (Figure 5-1).

The gas turbine engine is vastly superior to alternative engines in all propulsion metrics. This high level of performance reflects the intrinsic merits of the concept and the \$50 billion to \$100 billion invested in gas turbine research and development over the past 50 years. The power-to-weight ratio of gas turbines is three to six times that of aircraft piston engines. The difference in reliability is even greater. The in-flight shutdown (IFSD) rate, a measure of reliability, for gas turbine engines in large commercial aircraft is 0.5 shutdowns for every 10^5 hours of flight. For single-engine military jet aircraft, the IFSD rate is 2 for every 10^5 hours. The IFSD rate for light aircraft piston engines is considerably worse, about 5 to 10 for every 10^5 hours. Although the IFSD statistics are not available for small piston engines in current UAVs, anecdotally, they are even higher. Gas turbines can also operate for long periods of times (4,000 to 8,000 hours) between overhauls, compared to 1,200 to 1,700 hours for aircraft piston engines. The small piston engines in current UAVs are replaced every 100 hours or less of service. The attractiveness of small piston engines is their low cost and the lack of availability of high-performance gas turbines in very small sizes. Alternative propulsion concepts may only be desirable when suitable gas turbines are not available.

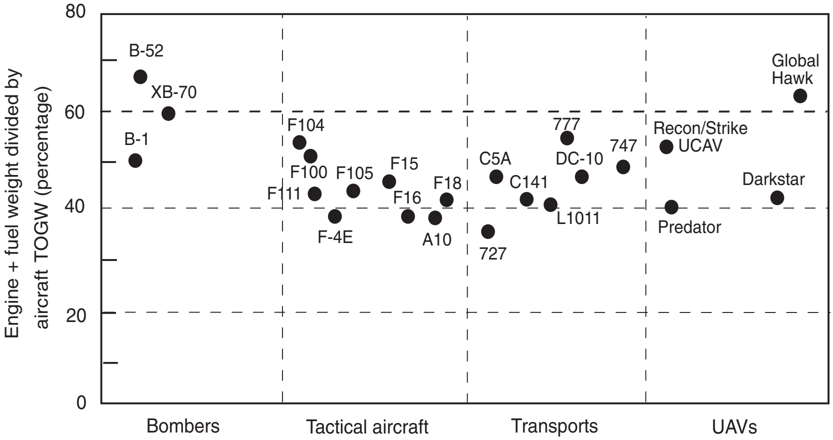


FIGURE 5-1 Propulsion system weight (engine plus fuel) as a percentage of aircraft takeoff gross weight (TOGW).

Both energy density and power density are important factors for propulsion systems. Energy density is a measure of the energy in the fuel and the conversion efficiency of the power converter (engine). Power density is a measure of the power converter. For example, the propulsion system weight of a long-range transport aircraft is dominated by the energy density of the fuel consumed (which may be 10 times the weight of the engines). In contrast, a solar-powered vehicle has zero fuel weight and, thus, very high energy density but low power density (the solar cells and power storage system are heavy). Figure 5-2 illustrates the range of power and energy densities for current UAVs.

Most air vehicles require about twice as much power for takeoff and climbing than for cruising. Therefore, the design of the propulsion system is a compromise between the weight of the engine (power-to-weight ratio) required for takeoff and the fuel weight required for cruising range (e.g., engine efficiency). The interactions between these factors for particular power system technologies will be discussed below.

Development cost has been a major factor for UAV propulsion systems in the past. The development of an all-new gas turbine engine for a tactical military aircraft can cost more than $1 billion, an inconceivable expense for the UAVs developed to date. Thus, the practice has been to adapt existing devices in a very budget-constrained, suboptimal manner, usually by sacrificing both performance and reliability. The cost of new technology, especially new concepts, will be as high for UAVs as it has been for conventional aircraft unless new ways for developing propulsion systems can be perfected.

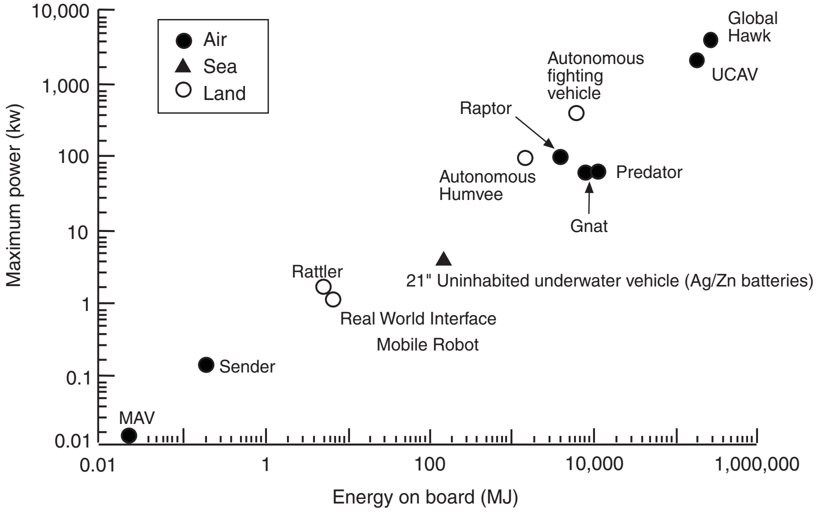


FIGURE 5-2 Characteristics of propulsion and power systems for UAVs.

BASIC RESEARCH

The range of UAV missions and applications is restricted by the lack of an adequate propulsion system. Missions that may be desirable but require the development of propulsion technology include very high-altitude (above 65,000 feet) vehicles, long-endurance reconnaissance/surveillance/communications relay vehicles, MAVs, and very low-cost, high-performance UCAVs.

High-Altitude, Long-Endurance UAVs

Substantial efforts are under way to develop propulsion technologies for HALE surveillance and communications-relay missions. The mission objectives for HALE UAVs are to operate at as high an altitude as possible to maximize the geographic coverage of sensors and communications. High altitude can also be an important contributor to survivability because high altitude reduces the aircraft's vulnerability to ground-to-air and air-to-air missiles. However, to be entirely safe from many widely deployed threats, operating altitudes must be above 75,000 or even 85,000 feet. These altitudes cannot be routinely reached with current propulsion technology.

At an altitude above 75,000 feet, there is very little air (the air density at 80,000 feet is only 3 percent of the density at sea level), which affects air-breathing fueled propulsion systems in two fundamental ways. First, engine weight is inherently higher. The fuel required to produce a unit of thrust per time is the same at high altitudes as it is at low altitudes, but the fuel-to-air ratio is fixed by the chemistry of combustion. As a result, the required mass flow rate of air is set by the power required.

Second, the large compression ratios required for gas turbines (additional compressor stages must be added), piston engines, and fuel cells (which require several stages of turbocharging) result in weight and drag penalties. The additional compression requirement significantly increases the weight of high-altitude propulsion systems. Because the compression process increases the temperature as well as the air pressure, the required pressure ratios result in temperatures that are too high for current technology. Thus, coolers (heat exchangers) must be added to the compression system. The weight and drag penalties of these heat exchangers are exacerbated by the very low ambient air density. High-altitude aircraft under development for NASA, which use piston engines, have more area and drag associated with heat exchangers than for the wings. The increased weight and drag of heat exchangers with altitude limit the operating altitude of these designs (Drela, 1996).

Areas for research include technology leading to low-weight, low-drag heat exchangers and low-weight, low Reynolds number, high-efficiency compression systems. These technologies will be important for both gas turbine and internal combustion engines, as well as for fuel cell systems (described below).

Propulsion approaches other than combustion engines have been proposed, notably fuel cells (Stedman, 1997) and solar power. Fuel-cell systems have the potential advantage of high energy densities but have relatively low power densities. Turbochargers and heat exchangers similar to those for piston engines would be required at high altitude. Unless fuel cells can operate on hydrogen (whose low density makes it difficult to integrate into an air vehicle), their complexity and weight quickly dominate the design. No liquid fuel systems are in routine operation today, and none has been designed for use in air vehicles. Fuel cells might be useful for very long-endurance missions for which fuel consumption is the dominant factor.

Because of the relatively low energy density of solar radiation, solar-powered aircraft must be extremely light and efficient, and they require exceptionally careful operation. Thus, they are probably only viable for niche military applications. The principal technology requirements for solar-powered aircraft are lighter, more efficient solar cell designs and compact, lightweight energy storage systems (for night operation).

Micro Air Vehicles

MAVs are currently defined by DARPA as having characteristic dimensions of less than 15 cm. This makes propulsion and power for MAVs very challenging indeed. A study was conducted by the Massachusetts Institute of Technology's Lincoln Laboratory on both the propulsion requirements and the technology options available to meet these requirements (Davis et al., 1996). Figure 5-3 illustrates how the amount of power required varies as a function of vehicle size for a class of conventional airplane configurations. In the figure, the flight power curve refers to the power (thrust times flight velocity) the vehicle requires for level flight. (Climbing and maneuvering may require 50 percent to 100 percent more power than level flight.) The flight power requirement is independent of the type of propulsion system. The shaft power curve in the figure refers to the mechanical power a motor must provide with a propeller propulsion system, regardless of the type of motor (e.g., electric, internal combustion, gas turbine). Assuming that the motor is electric, the electric power curve then represents the power that must be supplied by the source of electricity. Thus, vehicles of this type need on the order of 3 to 5 watts for cruising and 6 to 10 watts for climbing.

Conceptually, different propulsion systems have different relationships between motor weight and fuel weight, so the relative, overall mass of the propulsion system is a function of flight duration requirements. Figure 5-4 shows the trade-offs at the 50-watt level that would be required for some of the less power-efficient UAV concepts (e.g., hovering vehicles) (NRC, 1997b). Table 5-1 illustrates the propulsion system mass (including fuel where appropriate) to propel a vehicle with a takeoff weight of 50 grams for various flight times with different power systems (the only option that has been demonstrated is electrically driven

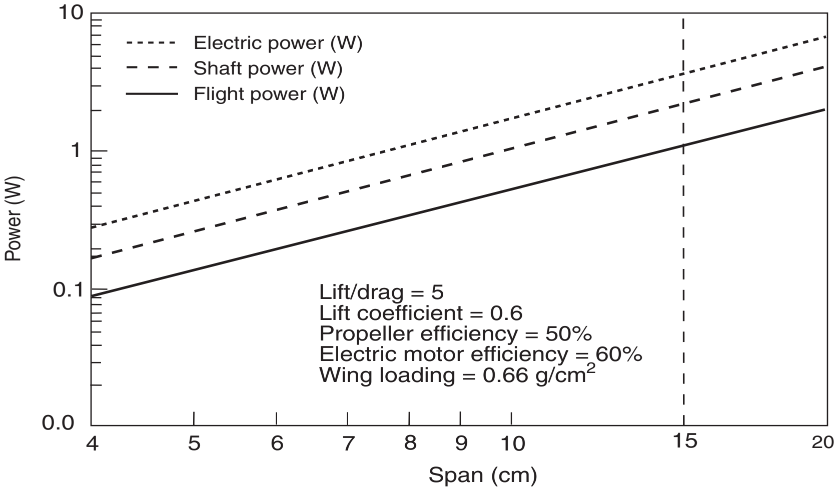
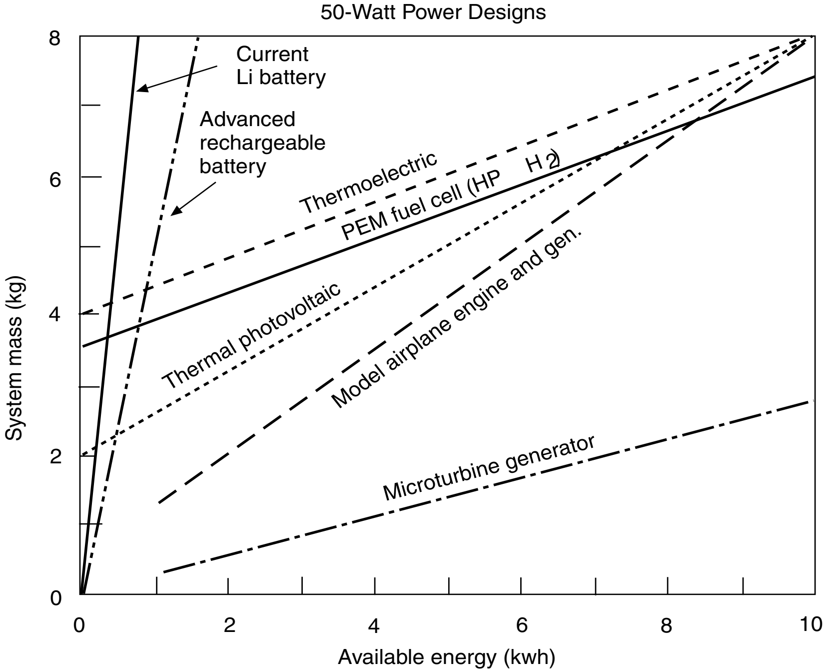


FIGURE 5-3 Typical power requirements for propeller-powered MAVs. Source: Massachusetts Institute of Technology, Lincoln Laboratory.

propellers). The nominal weight allowance for propulsion in the design is 36 grams; thus weights of more than 36 grams do not meet the specified flight times. The most attractive (lowest total weight) propulsion systems are air-breathing systems. The current DARPA MAV program is investigating four propulsion options: batteries, microdiesels, fuel cells, and micro gas turbines. The last three are projected to have about the same fuel consumption per unit power, but the micro gas turbine is considerably smaller and lighter.

Low-Cost, High-Performance UAVs

Reliable aircraft propulsion systems are expensive to develop, manufacture, and operate. Typical list prices range from $130 to $200 per pound of thrust for civilian engines and $200 to $400 per pound for military engines (civilian engine prices generally include amortization of the development costs; military engine prices do not). The price per pound increases as size is reduced because of relatively higher development costs and engine accessory costs (e.g., fuel pumps, controls, and electrical generators). Even "low-cost," short-lived (10-hour) cruise missile engines cost about $150 per pound. With current technology, an engine designer can trade off lower cost for lower performance by selecting less expensive materials and manufacturing approaches and reducing the number of parts. The most important question for many UAVs will be how to realize high performance while dramatically reducing costs, especially in the smaller engine sizes.



PEM = proton exchange membrane

FIGURE 5-4 System mass vs. energy for several advanced, small energy systems. Source: Massachusetts Institute of Technology, Lincoln Laboratory.

Significant cost reduction over the lowest cost with current technology will require advances in fluid mechanics, heat transfer, and materials technologies that emphasize cost instead of performance, which is traditionally emphasized. For example, increases in airfoil and end-wall boundary-layer loading can reduce the number of compressor and turbine stages, as well as the number of airfoils per stage. These increases might be realized through progress in passive (e.g., suction or casing treatment) or active (e.g., involving feedback) boundary-layer control.

Another example would be reducing the cost of hot sections (combustors and turbines) through the development of low-cost, high-temperature materials and coatings. An alternative approach would be to develop new cooling schemes that would reduce the cost of producing air-cooled parts. (A typical small engine may require drilling more than 100,000 cooling holes). Also, cooling is often less efficient in small engines because of limitations in manufacturing technology. Many fundamental problems with using vapor and liquid cooling approaches in engine environments will require basic research to be resolved.

TABLE 5-1 Total Propulsion System Mass for 50-Gram MAV

	Mass for 30-minute flight (in grams)	Mass for 60-minute flight (in grams)
Rocket (hydrogen-oxygen)	83	140
Pulse jet	45	80
Electric motor (0.38 W/gram, 60% efficient)		
Batteries	55	79
Solar[a]	35[a]	35[a]
Thermal photovoltaic[b]	25[b]	26[b]
Microturbine generator	20	24
Advanced fuel cell	25	31
Microfan jet	8	12
Internal combustion engine (5% efficient)		
Otto cycle	13	22
Diesel cycle	9	13

Note: Propulsion system design mass is 36 grams

[a] Solar panel size may exceed the available surface area.

[b] Excludes cooling drag.

Another major issue for engines of all sizes, but increasingly important as engine size is reduced, is leakage flows through the clearances between stationary and rotating parts. These leakages have a first-order impact on engine efficiency and operability. Engine complexity and costs are increased significantly by design features to reduce leakage. New technology and approaches for airfoils, end-wall flows, seals, and thermostructural interaction could reduce the impact of leakage. One example that has been tried is shape-memory alloys to control compressor blade clearances (Schetky et al., 1998).

Gas bearings are feasible in small sizes and are used in small turbomachinery, such as APUs. If gas bearings were used in small aircraft engines, they could reduce the complexity and cost of the bearing and lubrication systems.

Currently, most military engines are designed for specific applications; thus development costs for each new aircraft are substantial. One radical approach to reducing these costs would be to develop a miniature, high-performance, low-cost engine that could be grouped to provide greater thrust. This "one-size-fits-all" approach, however, is well beyond the state of the art and would require basic research. Existing technology can produce only miniature, low-performance, high-cost (per unit thrust) engines. In addition to the advances discussed above, the technologies for this new approach would include very small, low-cost accessories. MEMS could be an important element in miniature engines.

UNIQUE OR ENABLING APPLIED RESEARCH

Low-Cost, Storable, Limited-Life Propulsion Systems

As currently envisioned, propulsion systems for UAVs can be divided into two broad categories: (1) vehicles operated routinely in peacetime (e.g., high-altitude reconnaissance UAVs), and (2) vehicles used only in wartime, for which most, or even all, training will be done by simulation. Engines for the first category of UAVs will have conventional operations and maintenance requirements. But the requirements of store-in-peace/use-in-war vehicles will be closer to those of cruise missiles. These vehicles will require engineering solutions for subsystems, such as fuel and lubrication systems, that must be capable of unattended storage for years and very fast start-up.

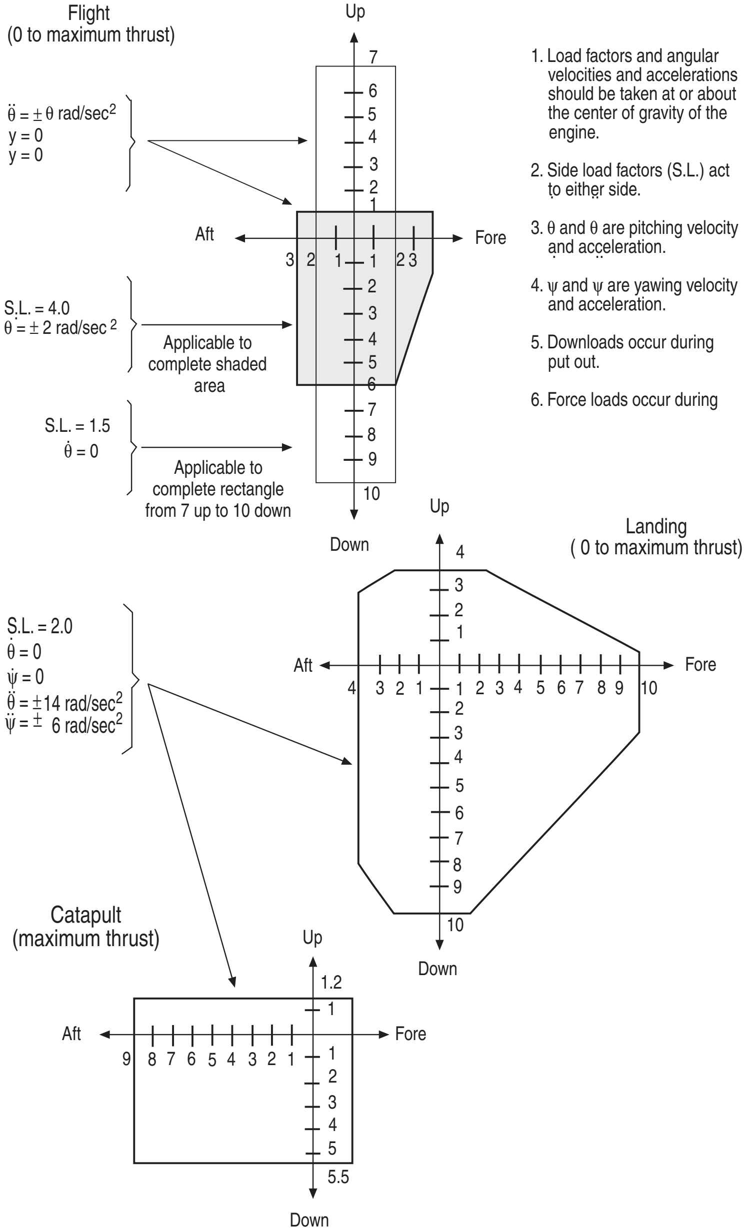
Traditionally, much of the profit for manufacturers of gas turbines has come from the sale of spare parts to replace parts consumed during military training. If vehicles are used only in wartime, manufacturers will have little or no opportunity to sell spare parts in peacetime (and thus no industry geared up to produce them), necessitating a different pricing structure for these engines. Therefore, although overall engine-related program costs might be reduced, costs would be shifted from the operations and maintenance budget to the procurement budget (i.e., the purchase price of engines would increase).

Engines are now nominally optimized for minimum life-cycle costs under the current market structure. A different life cycle can have different optimal conditions. For a given thrust, the optimum design for a 500-cycle engine life in a UCAV will be different than for a 4,000-cycle life (typical for a modern fighter) or for a 20,000-cycle life (for commercial aircraft). These differences will be apparent, for example, in the lower requirements for material creep life, maintenance, and survivability. The lower requirements might also be reflected in the selection of materials (for lower cost and weight), lighter weight structures (especially rotating parts), and less emphasis on aging and maintainability characteristics (e.g., thinner airfoils, more welds, and fewer bolted joints).

Technology for storable engines already exists for cruise missiles and smaller engine sizes (700-lb. thrust and below) with very limited lives (tens of hours). However, this technology has not been used for larger engines (more than 1,000-lb. thrust) with longer lives (500 hours), which are contemplated for UCAVs.

Propulsion for High-Speed, Highly-Maneuverable UAVs

Current engine designs accommodate steady inertial loads compatible with human life (nominally up to 9g's), as well as a capability to withstand additional impulsive loads from hard landings. (A typical military design requirement is illustrated in Figure 5-5.) If the maneuver envelope is increased for UCAVs, new



1. Load factors and angular velocities and accelerations should be taken at or about the center of gravity of the engine.
2. Side load factors (S.L.) act to either side.
3. $\dot{\theta}$ and $\ddot{\theta}$ are pitching velocity and acceleration.
4. ψ and ψ are yawing velocity and acceleration.
5. Downloads occur during put out.
6. Force loads occur during

FIGURE 5-5 Typical engine specifications for externally applied forces on takeoff, landing, and maneuvers.

designs would have to be developed to accommodate the significantly increased *g*-loads. Without design changes and/or technological innovations, the higher load requirements would translate into higher weights. Steady-state, inverted flight, for example, would require the development of new bearing lubrication schemes. Even without preliminary design and system studies, it is clear that stiff, lightweight structures; better fluid-sealing; and high-load, low-life bearings will be required.

SUMMARY OF RESEARCH NEEDS

Most research on propulsion systems will benefit UAV applications. However, focused research will be needed to develop some types of UAVs. The research topics are summarized in Table 5-2.

TABLE 5-2 UAV Propulsion Technologies

	Type of UAV		
	HALE	HSM	Very Low-Cost
General Topics			
High-altitude propulsion	E		
VTOL propulsion			E
Modeling	I	I	I
Cost reduction		I	I
Specific Topics			
Low Reynolds number turbomachinery	E		E
Low Reynolds number heat rejection	E		
Turbomachinery tip-clearance tolerance	I	E	E
Leakage desensitization		I	I
Thrust vectoring		I	I
Magnetic bearings	I	I	
Air bearings		I	I
Solid lubricated bearings		I	I
Low-cost accessories		E	I
Low-cost vapor and liquid cooling schemes		I	
Affordable high-temperature materials	I	I	I
Cooling for small engines		I	E

I = important
E = enabling

Recommendation. The U.S. Air Force should include research on propulsion systems for UAV applications in its long-term research program. The following general research topics should be included:

- high-altitude propulsion technologies, which may include gas turbines, internal combustion engines, solar-powered motors, or fuel cells
- propulsion systems for small, highly maneuverable vehicles, including vertical takeoff and landing (VTOL) capabilities
- computational modeling capability to reduce the need for engine testing during development
- cost-reducing technologies that, for example, reduce parts count and complexity

The following specific research topics should be considered:

- low Reynolds number turbomachinery, which is very important for both high-altitude operation and very small vehicles
- low Reynolds number heat rejection for high-altitude coolers and for cooling very small propulsion systems at lower altitudes
- turbomachinery tip-clearance desensitization (for highly loaded engines, high-altitude operation, and very small systems)
- desensitization to leakage and better, cheaper seals to reduce cost and enhance performance for highly maneuverable and very small vehicles
- thrust vectoring for highly maneuverable vehicles
- magnetic, air, and solid lubricated bearings to improve long-term storage, enhance high-altitude operation, and reduce complexity and cost
- technologies for low-cost accessories, which tend to dominate the cost of smaller engines
- low-cost vapor and liquid cooling schemes and affordable high-temperature materials (e.g., structural, magnetic, and electronic materials)
- more effective cooling technologies for small engines

6

Power and Related Technologies

Power generation aboard many classes of UAVs will be similar to power generation for conventional aircraft. The power system is driven by the main propulsion engines (so called “shared-shaft” power) or, in some cases, by an APU, which is a small gas turbine that drives nonpropulsion electric, hydraulic, or pneumatic loads on the ground or in flight. The situation for MAVs or HALE UAVs operating at extremely high altitudes may be different, however. For these vehicles, the propulsion system might not provide external power or may require electric power, or the required storage life of the power system might be longer than normal.

For typical aircraft, the electric or hydraulic power requirement is 100 to 1,000 times less than the power requirement for propulsion. Thus, excess propulsion power can easily be specified for these purposes at the design stage. However, the power requirements may not be realizable in practice because of other design constraints. Therefore, it would be wise to investigate alternatives to shared-shaft or APU power generation.

Unlike many other UAV subsystems, the power system interfaces with both the platform and the payloads. Depending on the mission, the payload will require electrical power from the UAV. This power demand may be a few tens or hundreds of watts for sensors or communications, or it may be tens of kilowatts or more for radar, jamming devices, or weapons. The committee did not attempt to explore the technology requirements to support this wide range of requirements but focused on the electrical power generation necessary for nominal housekeeping (or possibly, propulsion) power for the UAV platform.

In addition to electrical power, this chapter briefly discusses two related technologies—the thermal management system and actuators. Thermal management is often integrated into the power system because much of the thermal load is often generated by electrical devices. The operation of hydraulic system components and other actuators is also closely related to electrical system design requirements for peak versus average power.

BACKGROUND

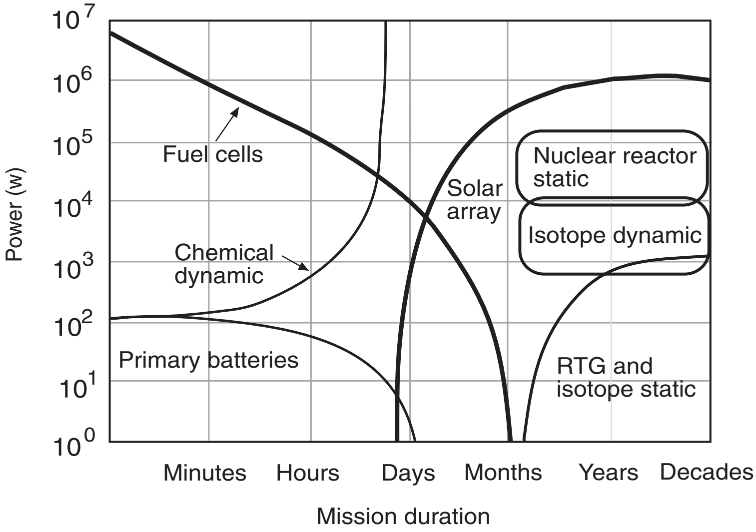
Much of the technology used in the design of conventional aircraft is directly applicable to UAVs. In fact, two Air Force programs, More Electric Aircraft and More Electric Engine, have advanced the state of the art for onboard power systems. This section reviews present technologies and identifies technology needs that could be addressed as part of a comprehensive UAV research program.

Electric Power System

The choice of an electric power system is dictated in large part by the mission requirements, specifically the amount of power required and the time over which the power is to be delivered (i.e., the total energy required). Although systems are usually described in terms of average power, the peak power can also determine the size of the overall system. (Peak power can often be accommodated through a power conditioning system.)

Figure 6-1 provides an overview of several options for a prime power source for a range of average power levels and flight durations. For modest loads and short flight times (minutes), batteries can provide hundreds of watts of power or more. Batteries are attractive because of their relatively low cost and modularity, especially at small sizes, but they have low power and energy densities compared to other alternatives. Fuel cells can provide power from hundreds of watts to hundreds of kilowatts. Because fuel cells have excellent efficiency, they may be an option for very long-endurance missions. However, fuel cells have not yet been developed for use in aircraft, and current fuel cell systems are relatively complex and require inconvenient fuels (e.g., hydrogen). At higher power levels, kilowatts to megawatts, conventional dynamic conversion systems, such as turbines or diesel generators, come into play. For extremely long operating times and modest loads, solar-battery systems might be applicable. Each of these alternatives is discussed below.

The prime power source is the first of several subsystems necessary to provide electrical power. The overall power system shown in Figure 6-2 reflects the many choices that are available. The selection of a prime power source will be determined by mission requirements and platform constraints. After the prime power source has been selected, the subsystems related to power conversion, power storage, and power management must be defined. The conversion process may be as simple as a battery or as complex as a gas turbine generator. Storage subsystems may be necessary for start-up, peak power, and transients. The power

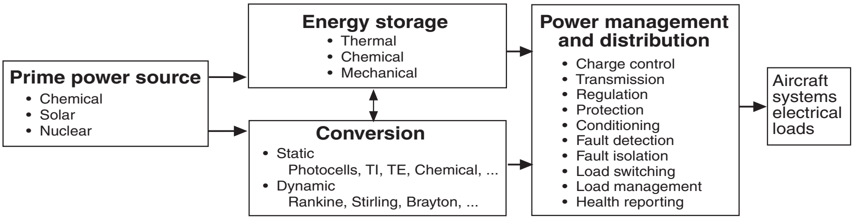


Note: RTG = radioisotope thermoelectric generator

FIGURE 6-1 Options for a prime power source for a range of average power levels and flight durations. Courtesy of A.K. Hyder.

management and distribution subsystem links the energy generation source to the energy storage elements and to the aircraft electrical loads. This management function involves regulation, distribution and control, and fault detection and isolation, as well as point-of-load power conditioning.

The technologies shown in Figure 6-2 have been used in the space program, and many advances in these technologies can be traced to the need for lightweight, low-volume, reliable electrical power aboard spacecraft. Some of the



Note: TI = thermionic
TE = thermoelectric.

FIGURE 6-2 Schematic representation of overall aircraft power system.

technologies have improved substantially, while others have changed little during the past decade or so. Table 6-1 shows the evolution of several key parameters for components and systems important to space operations, some of which are also applicable to UAVs.

As shown in Table 6-1, a key consideration in the selection of a power source is specific power (power per unit mass). The specific power of space-based technologies is compared with a broader selection of power sources in Figure 6-3. For automobile engines, large aircraft engines, and other applications for which power system mass is not a critical constraint, very high specific power can be realized. In the case of HALE UAVs or MAVs, the choices are considerably more limited.

Related Systems

Thermal Management

Thermal management remains a serious design function onboard all aircraft, including UAVs. Current avionics cooling systems provide a cooling capacity of about 50 W/cm^2 of avionics-system surface area. In the constrained volume of a UAV, and with a possible increase in avionics density for autonomous operation, cooling designs with perhaps five times that capacity may be needed.

Thermal management onboard current aircraft often involves a circulating liquid cooling system that collects heat from distributed loads and then rejects it to the fuel or to a liquid-air heat exchanger, cooled by ram (engine inlet) air. Some UAVs will certainly employ the same techniques. To reduce cost and complexity, however, advanced UAVs may employ a more integrated design that involves the vehicle structure, which could be used as a heat sink. Materials with poor thermal conductivity (e.g., composites) may be set aside in some areas in favor of materials with high thermal conductivity (e.g., aluminum) even though there may be a mass penalty from a structural perspective. Heat pipes might also be used, and endothermic fuels could be used to increase fuel heat sink capability. Batteries with less than optimal energy density could be selected if their chemical activity is endothermic. Thermal management is a systemwide issue.

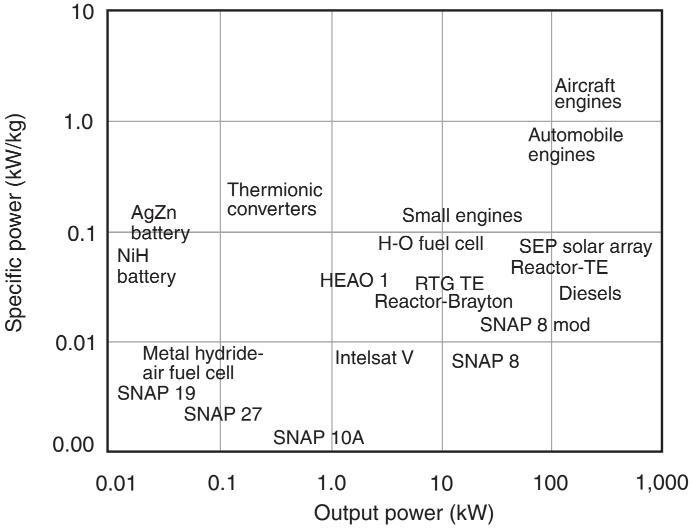
Actuators

Traditional hydraulic systems will not be used in most future UAVs because these systems represent a substantial vehicle weight penalty, reduce available volume for payloads, and increase vehicle complexity and production costs. Aircraft electromagnetic actuators (EMAs) could be the best alternative to hydraulic actuation for vehicle control. Although EMAs have increased in power and can reduce overall system weight, complexity, and cost, current EMA technology may not be able to meet all UAV needs, especially for MAVs. Higher torque,

TABLE 6-1 Key Parameters for Space Power Components and Systems Applicable to UAVs

System or Component	Parameter	Circa 1985	Estimated 2000
Solar array-battery system	System power output	5 kW	100 kW
	System specific power	10 W/kg	50 W/kg
	System specific cost	$3,000 /W	$1,000 /W
	Cell efficiency	14%	25%
	Array specific power	35 W/kg	150 W/kg
	Array design life	5 yr. LEO 7 yr. GEO	10 yr. LEO 15 yr. GEO
	Array specific cost	$500 /W	$500 /W
Battery			
Primary			
AgZn	Specific energy	100 W-hr/kg	125 W-hr/kg
	Design life	30 days	1 yr
Li-$SOCl_2$	Specific energy	150 W-hr/kg	700 W-hr/kg
	Design life	10 yr	10 yr
Secondary			
NiCd	Specific energy (LEO)	25–30 W-hr/kg	30 W-hr/kg
	Specific energy (GEO)	25–30 W-hr/kg	30 W-hr/kg
	Design life (LEO)	5 yr	10 yr
	Design life (GEO)	7 yr	15 yr
NiH_2	Specific energy (LEO)	40 W-hr/kg	50 W-hr/kg
	Specific energy (GEO)	40 W-hr/kg	50 W-hr/kg
	Design life (LEO)	5 yr	10 yr
	Design life (GEO)	5 yr	7 yr
Li-ion	Specific energy (LEO)	100 W-hr/kg	125 W-hr/kg
	Specific energy (GEO)	100 W-hr/kg	125 W-hr/kg
	Design life	1 yr	5 yr
Primary Fuel Cell	Power load	7 kW	50 kW
	Specific power	100 W/kg	150 kW/kg
	Specific cost	$40/W	$25/W
	Design life	2,000 hrs	4,000 hrs
Nuclear Power			
Reactor	Level	10 kW	10 kW
	Specific power	10 W/kg	10 W/kg
	Efficiency	10%	10%
RTG	Power level	2 kW	2 kW
	Specific power	6 W/kg	10 W/kg
	Efficiency	8%	12%

Note: GEO = geostationary or geosynchronous earth orbit
LEO = low earth orbit
RTG = radioisotope thermoelectric generator



Note: RTG = radioisotope thermoelectric generator; SEP = solar electric propulsion; SNAP = system for nuclear auxiliary power (a space nuclear reactor system; only SNAP-10-A was launched); TE = thermoelectric

FIGURE 6-3 Comparisons of specific power of space-based technologies with a broad range of power outputs.

lower mass, and lower power EMAs will be required. Hybrid electric-hydraulic actuators may be a near-term solution for UAVs that require very high power. Current programs at DARPA, including the Compact Hybrid Actuation Program, are exploring the development of EMAs and devices using smart-materials transduction elements, including piezoelectrics, electrostrictives, magnetostrictives, and shape memory alloys.

TECHNOLOGY NEEDS

For conventional UAV missions, electric power and related systems will not be critical or enabling for the next decade, although advances in the state of the art would certainly improve UAV performance. For MAVs and HALE UAVs, many of which are electrically powered, power generation is a pacing technology.

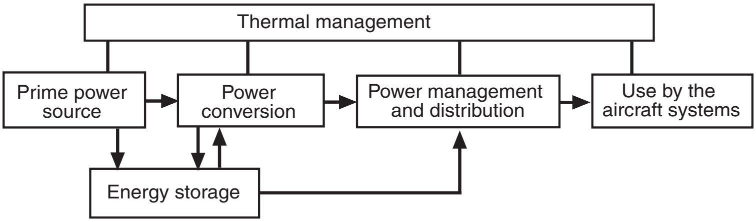


FIGURE 6-4 Electrical power system and primary subsystems.

Electrical Power System

The design of the electrical power system and its primary subsystems (see Figure 6-4) will involve trade-offs among several interacting technologies that can be used for power generation (prime power, energy storage, and power conversion [see Table 6-2]).

Prime Power Sources

Improvements in current integrated power-propulsion (shared-shaft) systems should lead to generators and power-conditioning equipment with higher efficiency, lower weight, and lower cost. APUs are an attractive alternative to shared-shaft systems in some cases, but many UAVs would require much smaller APUs than are currently being manufactured. The challenge will be to preserve performance, weight, and cost advantages in small-scale designs. Relevant technologies will include low Reynolds number turbomachinery, air bearings, and small heat exchangers.

MEMS are micron-scale to millimeter-scale machinery often constructed with semiconductor fabrication techniques. Initial development was concentrated on microsensors and actuators, but current research is being done on MEMS heat engines and electric generators, which could serve as very small APUs (Epstein and Senturia, 1997). Millimeter-diameter to centimeter-diameter gas turbine generators are under development, and initial design goals are 10 to 20 watts of power. Later developments may produce as much as 100 watts in a button-sized unit operating at sea level. Running on hydrocarbon fuels, these devices would have 10 to 30 times the power and energy density of state-of-the-art batteries. If they are produced in large numbers, the cost per unit power might be competitive with large power generators and batteries. In UAVs, MEMS power systems could be part of low-weight, modular, distributed, highly redundant power generators. From a systems perspective, MEMS would greatly reduce the need for a vehicle-wide power-management and distribution subsystem.

TABLE 6-2 Trade-offs among Interacting Technologies for Power Generation

Input Energy	Output Energy				
	Electricity	Heat	Chemical	Photons	Kinetic
Electricity	Superconducting magnets Inductors Capacitors	Ohmic heaters Heat pumps	Electrolysis Ionization and recombination	LEDs Discharges Light bulbs Lasers and transistors Microwaves	Flywheels JxB (magnetic flux) thrusters Motors
Heat	Thermoelectrics Thermionics Generators Fuel cells	Phase-change materials Chemical reactions High C_p materials	Thermochemical Electrolysis	Radiators	All thermodynamic cycles
Chemical	Fuel cells Capacitors Batteries	Combustors	Propellants Explosives	Chemical lasers	Rocket exhaust Gas turbines
Photons	Photovoltaic cells	Thermal concentrators Thermal absorbers	Photolysis Electrolysis	Resonant cavities Metastable atoms	Radiometers
Kinetic	MHD, comparators, generators	Friction	Impact ionization	Triboluminescence	Flywheels

Note: C_p = heat capacity
MHD = magnetohydrodynamic

Air-driven generators, like MEMS generators, could also be distributed around a UAV to provide spot power, but issues of aerodynamic integration, signature, and overall system benefit will first have to be resolved.

If fuel cells can operate with propulsion fuels—or propulsion systems can operate on hydrogen—power and propulsion systems could use the same fuel storage and distribution system. Research will be necessary for either approach, either to develop fuel cell technology compatible with propulsion fuels or to develop ways of efficiently storing, distributing, and releasing hydrogen at room temperature. Research related to hydrogen storage and distribution could also be used in a number of applications other than UAVs.

Although beamed energy could conceivably be used to power a UAV in a few scenarios, a wide range of issues must be resolved before this could be considered a realistic technology. Important unresolved issues include safety, operations, pointing, tracking, high-power beam handling, and target signatures. Beamed energy is, at best, a long-term research prospect.

Energy Storage

The availability of secondary batteries with improved energy densities and long shelf lives in the charged state would be useful for weight-constrained UAVs. Batteries with very high specific power and, in the case of primary batteries, a long shelf life could be used for limited-life MAVs by providing propulsion power, as well as housekeeping power. Battery research is being actively pursued by DOD.

Fuel cell research is also under way in support of many non-UAV applications, including the space program. The UAV design community would benefit from general advances in fuel-cell technology because the requirements for UAV applications are not unique. The USAF should closely monitor the development of new fuel cell designs that could lead to significantly higher specific energy (e.g., titanium plates in H_2–O_2 regenerative fuel cells).

Dynamic conversion processes, such as turbines or diesel generators, are clearly options for UAVs at higher power levels. These could be conventionally sized as central power units or distributed using MEMS technology.

Power Management and Distribution

UAV requirements for power management are similar to those for conventional aircraft. However, UAV systems, like spacecraft systems, must demonstrate a high degree of autonomy and, hence, robustness. Also, power conditioning is a particular concern for MAVs for which the lack of very compact, lightweight power conditioners is a major design constraint.

The mass of the power distribution subsystem could be greatly reduced through a distributed generation system of microgenerators, but only if their efficiency is comparable to larger power generation systems. The power management function will require sophisticated control systems that will not be unique to UAVs and can be expected to be available in the normal evolution of control technology.

Related Systems

Thermal Management Systems

Denser packaging of avionics and propulsion systems will place a premium on thermal management designs. Increasing the use of composites in UAV structures could make it significantly more difficult to transfer heat from the interior of the aircraft. Also, active cooling will probably be avoided whenever possible to minimize system complexity, mass, and power requirements. Research into microchannel plates and compliant diamond-film heat spreaders could lead to more efficient heat exchangers for cooling densely packed electronics.

One way to attack the thermal management issue is to reduce the amount of heat generated. Although this may not be possible with turbines or airfoil surfaces in high-speed vehicles, it will be possible with avionics packages by developing more efficient, lower power electronics. Extremely low-power electronics and high-efficiency electrical subsystems would also reduce overall power requirements.

Research into endothermic battery couples, which cool during operation, is another possible approach for using the design of the electrical system to enhance thermal management. Similarly, UAVs could also benefit from the development of fuels with increased heat capacities (a follow-on to JP-8+100),[1] which could be used as heat sinks.

Actuators

Hydraulic lines are likely to be replaced with EMAs. Research will be necessary to develop EMAs with higher torque, higher efficiency, and lower weight, especially for MAVs.

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[1] JP-8+100 is a JP-8 fuel with antioxidant additives. The "+100" denotes an increase in the upper temperature limit for the fuel at the combustor nozzles from 325°F to 425°F (Heneghan et al., 1996).

OPPORTUNITIES FOR FUNDAMENTAL RESEARCH

Finding. No fundamental research issues related to the generation of power aboard UAVs would have to be resolved to enable generation-after-next vehicles.

Although continued development of many prime power technologies would enhance UAV capabilities, most of these technologies will evolve with little or no intervention from the UAV community. Possible exceptions to this are specialized technologies for producing solar-powered HALE UAVs and air-driven or combustion-driven microgenerators that would distribute the power generation function throughout a UAV. The latter technology could be particularly useful in the design of MAVs.

7

Control Technologies

Beyond the differences in materials, structures, propulsion, and aerodynamic design, the single fundamental feature that most distinguishes UAVs from other aerial vehicles is control. UAVs rely more heavily on autonomous internal machine and remote links to humans than other systems. The utility, effectiveness, and acceptance of UAVs will depend on the exploitation of the capabilities, and recognition of the limitations, of control technologies.

The word *control* is used here to cover the entire gamut of automation, from inner-loop feedback servos to dynamic alterations of mission strategies in response to near-real-time surveillance of the consequences of past strategic actions. The committee envisions that UAVs will operate in integrated scenarios (Figure 7-1) involving several vehicles with specified missions to be accomplished by the collective; with communication links among vehicles and between vehicles and with remote human-operated control sites (perhaps in the local area, perhaps continents away); and with onboard and off-board sensing, actuation, and information processing capabilities to conduct vehicle and payload operations with a high degree of autonomy.

These integrated scenarios are not futuristic. Similar scenarios are used today in various applications at different levels of sophistication. However, automating real engineering systems in the absence of strong supporting scientific knowledge often creates problems. The challenge is to increase this knowledge so that designing complex autonomous systems becomes routine—that is, the integrated designs will be capable, reliable, trustworthy, and affordable.

Although research and development will be necessary for all of the elements illustrated in Figure 7-1, this report focuses on the four areas that present the most compelling case for USAF-supported basic research:

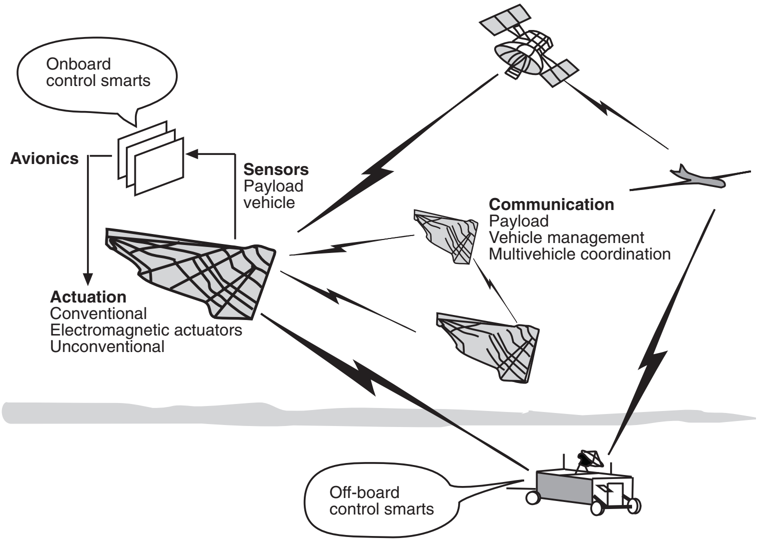

FIGURE 7-1 Integrated UAV control scenario.

- built-in intelligence, or control “smarts,” designed into system architectures and into onboard and off-board processing elements
- the allocation of tasks and construction of interfaces between humans and capable machines
- the capacity, security, and robustness built into communications links
- specialty sensors and actuators, especially MEMS devices, to support some of the unconventional aerodynamics described in Chapter 3

Although other elements in Figure 7-1 are also critically important to the overall UAV system, the committee believes less compelling cases can be made for USAF basic research in these areas. For example, the development of onboard and off-board hardware and software technologies for information processing, storage, and display is being driven by the commercial marketplace, and USAF investments will generally have only a small effect. Similarly, conventional actuators, such as hydraulic actuators and EMAs, require more support for engineering development and manufacture than for basic research. Finally, the payload requirements are very specific to the devices in question (e.g., radar, electro-optical and infrared sensors, communication repeaters, and weapons), and research support for them would be more appropriately provided by the relevant scientific and engineering subspecialties.

The subsections briefly describe the committee’s findings regarding current capabilities, identify basic research needs, and recommend specific research by the USAF.

BUILT-IN INTELLIGENCE OR CONTROL "SMARTS"

In considering technology related to built-in intelligence, the committee benefited from the groundwork laid at an AFOSR-sponsored Workshop on Research Needs in Dynamics and Control for UAVs held in August 1997 at the University of California-Los Angeles. The discussions, findings, and recommendations that follow are based on the results of that workshop.

The discussions at the AFOSR workshop were structured around a well defined functional hierarchy of vehicle control systems (illustrated in Figure 7-2). This hierarchy is used in manned vehicles today and is expected to remain essentially the same for UAVs and UAV systems well into the future. Hence, it can be considered a "fixed point" around which current capabilities and their evolution can be described.

The hierarchy in Figure 7-2 includes three layers of control for collections of vehicles. The first and lowest layer consists of each vehicle's *inner-loop* flight control functions; the second consists of each vehicle's *vehicle-management* functions; the third and highest layer consists of the *mission-management* function, which bridges the entire collection of vehicles. In the UAV systems envisioned today, the inner-loop and vehicle-management layers are typically implemented onboard each vehicle, and the mission-management layer, in whole or in part, is implemented off board.

A sublayer of the inner loop might be called *local control*. On conventional aircraft, this sublayer includes engine controls and actuator servos—tight local regulation of specific aircraft components. For future UAVs, local control would also include the local loops associated with flow control, drag reduction, and other aerodynamic manipulations (described in Chapter 3).

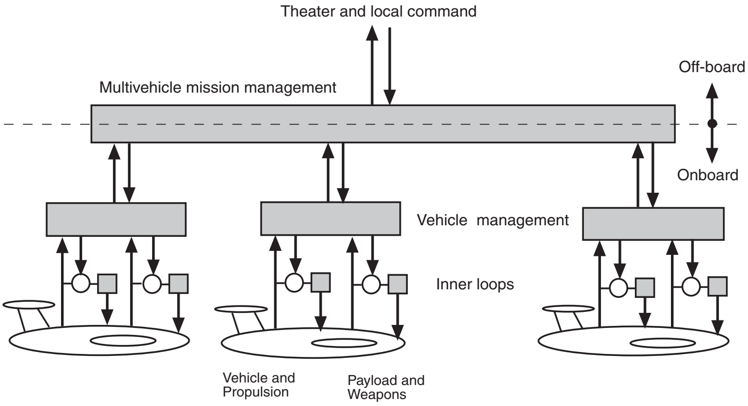

FIGURE 7-2 Functional hierarchy of vehicle control systems.

Inner-Loop Layer

Among the three major layers of the hierarchy, automatic control is most firmly established in the inner-loop layer. The basic function of the inner loop is to ensure vehicle stability and to establish and maintain desired flight parameters or execute specific flight phases, as commanded by the vehicle-management layer. Common control modes include following acceleration/rate command, maintaining altitude/speed/heading, automatic take-off/landing, flight to waypoints, and tracking trajectory. Automated systems routinely execute each of these functions on aircraft today, and the same functions must be accomplished by automation and/or remote control in UAVs.

Although the state of the art of control design for the various inner-loop modes is well advanced, the design of control systems for UAVs involves different design rules and is generally more difficult than for conventional aircraft. The current state of the art includes the basic techniques of robust multivariable control theory for linear systems combined with gain-scheduling and optimization, feedback linearization/dynamic inversion for nonlinear systems with invertible nonlinearities, and various special approaches (e.g., nonlinear filters, antiwindup, and bumpless transfer logic) for other cases. Although these techniques can be applied to the inner loops of UAVs, the very nature of UAVs changes the design problem. The absence of onboard manual controls eliminates the requirements related to quality of handling and pilot comfort that are enshrined in current military flight-control specifications. Instead, control systems can be focused solely on meeting mission needs within vehicle constraints. In addition, UAVs will be operated more aggressively than their manned counterparts, closer to authority limits of actuation and closer to the physical limits of airframes that will often be deliberately lightweight and flexible. Finally, the drive for affordability and short design cycles that underlies much of the interest in UAVs will call for changes in today's design practice, forcing increased use of automation in modeling, simulation, control law design, implementation on integrated digital hardware, verification, and testing. Increased reusability will also be important.

Recommendation. In light of the special factors driving the design of UAVs, the U.S. Air Force should strengthen its support for basic research programs addressing the rapid (automated) design and implementation of high-performance control laws. Areas of interest include basic theory for nonlinear and adaptive control, reusable control law structures and processes capable of full-envelope design, software tools for automated control design and analysis, automated code generation from high-level design tools, and simulation models with sufficient fidelity for affordable tests and verifications.

Vehicle-Management Layer

The function of the vehicle-management layer of the hierarchy is to manage onboard vehicle operations and to carry out commands from the mission manager. This includes managing the vehicle's mission time line (i.e., commanding all flight phases to the inner loops in proper sequence—from power-up through taxi, takeoff, ingress, mission phase flight, egress, landing, and return-to-the-ground support facility); establishing proper operating modes, component configurations, and resources (e.g., aero configuration, gear, sensors, actuators, fuel, and center of gravity) for each mission segment; monitoring vehicle health; and handling contingencies (e.g., changes in onboard status, mission parameters, and environmental conditions).

Although some automatic controls are used today to carry out vehicle-management functions, control methods are based largely on engineering heuristics and not on basic supporting scientific knowledge. The current design practice is to examine nominal operations and their contingencies in detail, determine appropriate vehicle-manager actions, and then program those actions as "if-then-else" rules in vehicle-management computers. Computer science techniques (e.g., expert systems, formal logic, and verification proofs) are used to improve the programming aspects of this process, but the initial specifications for each vehicle-manager action is still the responsibility of "domain experts."

The committee endorses the conclusion of the 1997 AFOSR workshop that research is needed to

> ...devise ways to formalize the generation of actions on the basis of underlying continuous dynamics of vehicles (synthesis), and also to devise ways to verify these actions such that all contingencies are covered and no undesired properties appear in any possible combinations of states (analysis). As in standard control theory, analysis improvements will probably precede synthesis. Examples of efforts to formalize these design steps can be found in the work on intelligent vehicle highway systems (Stein et al., 1997).

Recommendation. The U.S. Air Force should pursue basic research to provide scientific support for robust vehicle-management functionality.

Mission-Management Layer

The function of the mission-management layer, the highest layer of the control hierarchy, is to plan, rehearse, and execute missions assigned to collections of vehicles. This includes time lines for vehicle ground preparations, ingress trajectories, on-station operations (e.g., trajectories and attack patterns), evasion tactics, response to attrition, deconfliction, replanning, egress trajectories, and the evaluation of mission performance.

Mission management encompasses a very challenging set of functions, and science today provides little formal knowledge to help with the design of automated mission-management systems. In current practice, war-fighters and planners carry out most mission-management tasks, relying on the results of past engagements, exercises, training, and well practiced tactics and maneuvers, all informed by established doctrine. Their work is partly manual and partly aided by workstation-based planning tools to expedite data access and visualization and to help iterate and optimize specific tasks.

This situation (i.e., mission management based more on human insight and experience than on scientific principles) is unlikely to undergo a revolution in the next two decades. Nevertheless, the USAF can encourage evolutionary advances in the state of the art by supporting basic research in human-machine science (discussed in Chapter 2) and supporting the development of specific capabilities that will make current design tools and planning aids much more powerful.

Real-time path planning and optimization should be a core competency of organizations that design and manufacture controls that apply to the mission management layer of the UAV control hierarchy.

> Issues that need to be addressed include effects of vehicle attitude and trajectory on radar cross section and susceptibility to jamming, constraints on trajectory due to vehicle dynamics, stationary threats (e.g., fixed radars and jammers), variable numbers of dynamic threats (e.g., mobile radars and jammers), collision avoidance, vehicle and threat modeling, and computational requirements (Stein et al., 1997).

Control of dynamic networks offers a formal way of addressing a key application of some types of UAVs—that they will often be used in coordinated clusters rather than as independent platforms.

> ... this scenario can be described as a dynamic network where each node is a UAV. A dynamic network is characterized by a spatially distributed set of dynamic nodes which are coordinated (or integrated) by the mission objectives and possible dynamic coupling between the nodes. The mission objectives are to be obtained in the presence of large uncertainties due largely to a hostile environment. Within this context, nodes may fail at various levels, measurements may be highly corrupted and communication channels may be severely limited due to jamming. Communication links are further challenged due to power constraints and spatial dispersion producing tradeoffs between noisy information, latency, and bandwidth constraints. For this class of problems current mathematical paradigms break down and focused research is required for new paradigms (Stein et al., 1997).

Recommendation. The U.S. Air Force should enhance the capabilities of available design tools and planning aids by supporting ongoing efforts related to real-time path planning and optimization algorithms, and by embarking on a program of basic research in control of dynamic networks.

Management of Uncertainty

Driven by the prime motivators of risk avoidance and cost reduction, UAVs will make increasing use of modeling and simulation to shorten design and production cycles and to reduce operating costs. Expressed in current jargon, UAVs will increasingly rely on virtual engineering, a process in which prototyping, evaluation, and testing are done with simulated versions of objects instead of real-world (hardware) versions. Although virtual engineering has the potential to reduce cost and cycle times substantially, it also raises serious concerns about the fidelity of models and their inherent uncertainties. This concern is illustrated schematically in Figure 7-3. Figure 7-3(a) shows a traditional design sequence involving tight iterations of testing and redesign. Like any well designed, high-gain feedback loop, these iterations allow the modeling, design, and build steps of the sequence to be relatively imprecise because the testing and evaluation step with real-world objects will provide corrections. However, to obtain a satisfactory product, the sequence must be cycled repeatedly, which consumes time and resources and greatly increases the incentive for performing the same sequence in a virtual (simulated) environment.

The process illustrated in Figure 7-3(b) will only be successful if reducing the virtual error, which the virtual design loop will surely do, also reduces the real error. Unfortunately, many sources of real error, from the intrinsic variability of the real world being modeled to the multitude of assumptions and approximations introduced in the modeling and simulation steps, cannot currently be accounted for formally and explicitly (so-called uncertainty management).

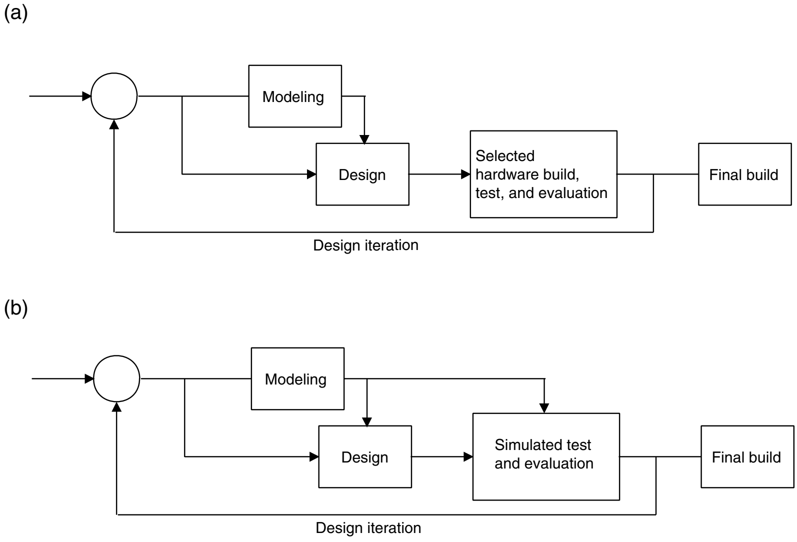

FIGURE 7-3 Comparison of (a) traditional engineering design process with (b) virtual engineering design process.

> ... a critical need in the new virtual paradigm is for systematic and explicit methods to represent and propagate uncertainty throughout the modeling and design steps. This is a major challenge to achieve fully, but there are many incremental gains along the way that will help to avoid major failures or disasters and to ensure the acceptance of the real paradigm shift needed. Research issues include (1) propagating uncertainty in models from component materials and geometry through system performance/cost/risk, (2) designing complex systems to operate in the presence of significant uncertainties in the environment as well as uncertainties in system components (using concepts such as averaging, protocols, and feedback), and (3) using model-based assessments of sensitivities to augment virtual prototyping with selected physical prototyping of components whose uncertainty descriptions are most critical (Stein et al., 1997).

Recommendation. Motivated by the urgent need for a better understanding of the role of uncertainty in virtual engineering, the U.S. Air Force should establish a basic research program in uncertainty management.

SENSORS AND ACTUATORS

Sensors and actuators are essential for aircraft operation. Global positioning system (GPS) receivers and/or gyroscopes are often used for guidance, and sensors for speed, roll, pitch, and yaw are used to control aircraft motion. Control surfaces provide aerodynamic forces and moments for aircraft maneuvering. Actuators are commonly used for moving control surfaces or for engine controls. Surveillance information can be gathered by radar, cameras, or various other sensors.

Minimizing weight and volume are important aircraft design criteria for sensors, actuators, and other subsystems. Weight and volume constraints are even more stringent for UAVs because of their size and payload limitations. Emerging MEMS technology can provide transducers as small as tens to hundreds of microns (NRC, 1997c). The weight and volume of MEMS transducers are practically negligible when compared with traditional devices. In addition, integrating microtransducers with complementary metal oxide semiconductor (CMOS) electronic circuitry to create an integrated system capable of sensing, analyzing, and actuating would be cost effective. This capability would enable many innovative uses for MEMS-based transducers, including many uses relevant to future military UAVs. For example, by applying a distributed transducer network to structural controls to enable strength-on-demand operations, a considerable reduction in structural weight would become feasible (Chase et al., 1997). Using MEMS transducers to manipulate the aerodynamic forces and moments could also have a great impact on the aerodynamic performance of UAVs (see Chapter 3). Potential flow control techniques include separation control and riblets for drag reduction.

In addition to satisfying payload limitations, UAV-specific transducers would enable remote operators and onboard autonomous systems to maintain situational awareness. For example, a collision-avoidance sensor will be essential for small

UAVs traveling around trees and buildings. In addition, UAV-compatible biological, chemical, and nuclear sensors could expand UAV operations to nontraditional missions that would be too hazardous for piloted aircraft.

MEMS-based sensors have several unique characteristics:

- very small size
- ability to distribute a large number of sensors into an array
- ability to integrate directly with integrated circuits

These characteristics can lead to new dimensions in the performance of sensors with aircraft applications.

Inertial Sensors

MEMS-based accelerometers are already well developed. A single sensor can provide a dynamic range of 84 dB. With an array of sensors, each covering a different range, the total dynamic range can be extended for a wide spectrum of applications. It is already possible to integrate three-axis accelerometers with on-chip analog-to-digital conversion and sensitivity enhancement circuits (Allen et al., 1998). However, research is still needed to develop microgyros suitable for UAV navigation. In the very near future, the drift rate of microgyros will be reduced to about 1 degree per hour, but this is still far greater than navigational requirements for UAVs.

Aerodynamic Sensors

During the development stage, UAVs will require various flow sensors to support wind-tunnel tests. Microsensors could be used extensively on small wind-tunnel models to replace traditional sensors, which are extremely expensive.

A full line of micro-flow sensors for measuring pressure, shear stress, temperature, and heat flux has already been developed (Ho and Tai, 1998), and some have been flight tested. Additional research is needed to develop packaging and interconnecting techniques for flight applications.

Structural Sensors

Micro-strain gages were one of the first kinds of microsensors developed for structural applications. Arrays with a large number of micro-strain gages can be made easily. For health monitoring, these microsensors would be distributed around the whole aircraft; the signal path would also have to cover the whole aircraft. A low-cost packaging technique to distribute microsensors on a macro scale is the remaining outstanding challenge.

Surveillance Sensors

Current biological and chemical sensors are bulky and heavy and require experienced technicians to operate them. Several MEMS-based biological and chemical warfare sensors under development that could be packaged in a container the size of a shoe box could automate the detection process.

Infrared cameras are widely used for surveillance, but liquid gas coolers, which are required for conventional cameras, impose a significant operational burden. A MEMS-based infrared camera would not require a low-temperature operating environment and would greatly expand the surveillance capabilities of UAVs.

Actuators

UAVs could use MEMS-based actuators for steering fiber optics and for signal switching of onboard electronics. Systems to control flow separation will require actuators with displacements on the order of millimeters and actuation forces on the order of milli-Newtons. Three types of force are available for actuation: electrostatic, electromagnetic, and thermal-pneumatic forces. EMAs can provide the forces required for UAVs. Electrostatic forces usually are an order of magnitude too low. Thermal-pneumatic actuators offer the highest force level, but packaging is more involved, and the frequency response is low.

A much greater force will be necessary for structural control. Possible candidates for these actuators include thin piezoelectric actuators, magnetostrictive alloys, and shape-memory alloys. The typical displacement of current actuators using these technologies (typically in the micron range) is too low for use in UAVs. In addition, thin-film processing technology requires further development to make thin piezoelectric actuators a practical alternative. Versatile thin-film, smart material-processing technologies compatible with microtransducer fabrication techniques would significantly reduce packaging costs. Research is needed to overcome the limitations of current technology and satisfy the demand for miniature actuators.

Recommendation. The U.S. Air Force should monitor developments in microelectromechanical system (MEMS) and undertake research to develop and apply a new generation of MEMS sensors and actuators.

8

Research on Vehicle Subsystems

Part II of this report has focused on research opportunities for major vehicle subsystems, including aerodynamics (and vehicle configuration), airframes (with a focus on materials and structures), propulsion, power and related technologies, and controls. The committee analyzed subsystem needs based on three notional vehicle types indicative of the range of technologies required to support general advances in the USAF's capability of designing, producing, and fielding the generation-after-next UAVs. The three vehicle types were:

- HALE (high-altitude, long-endurance) vehicles
- HSM (high-speed, maneuverable) vehicles
- very low-cost vehicles

The committee identified crosscutting research opportunities, that is, research that would benefit all of the vehicle types, as well as research opportunities especially important to specific vehicle types.

CROSSCUTTING TECHNOLOGIES

The committee identified crosscutting research opportunities for vehicle subsystems in four areas: (1) computational modeling and simulation; (2) propulsion technology for small engines; (3) integrated sensing, actuation and control devices; and (4) controls and mission management.

Recommendation. The U.S. Air Force long-term UAV research program should focus on crosscutting subsystem technologies.

Computational Modeling and Simulation

The need for affordability and short design cycles that underlies much of the interest in UAVs will require changes in design practices, resulting in increased reliance on computational modeling, simulation, verification, testing, and training. Although these technologies could greatly reduce cost and cycle time, they also raise serious concerns about the fidelity of models and about their inherent uncertainties. Unfortunately, many sources of real error, from the intrinsic variability of the real world being modeled to the multitude of assumptions and approximations introduced in the modeling and simulation steps, cannot presently be accounted for formally and explicitly. Research opportunities for the development and validation of computational modeling and simulation tools are listed below:

- development, validation, and application of computational tools for major subsystem design, including unsteady, nonlinear, three-dimensional aerodynamics models; structural analysis and aeroelasticity models; aerodynamic modeling concepts for designing vehicle control systems; propulsion system models; and simulation models for assessing new control laws
- validation of manufacturing process models for UAV components
- clarification of the role of uncertainty in computational analysis
- integration of models and simulations to provide "virtual mockups" for testing and evaluation of the total system

Propulsion Technologies for Small Engines

In the past, development costs have been a major factor in the development of UAV propulsion technology. The development of an all-new gas turbine for a tactical military aircraft can cost more than $1 billion, an inconceivable expense for a low-cost UAV development program. To meet program budget constraints, the practice has been to adapt existing devices, usually at the expense of both performance and reliability. The cost of new technology, especially of new concepts, will be as high for UAV development programs as it has been for conventional aircraft unless new ways of developing propulsion systems can be perfected. To address this concern, the committee recommends that research be focused on technologies to enable development of small, low-cost turbine engines. The following topics should be considered:

- low-cost, high-temperature materials and coatings
- cooling schemes to reduce the need for costly air-cooled parts
- technology and approaches to reducing leakage through clearances between stationary and rotating parts
- bearing and lubrication systems that will be more reliable after long-term storage
- small, low-cost propulsion system accessories (e.g., fuel pumps, engine controls, and electrical generators)

Integrated Sensing, Actuation, and Control Devices

Sensors and actuators are essential for aircraft operation. Minimizing the weight and volume of sensors, actuators, and other subsystems will be critical for UAVs, which will have stringent size and payload limitations. Emerging MEMS technology can provide transducers as small as tens of microns. By integrating microtransducers with CMOS electronic circuitry, a cost-effective, integrated system capable of sensing, analyzing, and actuating becomes feasible. Potential MEMS-based sensors include inertial sensors, aerodynamic sensors, structural sensors, and surveillance sensors. MEMS-based transducers may have many innovative uses, including the following:

- structures that are responsive to load variations
- aerodynamic flow control
- situational awareness (e.g., collision avoidance and detection of biological and chemical agents)

Controls and Mission Management Technologies

The single fundamental feature that distinguishes UAVs from other aerial vehicles is control. UAVs rely more on autonomous internal machine and remote links to humans than any other systems. The utility and effectiveness of UAVs will require exploiting the capabilities, and recognizing the limitations, of controls and mission management technologies. The committee envisions that UAVs will operate in integrated scenarios with the following features: several vehicles with specified missions; communication links among vehicles and between vehicles and remote human-operated control sites; and the capability to use sensors and information processing systems located onboard each vehicle, on other vehicles, and at ground sites. Important areas for research in controls for UAVs include the following:

- rapid (automated) design and implementation of high-performance control laws

- robust vehicle management functions (e.g., to carry out mission sequences)
- mission management technologies, including real-time path planning and control of dynamic networks

RESEARCH ON SPECIFIC VEHICLE TYPES

In addition to the crosscutting vehicle subsystem technologies just described, the committee identified research opportunities that would support the development of each notional vehicle type.

Recommendation. As the long-range plans and priorities for UAVs emerge, the U.S. Air Force should include the applicable research opportunities in the long-range research program.

High-Altitude, Long-Endurance UAVs

HALE vehicles were analyzed as a focal point for technical advances for reconnaissance and surveillance aircraft a generation beyond current UAVs. The key attributes of HALE vehicles will be operation at very high altitudes (> 65,000 feet) and long endurance (from days to "indefinite" duration). Key subsystem technologies that will enable the development of HALE UAVs are listed below:

- vortex drag reduction (e.g., lifting systems and tip turbines)
- laminar-to-turbulent transition for low Reynolds numbers
- aeroelastic controls
- high-compression operation of gas turbines or piston engines
- alternative propulsion systems (e.g., fuel cells, solar cells, and energy storage systems)
- materials and designs for aeroelastic tailoring
- low-rate manufacturing technologies for ultra-lightweight airframe structures

High-Speed, Maneuverable UAVs

HSM UAVs were analyzed as a focal point for potential second-generation UCAVs. The goal of HSM vehicles will be to carry out high-risk combat operations at a significantly lower cost than for inhabited vehicles. The key consideration for HSM vehicles will be survivability, which will require trade-offs of stealth and maneuverability against speed, maximum altitude, and damage tolerance. The following key subsystem technologies will enable the development of HSM UAVs:

- nonlinear, unsteady aerodynamics
- simulation of flow fields for complex configurations
- modeling tools for propulsion-airframe integration
- stiff, lightweight structures for highly-loaded propulsion systems
- fluid seals
- high-load, long-life bearings
- probabilistic structural design methods for a high-speed, high-*g* environment
- automated manufacturing processes for high-performance structural materials
- high-temperature composite materials[1]

Very Low-Cost UAVs

Very low-cost UAVs were considered as a focal point for trade-offs of cost against performance in vehicle design. The following key subsystem technologies will enable the development of very low-cost UAVs:

- very low Reynolds number aerodynamics
- bearings for long-term storage
- low-cost accessories for propulsion systems (e.g., fuel pumps, engine controls, and electrical generators)
- structural design criteria for expendable, low-use systems
- expanded suite of structural materials (including low-cost, commodity-grade materials)
- modular designs for low-cost manufacture

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[1] Some important research and development programs in composite materials and structures, such as NASA's High Speed Research Program, have recently been discontinued.

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List of Findings and Recommendations

A complete list of the committee's findings and recommendations appears below in the order they appear in the body of the report

CHAPTER 2 The Uninhabited Air Vehicle as a System

Recommendation. The U.S. Air Force should establish a research and development program to develop fundamental technologies that will advance the use of UAVs by enabling them to carry out unique missions or by providing significant cost savings.

Finding. The USAF Scientific Advisory Board has provided a comprehensive analysis of the USAF's needs and potential missions for UAVs. This analysis of short-term and midterm needs was the basis for the committee's assessment of long-term technical and operational requirements.

Finding. Communications and data processing are not limiting technologies for the development and operation of military UAVs. Available technologies can accommodate the needs of currently conceived missions, and developments under way in the telecommunications community will be able to satisfy the needs of expanded military missions for UAVs.

Finding. The design decision that has the most profound effect on the human-machine sciences is degree of autonomy.

Recommendation. The U.S. Air Force should continue to strengthen its activities on human-machine science related to the design and development of UAVs. Research should be pursued in the following key areas:

- *integration of human-machine systems into the design process*, including (1) the optimal and dynamic allocation of functions and tasks and (2) determination of the effects of various levels of automation on situational awareness
- *human performance*, including (1) the investigation of human decision-making processes, (2) the development of methods to define and apply human-performance measures in system design, and (3) the enhancement of force structure through improved methods of team interaction and training
- *information technologies*, including (1) the determination of the effects of human factors on information requirements and presentation and (2) the development of enhanced display technologies to improve the human operator's ability to make effective decisions

CHAPTER 3 Aerodynamics

Recommendation. The U.S. Air Force should focus aerodynamic research on the following areas to maximize the benefit to future UAVs:

- boundary-layer research focused on issues important to UAVs, including (1) transition prediction with (three-dimensional) pressure gradients, Reynolds numbers, and Mach numbers typical of UAV flight conditions and (2) improved flow modeling with part-chord natural laminar flow
- techniques for real-time flow sensing and actuation
- design architectures for complex multidisciplinary problems, including highly integrated systems
- aeroelastic analysis and design approaches, especially for very flexible, unrestrained, actively-controlled aircraft
- novel vehicle control concepts, including flow control
- exploitation and modeling of unsteady, nonlinear, three-dimensional aerodynamics
- design concepts for very low Reynolds numbers, including steady and unsteady systems
- aerodynamic modeling concepts for designing vehicle control systems

CHAPTER 4 Airframe Materials and Structures

Recommendation. To support the development and introduction of probabilistic methods for UAVs, the U.S. Air Force should sponsor research on (1) analytical tools, (2) characterization and testing, (3) simulation methods, and (4) design criteria.

Recommendation. As part of an integrated approach to vehicle configuration and structural design, the U.S. Air Force should conduct research to develop a fundamental understanding of design and analysis methods for aeroelastic tailoring of composite structures. This capability will be especially important for high-altitude, long-endurance configurations.

Recommendation. The U.S. Air Force should monitor the progress of the Composites Affordability Initiative and conduct research to develop a fundamental understanding of processes with promise for UAV structures.

Recommendation. The U.S. Air Force should conduct research to develop a fundamental understanding of metals processes applicable to UAV structures, such as research on low-cost processing of UAV airframe components.

Recommendation. The U.S. Air Force should expand the suite of materials and processes for use in small, low-cost vehicles to include very low-cost, commodity-grade materials that are not used in conventional aircraft constructions.

Recommendation. The U.S. Air Force should develop computational models for new materials and processes and apply them to UAVs.

Recommendation. The U.S. Air Force should develop improved health monitoring technologies that take advantage of recent advances in sensors, controls, and computational capabilities. Specific opportunities include the following:

- microelectrical mechanical systems (MEMS) and mesoscale technologies for integrated sensor-actuation-control devices
- improved load and condition-monitoring capabilities that use piezoelectric sensors and neural networks for data analysis
- active flutter suppression and buffet load suppression systems that link condition-monitoring capabilities with piezoelectric transducers/actuators and intelligent controls

CHAPTER 5 Propulsion Technologies

Recommendation. The U.S. Air Force should include research on propulsion systems for UAV applications in its long-term research program. The following general research topics should be included:

- high-altitude propulsion technologies, which may include gas turbines, internal combustion engines, solar-powered motors, or fuel cells
- propulsion systems for small, highly maneuverable vehicles, including vertical takeoff and landing (VTOL) capabilities
- computational modeling capability to reduce the need for engine testing during development
- cost-reducing technologies that, for example, reduce parts count and complexity

The following specific research topics should be considered:

- low Reynolds number turbomachinery, which is very important for both high-altitude operation and very small vehicles
- low Reynolds number heat rejection for high-altitude coolers and for cooling very small propulsion systems at lower altitudes
- turbomachinery tip clearance desensitization (for highly loaded engines, high-altitude operation, and very small systems)
- desensitization to leakage and better, cheaper seals to reduce cost and enhance performance for highly maneuverable and very small vehicles
- thrust vectoring for highly maneuverable vehicles
- magnetic, air, and solid lubricated bearings to improve long-term storage, enhance high-altitude operation, and reduce complexity and cost
- technologies for low-cost accessories, which tend to dominate the cost of smaller engines
- low-cost vapor and liquid cooling schemes and affordable high-temperature materials (e.g., structural, magnetic, and electronic materials)
- more effective cooling technologies for small engines

CHAPTER 6 Power and Related Technologies

Finding. No fundamental research issues related to the generation of power aboard UAVs must be resolved to enable generation-after-next vehicles.

CHAPTER 7 Control Technologies

Recommendation. In light of the special factors driving the design of UAVs, the U.S. Air Force should strengthen its support for basic research programs addressing the rapid (automated) design and implementation of high-performance control laws. Areas of interest include basic theory for nonlinear and adaptive control, reusable control law structures and processes capable of full-envelope design, software tools for automated control design and analysis, automated code generation from high-level design tools, and simulation models with sufficient fidelity for affordable tests and verifications.

Recommendation. The U.S. Air Force should pursue basic research to provide scientific support for robust vehicle-management functionality.

Recommendation. The U.S. Air Force should enhance the capabilities of available design tools and planning aids by supporting ongoing efforts related to real-time path planning and optimization algorithms, and by embarking on a program of basic research in control of dynamic networks.

Recommendation. Motivated by the urgent need for a better understanding of the role of uncertainty in virtual engineering, the U.S. Air Force should establish a basic research program in uncertainty management.

Recommendation. The U.S. Air Force should monitor developments in microelectromechanical systems (MEMS) and undertake research to develop and apply a new generation of MEMS sensors and actuators.

CHAPTER 8 Research on Vehicle Subsystems

Recommendation. The U.S. Air Force long-term UAV research program should focus on crosscutting subsystem technologies.

Recommendation. As the long-range plans and priorities for UAVs emerge, the U.S. Air Force should include the applicable research opportunities in the long-range research program.

Acronyms

ACTD	advanced concepts technology demonstrator
AFOSR	Air Force Office of Scientific Research
APU	auxiliary power unit
CAI	Composites Affordability Initiative
CAIV	cost as an independent variable
CMOS	complementary metal oxide semiconductors
CNI	communication, navigation, identification
DARPA	Defense Advanced Research Projects Agency
DOD	U.S. Department of Defense
EMA	electromagnetic actuator
GNC	generative numerical control
GOPS	giga-operations per second
GPS	global positioning system
HALE	high-altitude, long-endurance
HSM	high-speed, maneuverable
IFSD	in-flight shutdown
ISR	intelligence, surveillance, and reconnaissance

MALD	Miniature Air-Launched Decoy (Program)
MAV	micro air vehicle
MEMS	microelectromechanical system
NASA	National Aeronautics and Space Administration
SAB	Scientific Advisory Board
SEAD	suppression of enemy air defenses
TDMA	time division multiple access
UAV	uninhabited air vehicle
UCAV	uninhabited combat air vehicle
USAF	U.S. Air Force
VTOL	vertical takeoff and landing