Aerospace Control

Christian Philippe, Anuradha Annaswamy, Gary Balas, Johann Bals, Sanjay Garg, Alexander Knoll, Kalmanje Krishnakumar, Massimo Maroni, Robert Osterhuber, and Yin C. Yeh

Apollo as the Catalyst for Control Technology

Advanced control technology played a fundamental role in putting the first man on the moon. To meet the challenging lunar descent and landing requirements, time and fuel optimal nonlinear control laws and variable Kalman-filter-based state estimators were developed and implemented into the Apollo lunar module first-generation digital flight computer. Remarkably, the memoryless thrust vector control law was the first application of the minimum time control law for a third-order plant. The success of the Apollo program also paved the way for embedded software, online reconfiguration software, concurrent control design and software engineering processes, man-machine interfaces, and digital fly-by-wire technologies.

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Control technology developed during the Apollo program was a catalyst for safer and more efficient aircraft. In the late 1960s, engineers at NASA Flight Research Center (now NASA Dryden) proposed replacing bulky mechanical flight-control systems on aircraft with much lighter weight and more reliable analog fly-by-wire technology. As the Apollo program came to completion in the early 1970s and following Neil Amstrong's recommendation, NASA Dryden engineers developed a digital fly-by-wire (DFBW) solution using the specialized software and hardware developed for Apollo. On 25 May 1972, the successful testing of the world's first-ever DFBW technology on a modified F-8 Crusader jet fighter precipitated a revolution in aircraft design and performance [1].

For military aircraft, the deployment of DFBW control systems allowed the development of highly maneuverable fighter aircraft and the improvement of their "carefree handling" performance and combat survivability by preventing stalling, spinning, and actuator hydraulic failures. In the commercial airline market, Airbus introduced full-authority fly-by-wire controls in 1988 with the A320 series, followed by Boeing with their B-777 in 1995. The primary benefits were (1) a reduction of the airframe weight through the use of smaller, lighter aerodynamic control surfaces and (2) increased aircraft safety and reliability.

> *Fly-by-wire control systems enabled the development of highly maneuverable fighter aircraft and improvements in handling performance and combat survivability.*

Nowadays, DFBW control systems are commonly implemented in high-performance jet fighters and aboard commercial airliners.

With regard to space applications, control-enabled solutions have guaranteed access to space through the successful development of launchers and space transportation systems, bringing many benefits to society. For instance, the successful deployment of interplanetary probes and space-based observatories such as Pioneer, Voyager, Cassini-Huygens, and the Hubble Space Telescope has allowed the exploration of our solar system—Venus, Mars, Jupiter, and Saturn's moon, Titan—and a greater knowledge of the universe. Thanks to space-based data from remote sensing and meteorological satellites, a better understanding of the earth, its climate, and its changing environment has been made possible. For example, the Franco-American mission Topex-Poseidon has shown through space altimetry that the oceans have been rising over the past decade; it has also provided unexpected information for monitoring oceanic phenomena such as variations in ocean circulation on the level of the 1997-1998 El Nino event.

Finally, since the launch of the first telecommunication satellites in the sixties, control technology has continued to play an important role in the successful deployment of more powerful satcoms featuring large flexible deployable antenna and solar arrays. Today telecommunication and navigation satellites are part of everyone's life: Internet, tele-education, telemedicine, videoconferencing, mobile communications, digital broadcasting, search and rescue, and traffic management.

Successful Applications and Demonstrations

Both aeronautics (commercial and military aircraft and unmanned aerial vehicles (UAVs)) and space (launchers, manned and unmanned space transportation vehicles, satellite and planetary rovers) application fields share common and specific control-relevant requirements. These requirements are listed in Fig. 1.

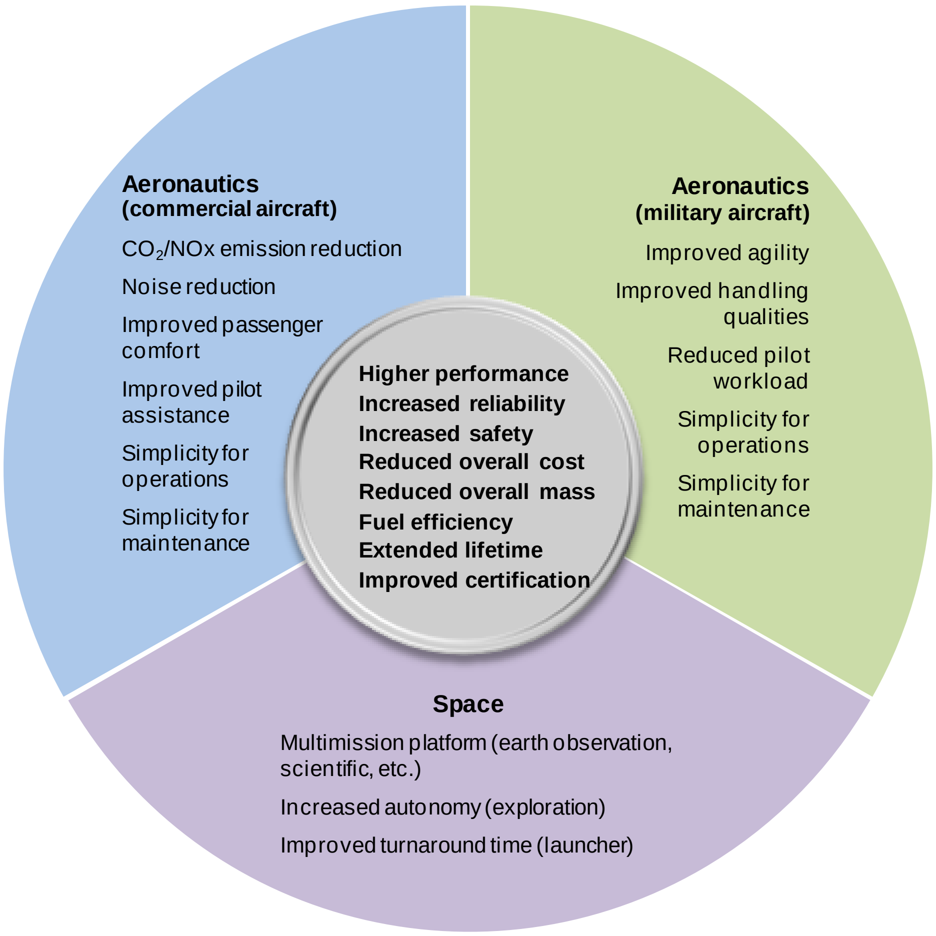


Figure 1. Common and specific control-relevant requirements for aeronautics and space.

Over the last 50 years, both application fields have seen the successful deployment of control technologies for satisfying the above control-relevant requirements. Both application fields require rigorous engineering processes, including standards such as Radio Technical Commission for Aeronautics/Design Objective-178B for aeronautics and European Cooperation for Space Standardization, and they both demand efficient and rigorous (model-based) design, development, and validation methods and tools.

Since at the conceptual level the list of control techniques investigated by academia, agencies, research organizations, and industries is lengthy and the techniques are often applied without taking into account the specific needs and constraints (implementation, validation, certification, financial) associated with the applications, the enumeration of successful control applications is limited to those that have been successfully deployed by the aerospace industries or investigated by research organizations. A clear assessment of the impact of advanced control technologies on past and present operational projects cannot be made due to information restrictions or confidentiality resulting from military applications or industry competitiveness concerns.

Commercial Aircraft

In addition to digital fly-by-wire control technology, which has reduced the operating cost of commercial airplanes, NASA Dryden Flight Research Center has initiated the development of propulsion controlled aircraft (PCA) technology with the main goal of reducing the aircraft accident rate by a factor of 10 within 20 years. The PCA is a computer-assisted engine control system that enables a pilot to land a plane safely when its normal control surfaces are disabled. The first successful demonstration of the PCA technology on an airliner took place in 1995. Although the technology is proven, it has not yet been incorporated into future aircraft designs. A further extension to DFBW flight control systems is to implement functions capable of compensating for aircraft damage and failure during flight, such as automatically using engine thrust and other avionics to compensate for severe failures—loss of hydraulics, loss of rudder, loss of ailerons, or loss of an engine. This new generation of DFBW flight control systems is called *intelligent flight control systems* (IFCS).

As a result of the miniaturization of sensor technologies, increasing actuator performance capabilities, and increasing processing resources, integrated flight-structural control technologies are being investigated that should further improve the safety and environmental performance of the aircraft as well as the comfort of passengers. For instance, one potential “green” aviation technology is *active wing shape control,* which holds promise for improved aerodynamic efficiency, lower emissions, reduced noise, and minimized carbon footprint. This control technology consists of shaping the wing structure in flight by actively controlling the washout twist distribution and wing deflection so as to affect local angles of attack in a favorable manner that leads to lower drag and higher lift. Another example is active load control technology, which could reduce structural weight considerably by reducing aerodynamic peak and fatigue loads at critical locations in the airframe structure. The associated functions are realized by control allocation and coordination, affecting distribution of aerodynamic loads over the airframe, as well as by active damping of airframe structural modes.

Military Aircraft and UAVs

To respond to the continuous demand for increased performance in military aircraft, the deployment of active control technologies has been mandatory. For example, the following functions are currently implemented onboard fighter aircraft:

- Carefree handling by providing angle-of-attack control and angle-of-sideslip suppression, which lead to automatic protection against stall and departure;
- Carefree handling by the automatic limiting of normal acceleration and roll rate to avoid over-stressing of the airframe;
- Automatic controller reconfiguration, allowing mission continuation or safe recovery following system failures or battle damage;
- Automatic terrain-following functions using information from the radar altimeter or digital terrain elevation database, aiming at holding the aircraft at a constant distance above ground level;
- Advanced autopilots, providing significant reductions in pilot workload and weapon system performance benefits.

Along with the increase in aircraft performance, specific safety functions are now implemented to protect the pilot, such as the pilot-initiated *spatial disorientation* automatic recovery mode from both nose high and low situations and automatic *g-loc* (g-force-induced loss of consciousness) recovery mode.

Aircraft Engines

With the increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircraft, corresponding progress needs to be made in the area of aircraft propulsion systems. Over the years, considerable improvements have been made in engines, with control playing a significant role. One such example is the work being carried out at NASA Glenn Research Center in partnership with the U.S. aerospace industry and academia to develop advanced controls and health management technologies through the concept of an *intelligent engine.* Turbine engine manufacturers such as Siemens-Westinghouse, Rolls-Royce, and United Technologies have successfully employed control principles in improving efficiencies and performance. In most cases, passive control methodologies have entered the production phase, with active control successes demonstrated in academia and research laboratories. The key enabling technologies for an intelligent engine are the increased efficiencies of components through active control of inlets, compressors, and combustors, advanced diagnostics and prognostics integrated with intelligent engine control to enhance component life, and distributed control with smart sensors and actuators in an adaptive fault-tolerant architecture.

Notable recent successes include:

- Development of life-extending control through intelligent modification of the engine acceleration schedule to minimize thermomechanical fatigue for each takeoff-to-landing cycle. Demonstrated 20% improvement in “on-wing” engine life through real-time engine/control simulation.
- Successful demonstration of control of thermoacoustic instability in combustors in gas turbine engines by modulating the fuel entering the engine using servo-valves and control strategies.
- Flight demonstration of high-stability engine control, which allows operation of engines with reduced stall margins during cruise, thus increasing fuel efficiency by up to 3%. The technology

works through estimation of inlet distortion effects on stall margin using pressure sensors on the fan circumference and coordinating fuel flow and nozzle area control to maintain a desired stall margin.

Space

Robust control techniques such as H_∞/H_2 have been successfully applied to deal with complex architectures such as large flexible appendages (solar arrays and deployable reflectors) and requirements such as tight pointing stability performance, while reducing development cost and schedule.

For instance, the Linear Quadratic Gaussian (LQG) controller used for the atmospheric flight phase of the Ariane 5 launcher was replaced by a H_∞-based controller for the Ariane 5 Evolution [2]. This change was deemed necessary to optimize the control design tradeoff between the low-frequency performance requirements, such as load reduction and tracking of the attitude setpoint, and the attenuation of the low-frequency structural bending and fuel sloshing modes. For telecommunication satellites, the introduction of a robust control approach through a loop-shaping H_∞ design has allowed a 10% reduction in propellant mass consumption during station-keeping maneuvers.

Nowadays, increasing computing capability allows multidisciplinary modeling and simulation, which are essential for the development of robust controllers for complex uncertain systems. Recent progress in multidisciplinary requirements and integrated design processes, advanced analysis tools, commercial automatic production code generators, automatic advanced formal verification and test case generation tools, and the like, has reduced the development time and cost of embedded flight control systems.

Whatever the application field, decision makers rely on already proven technical solutions. This is especially true for space applications, as solutions cannot be tested beforehand due to the difficulties of reproducing space-representative conditions on Earth. Thus, for critical space control technologies or new control system concepts, dedicated precursor missions, usually named Pathfinder or X-vehicle, are typically implemented before deployment on the full-fledged mission. This approach is necessary for decreasing the technical risk and cost of the overall mission.

Furthermore, the gap between new control techniques and associated certification processes, including tools, methods, and standards, cannot be too large, otherwise the control technologies cannot be operationally deployed. Finally, despite the potential advantages afforded by advanced control techniques, they usually add complexity in the design, analysis, and tuning of the flight control system, thus requiring more skillful control engineers.

Market Sizes and Investments

Both Boeing and Airbus estimate that new aircraft demand will average around 1,300 per year over the next 20 years (2009-2028). This corresponds to a commercial airline market value of around $3 trillion. For UAVs, Teal Group's 2009 market study estimates that spending will almost double over the next decade from current worldwide UAV expenditures of $4.4 billion annually to $8.7 billion within a decade, totaling just over $62 billion [3]. The most significant catalyst to the UAV market is the enormous growth in interest by the defense sector.

Over the last 15 years, the average European space industry sales, including commercial and institutional programs, is around €4.5 billion annually. In 2007, space industry sales amounted to €6 billion [4]. Euroconsult estimates that around 1,200 satellites, excluding microsatellites (weighing less than 40 kg) and classified military satellites, mainly from United States and Russia, will be built and launched worldwide over the next decade (2008-2018), an increase of 50% compared to the previous decade [5]. Market revenues generated from the manufacturing and launch of these satellites are forecast to grow at the same rate, reaching $178 billion. Earth observation (EO) is emerging as the largest application with a total of 230 satellites, reflecting the priority given by governments to the challenges of global warming and climate change.

Depending on the application type—launcher, EO satellite, satcom, scientific satellite—the cost of the avionics system, including the embedded GNC software and equipment, represents around 8-15% of the overall cost of the satellite. For aircraft, the average value of the avionics system is 12%. Therefore, the market for control technology over the next decade can be conservatively estimated at not less than $25 billion for civil, military, and governmental space applications, $225 billion for both commercial and military aviation, and $5 billion for unmanned systems (Fig. 2). (Engine control systems, cabin environmental control systems, and other “embedded” applications of control are additional to avionics.)

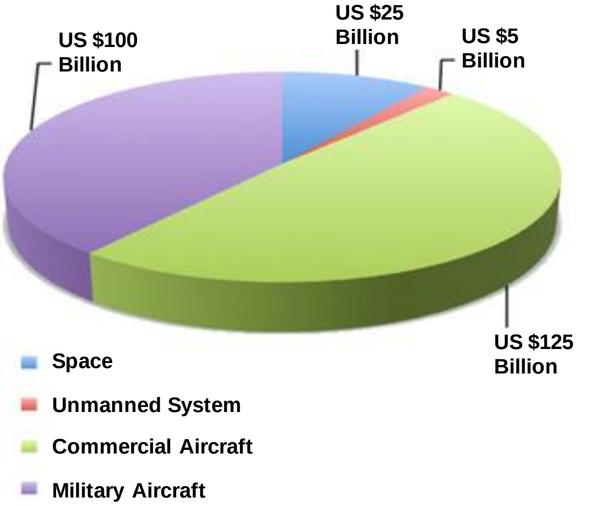


Figure 2. Estimated market for commercial and military aircraft, unmanned systems, and space (civil, military, and governmental) applications over the period 2009-2019.

Future Challenges

Air traffic demand is predicted to double in the next 10 to 15 years and to triple in 20 years’ time. This growth cannot be sustained without a complete overhaul of the air traffic control infrastructure to optimize air routes and eliminate congestion. As a result, the U.S. Federal Aviation Administration (FAA) has initiated NextGEN (Next Generation Air Transportation System), whose primary goals are to provide new capabilities that make air transportation safer and more reliable, improve the capacity of the National Airspace System (NAS), and reduce aviation’s impact on our environment [6]. A sister initiative in Europe called SESAR (Single European Sky ATM Research) aims to increase air transport safety and reduce greenhouse gas emissions by 10% per flight. The projected SESAR program cost is €50 billion at completion in 2020 [7].

In addition to air traffic management, aeronautics research investment priorities in Europe are to develop safer, greener, and smarter transport systems. Air travel is the fastest-growing source of greenhouse gas emissions in the world, and air transportation system energy requirements are expected to more than double in the next three decades. Each long-distance flight of a 747 adds about 400 tons of CO_2 to the atmosphere (about the same amount a typical European uses for heating and electricity in a year). Aviation now consumes about 13% of transportation-related energy, and this percentage is growing rapidly. Emissions at altitude are estimated to have two to four times greater impact, relative to terrestrial emissions, than reflected by the percentage of carbon emissions. Energy efficiency in air traffic management, in flight control of individual aircraft, and in engine control systems are all priority research needs.

The European Commission’s CleanSky effort will amount to €1.6 billion (2008-2013), whereas the research effort of NASA’s aeronautics programs is $2.6 billion (2009-2014). NASA’s research programs will focus on the following technologies [8]:

- *Integrated vehicle health management* technology will enable nearly continuous onboard situational awareness of the vehicle state for use by the flight crew. It will also improve the safety and reliability of the aircraft by performing self-diagnosis and self-correction of in-flight anomalies.
- *Integrated intelligent flight deck* technology will allow robust detection of external hazards with sufficient time-to-alarm for safe maneuvering to avoid the hazards. It will also support new pilot tasks consisting of collaboration and negotiation with other aircraft and air traffic controllers.
- *Integrated resilient aircraft control* technology aims at enabling the aircraft to automatically detect, mitigate, and safely recover from an off-nominal condition that could lead to a loss of control in flight.
- *Advanced validation and verification of flight-critical systems* will provide methods for rigorous and systematic high-level validation of system safety properties and requirements from initial design through implementation, maintenance, and modification, as well as understanding of tradeoffs between complexity and verification in distributed systems. In addition, tools will be developed for analysis and testing of systems-of-systems capabilities.

In addition, the research programs will start to address the technical and regulatory issues related to the integration of unmanned aircraft systems in NAS. In support of NextGEN, enabling control optimization technologies will be developed for traffic scheduling and route planning, as well as balanced allocation of resources to maximize airspace productivity in response to arrival, departure, and traffic demands.

For military aircraft, the following control technologies are being investigated that should have safety, financial, and environmental benefits:

- Damage-tolerant flight control should automatically reconfigure the aircraft flight controls after significant loss of control due to battle damage.
- Automatic collision avoidance should reduce the risk of ground and midair collisions.
- Autonomous formation flight should provide a 5-10% reduction in fuel consumption by a trailing airplane during cruise.
- Autonomous midair refueling should allow unmanned air systems to significantly increase their mission times and operational range.

For future stealth aircraft, advanced air data systems will be required because external measurement devices need to be minimized. Moreover, the unusual shaping of such aircraft and the need to reduce the number and size of control surfaces for low observability, the possible reliance on thrust vectoring, and the development of novel control methods such as nose suction/blowing, are likely to lead to highly nonlinear aerodynamic characteristics that will require advances in the development of robust flight controllers. Finally, for some specific missions, combat UAVs will become the preferred weapons platform. The introduction of such technologies and systems will present flight control system engineers with interesting design, development, and certification challenges.

Engines are also an active topic for research in aerospace controls. Propulsion subsystems such as combustors and compressors have the potential to exhibit improvements in performance, reliability, and reduced emissions by integrating control into their design. Specific research initiatives that are under way include the following:

- Distributed, fault-tolerant engine control is being explored for enhanced reliability, reduced weight, and optimal performance, even with deterioration in the system and its components. The use of smart sensors and actuators together with advanced robust and adaptive control methods is being explored.

- Advanced health management technologies for self-diagnostics and prognostics are yet another example where controls are playing an increasing role. In problems such as life-usage monitoring and prediction, data fusion from multiple sensors and model-based information are being explored.

- Control of flows at the inlet are being investigated so as to circumvent separation as well as stall. Current research areas are focused on the development of microactuators that can provide a distributed multitude of inputs such as pressure, velocity, and fuel-to-air mixture; arrays of pressure and velocity sensors; models that capture the underlying spatiotemporal complexity with the available computational resources; and the corresponding distributed control strategies that can guarantee robust and optimal performance.

The exploitation of future space systems for civil, commercial, scientific, and space exploration also gives rise to a set of challenges and opportunities in the area of control. With the rapid advances in computing, communications, and sensing technology, three main categories of guidance, navigation, and control (GNC) systems can be defined:

- Low-end (recurring) GNC systems are often incorporated in existing multimission (EO applications) or commercial platforms (telecom applications). Industrial competition in the global space market drives the need for permanent reduction of production cost and schedule. This low-end GNC system might require some level of innovation in the development of certain operational modes and vigorous research effort in improving the verification and validation process.

- High-end GNC systems are generally required for satisfying challenging control performance requirements (such as pointing accuracy, pointing stability, safe precision landing, space object interception). Future space missions requiring such GNC systems are listed in Table 1. The high-end GNC systems often rely on innovative designs in the area of navigation, guidance, and control technologies. In some cases, increasing levels of autonomy are required in order to meet mission requirements.

- Safety-critical GNC systems include mainly launchers and manned space transportation systems. For example, the Automated Transfer Vehicle (ATV) GNC system falls in this category due to proximity operations and docking with the International Space Station (ISS).

Table 1. Proposed GNC System Classification for Space Applications

GNC System Class	Past/Present Missions	Ongoing Missions	Future Missions
Low-end (recurring)	Earth Observation (multi-mission platform) Telecommunication (commercial platform)	Navigation (Galileo) Small Telecom Satellite (SmallGEO)	Affordable low-earth orbit (LEO) platform Agile small LEO platform (300-kg class)
High-end	Earth's gravity field (GOCE) Comet rendezvous and lander deployment on the surface (Rosetta) Astronomy (Hubble Space Telescope)	Astrometry (GAIA) Astronomy (James Webb Space Telescope) Fundamental Physics (LISA) Planetary Entry Descent and Landing System (Mars Science Laboratory) Planetary rover	Jovian mission Interferometry mission (formation flying) Sample return mission (moon, Mars, asteroid) Solar power satellites
Safety-critical	Launcher (Ariane 5, Delta, Proton) Shuttle Resupply cargo (ATV)	Launcher (Vega, Ariane 5, etc.)	Next-generation launcher (AR6, Vega Evolution) Moon cargo lander Space tourism (suborbital and orbital) Commercial in-orbit servicing

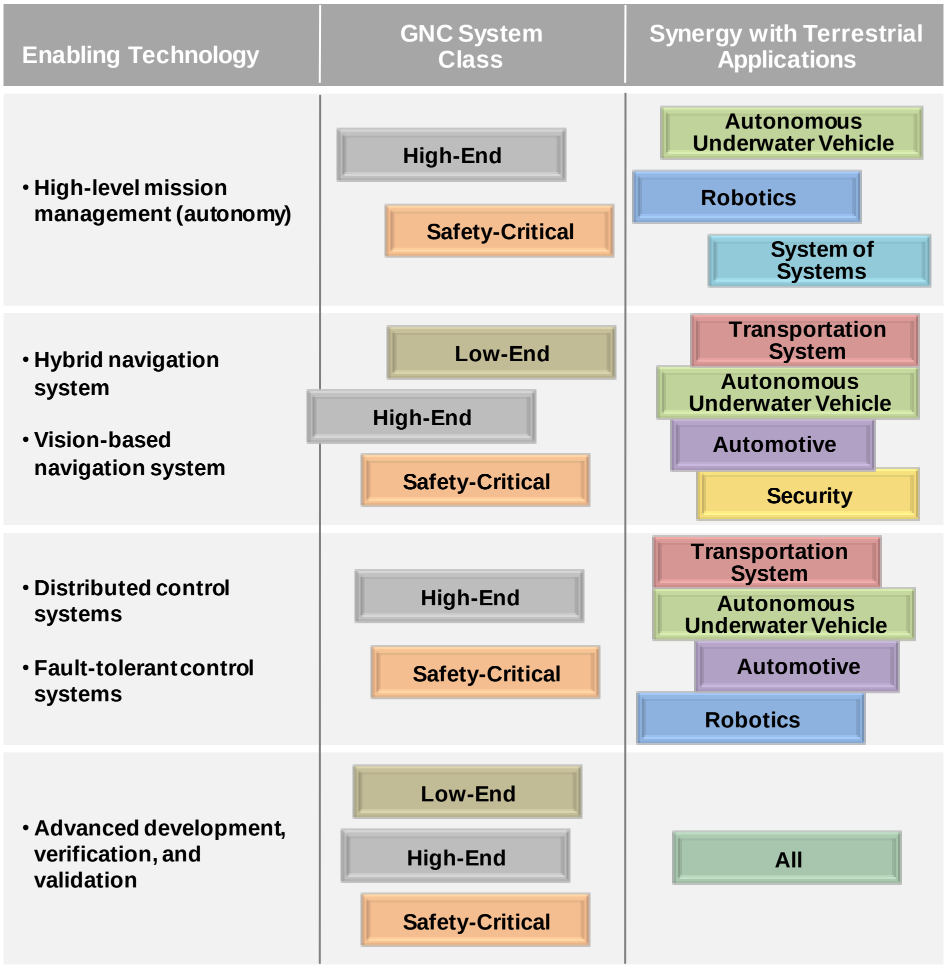
For each GNC system class, Fig. 3 provides some examples of enabling control technologies. Synergy with other terrestrial applications is also indicated.

Opportunities for Research

Recommendation No. 1

Development of advanced analysis, verification, and validation technologies (theory, methods, and engineering tools) for supporting the certification of autonomous aerospace systems and systems of systems (SoS) and for reducing the "time to market" and associated development effort. The focus shall be on but is not limited to:

- Development of new worst-caseanalysis techniques for hybrid and nonlinear systems
- Enhancement of statistical approaches
- Improvement of transparent robust control design methods
- Development of "trouble-shooting" control techniques
- "Smart" interpretation and presentation of results



Enabling Technology	GNC System Class	Synergy with Terrestrial Applications
• High-level mission management (autonomy)	High-End Safety-Critical	Autonomous Underwater Vehicle Robotics System of Systems
• Hybrid navigation system • Vision-based navigation system	Low-End High-End Safety-Critical	Transportation System Autonomous Underwater Vehicle Automotive Security
• Distributed control systems • Fault-tolerant control systems	High-End Safety-Critical	Transportation System Autonomous Underwater Vehicle Automotive Robotics
• Advanced development, verification, and validation	Low-End High-End Safety-Critical	All

Figure 3. Examples of enabling control technologies for each GNC system class.

Recommendation No. 2

With the rapid trends toward autonomy (space exploration, UAVs, and virtual co-pilots), revolutionary control solutions need to be developed in order to deliver (high-performance) robust outer loops and to support advanced capabilities such as situation awareness and avoidance. The technology focus shall be on but is not limited to:

- Sensor fusion
- On-line trajectory and optimal path planning
- On-line system identification
- Robust fault detection, diagnosis and prognosis
- Decision making
- Adaptive reconfiguration control
- On-line planning and executive decision making

Recommendation No. 3

With emerging system-of-systems applications such as air traffic control, space interferometer, and swarms of UAVs, transformational control technologies are required to meet the new challenges:

- Numerical modeling of complex multisystems and their validation
- Information transmission over networks
- Decentralized control and decision making
- Subliminal control
- 4D trajectory planning
- Self-separation
- Conflict detection and resolution

Conclusions

The development of commercial and military aircraft and space vehicles is impossible today without flight control systems or guidance, navigation, and control systems. Industrial competition in the global aerospace market drives the need for continuous improvement of capabilities as well as reducing development and production cost. Control technologies will continue to have an important role for the successful realization of the next generation air transportation systems, including air traffic management and the vehicles that operate in this system. As our quest for knowledge continues to grow, control technologies will also play an important role in pushing back the frontiers of space exploration and protecting and securing the environment by gathering more accurate satellite data.

Acknowledgments

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Selected recommendations for research in aerospace control:

- Autonomy is a key trend; for its promise to be realized, new control system architectures, high-performance robust outer-loop control solutions, and situation awareness and avoidance technologies must be developed.
- Advanced analysis, verification, and validation technologies for supporting certification and reducing development effort are essential for industrywide deployment of advanced control.
- Several “systems-of-systems” opportunities are emerging in aerospace that require transformational control technologies to be developed.

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Related Content

The Impact of Control Technology report also includes more than 40 flyers describing specific “success stories” and “grand challenges” in control engineering and science, covering a variety of application domains. The ones below are closely related to the topic of this section.

Success Stories

- Automated Collision Avoidance Systems – *C. Tomlin and H. Erzberger*
- Control of the Flexible Ares I-X Launch Vehicle – *M. Whorton*
- Digital Fly-by-Wire Technology – *C. Philippe*
- H-infinity Control for Telecommunication Satellites – *C. Philippe*
- Nonlinear Multivariable Flight Control – *J. Bosworth and D. Enns*
- Robust Adaptive Control for the Joint Direct Attack Munition – *K.A. Wise and E. Lavretsky*

Grand Challenges

- Control of Combustion Instability – *A. Banaszuk, A. Annaswamy, and S. Garg*
- Energy-Efficient Air Transportation – *J. Alonso et al.*
- Verification, Validation, and Certification Challenges for Control Systems – *C. Philippe*

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