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Innovations in Aeronautics

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Abstract

The first fifty years of aviation were punctuated with frequent innovations, transforming what were once daring stunts into an engine of our modern economy. The second fifty years seems to many, just a tuning of this engine, with significant, but evolutionary improvements. This paper considers possible innovations in aeronautics over the next fifty years and examines some of the technologies and requirements that may drive them. Focusing on three examples of fields in which future innovation appears likely, the paper suggests that many opportunities exist for innovation in aeronautics over the next few decades.

Introduction

For hundreds of years prior to the advent of human flight, people dreamed about aeronautics. Numerous innovative attempts at flight showcased the participants' creativity, determination, and lack of knowledge [1]. With the first truly successful gliders by Lilienthal [2] in the 1890's and the first powered flights by the Wright brothers about 10 years later, the combination of new technologies, improved understanding of aerodynamics, and a passion for flight led to a revolution that changed our world in many respects. Innovations in aeronautics were numerous over the subsequent fifty years, from the Wright Flyer to passenger-carrying aircraft in just a few years, to the Boeing 367-80, 707 prototype, which flew in 1954.

Despite the dramatic innovations over the first fifty years of air transportation, or perhaps because of them, modern aircraft appear almost unchanged from their ancestors (Figure 1). And although the similar appearance belies a dramatic reduction in fuel usage and costs, other measures of performance have shown little change in decades. Figure 2 (data from [3]) illustrates how the product of Mach number and lift-to-drag ratio has changed little in the past 40 years. Ref. [4] reports that door-to-door travel times for flights of 500 miles or less are 35-80 miles per hour.

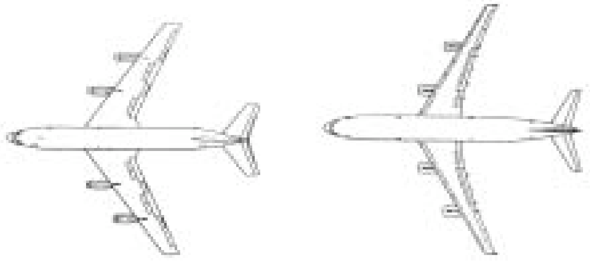

Figure 1. Boeing 707 (1954) and A340 (1991)

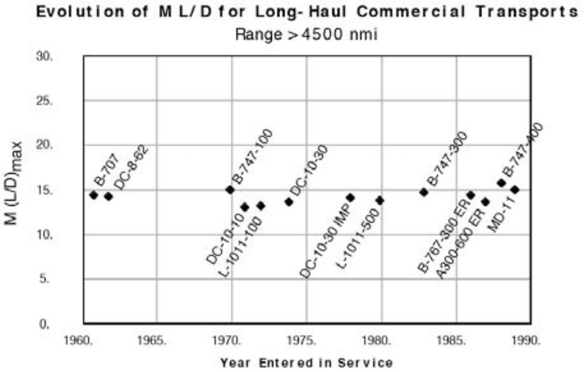

Figure 2. Product of Mach number and maximum lift/drag for several commercial aircraft (1960 – 1990).

This apparent lack of innovation has caused some to suggest that aeronautics is a mature field. One might attribute the current interest in aeronautical innovation to the apparent lack of it in recent history, and irrespective of whether this judgment is correct, many have raised concerns about the future of the industry and its ability to attract tomorrow's innovators [4].

The cause of the apparent stagnation in this field has been attributed to several factors. Some argue that all of the important breakthroughs were made in the first 50 years of aviation and that the A340 looks like the 707 because the engineers got it right in 1954. Others argue that the tremendous cost and risk associated with

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a new technology makes it difficult to make a business case for innovation, especially in the field of large transport aircraft. Christensen [5] notes that "The highest-performing companies, in fact, are those that… have well-developed systems for killing off ideas that their customers don't want." And until new ideas are well-proven, most customers prefer low-risk incremental improvements.

The solution to this dilemma – that innovation is too risky, but its absence may eventually destroy the industry – may lie in two factors. First, as necessity motivates invention, the need for significant changes in air transportation over the next decades may well inspire innovation. These changes will most likely be associated with environmental requirements for dramatically lower noise and emissions or with issues related to air transport system capacity. Second, the introduction of new technologies, even in indirectly related fields, can enable new concepts that may revolutionize aeronautics.

The purpose of this paper is therefore not to recount a history of aeronautical innovation, nor to describe the concept of technology S-curves, how managers might deal with the innovator's dilemma, or how a specific technology, such as nano-scale engineered materials might affect aircraft performance. Instead it will focus on three promising and fundamental areas of research that may drive future innovation. Such innovation will still depend on future market demand, continued development of sustaining technologies, and a longer term vision from industry, government, and academia, but the next fifty years of aviation may well be as innovative as the first.

Three Technology Areas that May Drive Future Aeronautics Innovation

Just as a history of aeronautical innovation would require volumes, not pages, a prediction of possible future aeronautical ideas would be hopelessly ambitious and most surely wrong -- as Wired [6] declares in its Dec. 2003 edition, 'Futurism Is Dead.' Rather, three general areas that may lead to new concepts of use in aeronautics are described as examples to motivate the idea that aeronautics is hardly a mature endeavor.

These three areas include:

1. Exploiting computational advances for high-fidelity simulation and multidisciplinary design.
2. Removing the constraint that aircraft must be designed around pilots or passengers.
3. Designing the system rather than the vehicle: collectives and systems of systems.

High Fidelity Simulation and Design

The revolution in computing has, over the past few decades eclipsed progress in aeronautics. Yet this revolution has, itself, only begun and has only begun to be exploited in aeronautics. Researchers in this field sometimes bemoan the idea that there is no equivalent of Moore's Law for aeronautics. Yet, it is precisely Moore's Law that may lead to some of the greatest advances in aeronautics through the use of almost unimaginable computational capabilities projected in the next few decades. Bill Joy [7] argues that molecular electronics may well extend the applicability of Moore's observation to 2030 or beyond, leading to computational capabilities some 10^6 times more powerful than those of today. Simulations that would require 1000 years with today's computers could be completed in 8 hours.

Although researchers at NASA, industry, and academia succeeded in developing algorithms for solving the nonlinear equations of fluid flow in the 1970's and 80's and it is sometimes suggested that CFD is no longer a research field, the use of computational simulation in many areas is just beginning and promises to revolutionize the way new aerospace products are developed. Skeptics note that even rather modern aircraft benefited little from extensive computational simulation (although Johnson, et al. [8] cites several compelling examples of its use in the development of several commercial aircraft). Examples of current CFD capabilities include Reynolds-Averaged Navier Stokes simulations of a Boeing 777 in high-lift configuration, with detailed geometry including flap tracks and some 30 million nodes in the computational mesh. This calculation is currently completed in as little as a week [9]. Current capabilities permit drag computation of wing/body/nacelle/pylon configurations to within +/- 2% to 4% [10]. Evolving capabilities under development as part of the ASCII program [11] will soon permit complete unsteady modeling of internal engine flows, including compressor, combustor, and turbine stages with fuel spray modeling and subproduction, utilizing LES in the combustor simulation.

The next few decades will bring even higher fidelity simulations for cases involving unsteady flows, fluid-structures-controls coupling, large scale separation, and laminar-turbulent transition. Dynamic simulations of complete vehicles, including nonlinear, time-domain, 6+ DOF may include much-improved aerodynamic, propulsion, and structural models and the impact of these systems on the environment may be evaluated with a level of detail that is impossible with current tools.

The development of such a capability may have a direct effect on future innovation by reducing the risk associated with new ideas that exploit complex phenomena. This is especially important when experiments that might provide new insight or validation would be very expensive. Two recent examples of this, which have utilized newly developed computational simulation tools and which would benefit greatly from further simulation capabilities, are DARPA's Shaped-Supersonic Boom Demonstration [12], and recent designs exploiting supersonic natural laminar flow [13].

In the SSBD program, a modified F-5 was used to demonstrate the idea that a supersonic airplane ground signature might be to significantly reduce its loudness. This concept was suggested by Seabass and George [14] early in the development of supersonic aerodynamics and propagation theory, but the role of certain nonlinear effects on signature development and the influence of real atmospheric characteristics on this type of signature were uncertain.

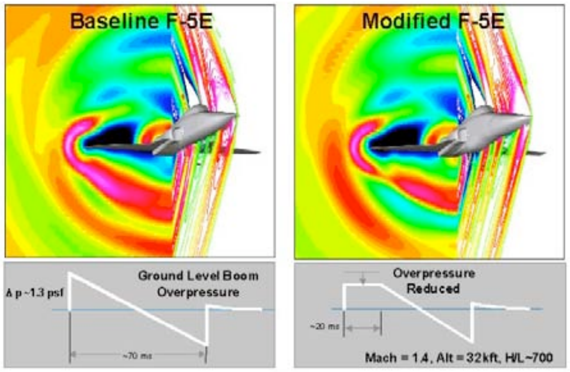

Figure 3. Pressure fields associated with baseline F5 and version modified to produce desired signature. (From [12]).

Flight tests of a supersonic aircraft, even one that represents a modification of an existing design, are very costly and correct modeling is essential to ensure a successful flight program. The analysis for this application is especially difficult because of the need to capture accurate pressures some distance from the vehicle and taxes current CFD capabilities.

The quest for efficient supersonic flight utilizing extensive laminar flow is similarly challenging, relying on nonlinear CFD computations, boundary layer modeling, and transition estimation, again taxing the capabilities of simulation tools and requiring flight confirmation.

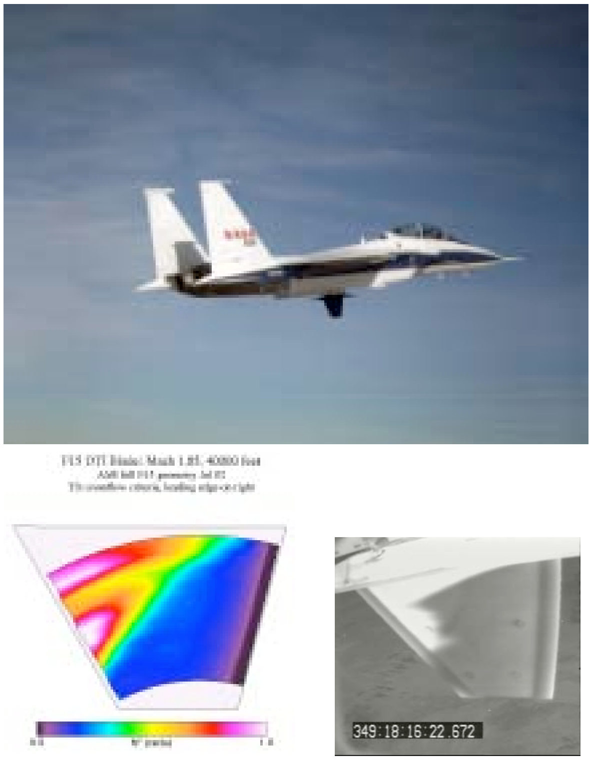

Figure 4. Computed amplification factors on supersonic test wing (left). Infrared image of test wing showing turbulent areas in white (right). F-15B with test wing mounted below (top).

Perhaps the most useful application of expanded computing power is the extension of computational simulation from analysis to design. This field, starting with single-discipline optimization and inverse design, has grown to include multidisciplinary optimization as well as distributed, multiobjective, and topological design. At the moment, most high fidelity optimization is used to refine a configuration that has been defined using simpler but more comprehensive analyses or design intuition, but as computing power increases, these tools will be used more at the conceptual design phase, leading to the possibility of innovative conceptual solutions that appear from the optimization automatically. This type of emergent innovation is suggested in some recent examples that illustrate how unexpected fundamental concepts can arise from robust configuration optimization. Figure 5 shows the computational grid defining a blended-wing-body design. This configuration was optimized using a Navier-Stokes simulation together with propulsion modeling to investigate propulsion/airframe interactions [15].

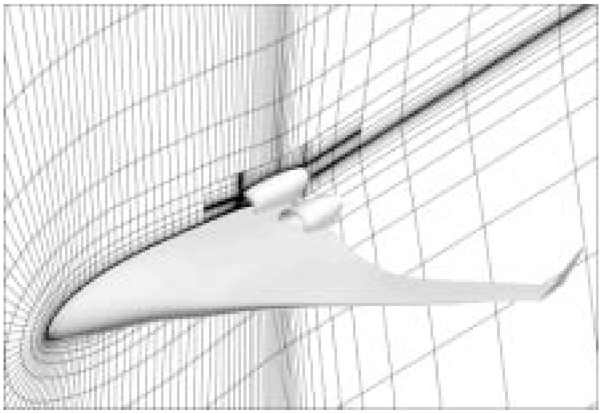

Figure 5. RANS-based Optimization of BWB

Optimization was also used to determine the maximum allowable thickness of the wing center section. As shown in figure 6, the center section can maintain weak shocks and low transonic drag, despite the freestream Mach number of 0.85 and an 18% thickness to chord ratio. This dramatic 3-D effect was not envisioned in the initial conceptual design of the BWB and permits configurations that might have been overlooked if 3-D nonlinear design tools were not available.

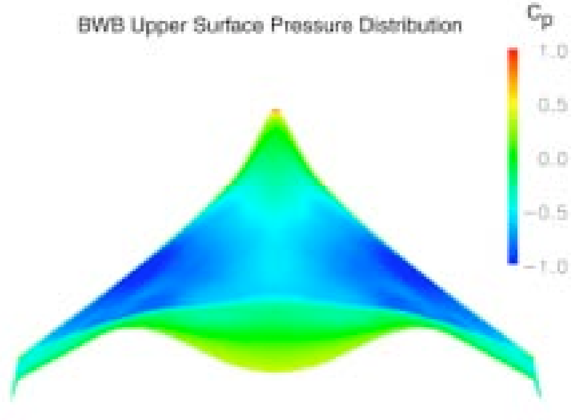

Figure 6. Blended Wing Body Cp Distribution (from [15]).

Another example of unexpected results appearing from topological optimization is summarized in figure 7. In this work, an evolutionary optimization algorithm was used to find the wing geometry that produced minimum total drag, yet fit inside a box of fixed height and span. Although the analysis was simplified, interesting and somewhat surprising results emerged and the idea was subsequently incorporated in the design of a very large airplane concept (figure 8) [16].

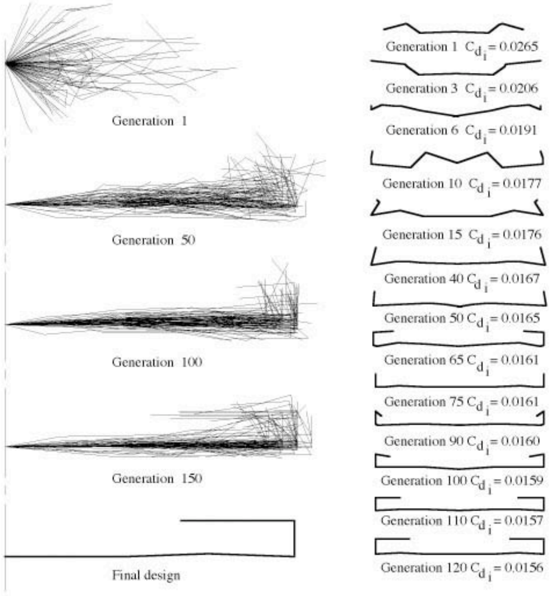

Figure 7. Evolution of C-Wing design from generic nonplanar wing model.

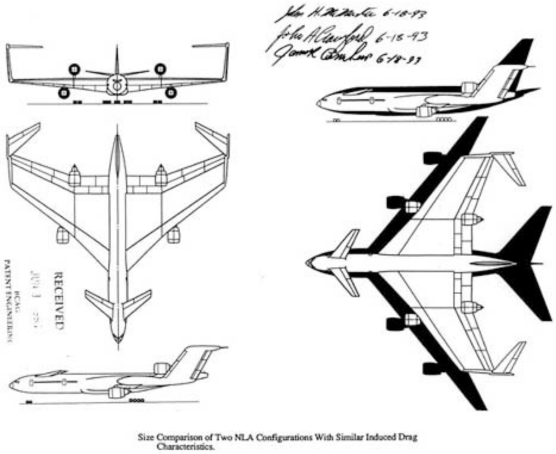

Figure 8. C-Wing transport aircraft concept [Boeing].

The utility of robust optimization methods, such as simulated annealing or genetic algorithms, which are generally much less efficient than traditional gradient-based optimization algorithms, improves as computational resources become more capable. By avoiding some local minima, not requiring smooth functions, and easily supporting large parallel computing environments, such approaches may find expanding applications in future conceptual designs. These methods are particularly well suited to topological and multi-objective design and have been applied successfully for quiet supersonic aircraft design problems using both Euler and linear analysis methods [17, 18].

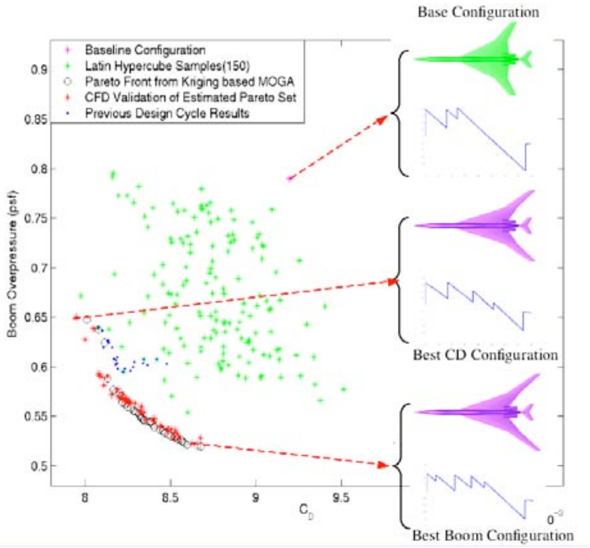

Figure 8. Multiobjective (boom and drag) optimization of a small supersonic aircraft using a genetic algorithm.

Man is (No Longer) the Measure of All Things Aeronautical

Continued advances in computation and electronics may have a more dramatic impact on aeronautics as automated systems replace pilots on an increasing number of aerospace platforms. While this might, at some time, be used to reduce the operating costs of cargo aircraft or eventually, perhaps, other transport aircraft, its more significant effect may be in enabling new roles for aircraft. With the fielding of military UAV's, aircraft are being used for reconnaissance and surveillance in situations, and for mission durations, incompatible with piloted airplanes. A more extreme example of how UAV's may be used in the future to expand the role of aeronautics is seen in the recent development of the ARES aircraft (Aerial Regional-scale Environmental Survey) for Martian exploration [19].

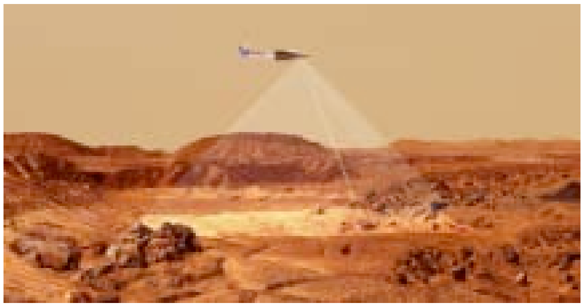

Figure 9. Artist's concept of ARES rocket-powered UAV for Mars exploration.

The use of autonomous aircraft for exploration of planets such as Mars or Titan is appealing, allowing high resolution imagery and *in situ* measurements of atmospheric and magnetic properties over a large region and bridging the scale and resolution measurement gaps between global-scale orbiters and higher resolution landers or rovers. As sensor and flight control electronics become smaller, the cost of such systems is dramatically reduced. In this program, the ability to reduce the aircraft scale was also exploited in the design and successful flight test of a subscale aircraft, dropped from a balloon at about 100,000 ft. The resulting data provided valuable insight on the vehicle aerodynamics, wing folding mechanization, and drogue chute dynamics.

It is sometimes imagined that the revolution in digital electronics occurred in the 1970's and that continued advances simply improve performance incrementally. Yet advances in microprocessors and surface-mount components just over the past few years have enabled inexpensive autopilots with masses measures in grams rather than kilograms. As an example of how this technology is changing aircraft capabilities, students in the aircraft design course at Stanford were challenged to design a small, low cost, fully autonomous aircraft using GPS navigation. Figure 10 illustrates the successful design, which weighed less than 300 g and was developed over the past 3 months.

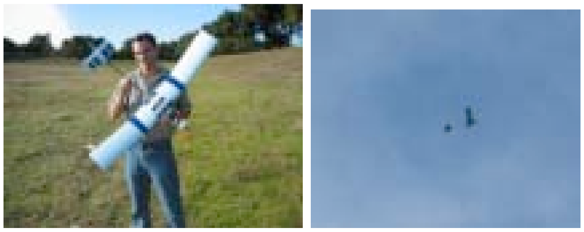

Figure 10. Autonomous electric aircraft developed in a few months using a 12g GPS unit, with airframe and flight software designed by the students.

As the weight and size of sensors and flight control systems drops, the connection between aircraft scale and human scale is less direct, and the opportunities for aircraft design once this constraint is removed are tremendous.

Micro-air vehicles, now being developed at aerospace companies, government labs, and universities have been rather arbitrarily defined as flight vehicles with spans of less than 15cm. Many such designs have flown successfully and work is now focusing on performance improvements, operational integration, and sensor development.

Figure 11. Micro air vehicle by MLB [20] with integrated video.

Although much of the current work in this field consists of system integration and product development, interesting, more fundamental research involves studies of low Reynolds number wing and rotor design, nonlinear control issues, and some work on flapping wing flight (since if flapping wing vehicles make sense anywhere, it would be at these small scales where inertial loads are less significant and the benefits of propulsion airframe integration are large).

Very small aircraft, ranging in size from a few centimeters to a few meters will likely find a variety of military and civilian roles in the future and provide an opportunity for further innovation in aerodynamic design, control, and propulsion.

As an example of some of the challenges associated with very small aircraft development, Stanford University researchers, sponsored by NASA's Institute for Advanced Concepts, considered issues in aerodynamics, control, manufacturing, and power needed for a centimeter-scale rotorcraft.

Figure 12. Mesicopter studies included optimal rotor design and testing of very small vehicles, including constrained tests of this 4-rotor design.

Challenges included 2-D airfoil and 3-D rotor design with insect-scale aerodynamics that necessitated Navier Stokes computation of the highly viscous low Reynolds number flows, accurate manufacturing of sections with 50 micron thickness, and stability and control issues arising from small time scales and very demanding weight constraints [21, 22].

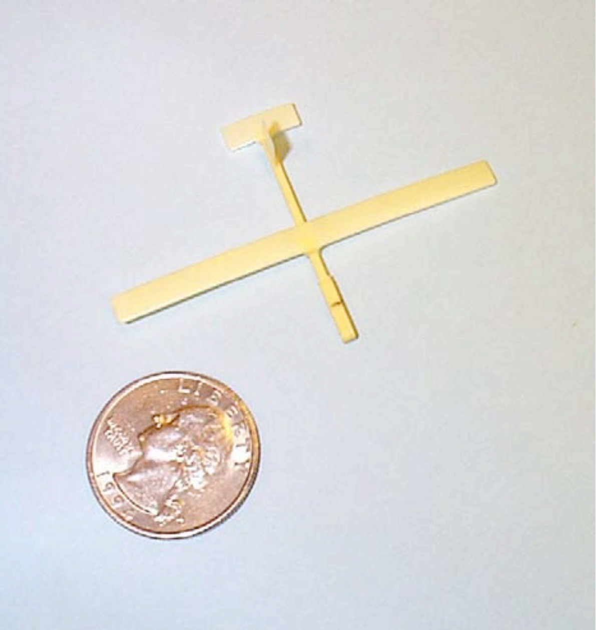

Figure 13. In addition to computational analysis and optimization, research included experimental tests of very low Reynolds number sections on micro-sailplanes.

A variety of test rotors and complete flight vehicles were constructed in this program, ranging in weight from a few grams to 200 g. The goal of the research was to explore a variety of technologies that might someday be of use in the design of very small aircraft, but the unavailability of commercial batteries at very small sizes prevented the development of useful vehicles at the time. Interestingly, this technology has evolved rapidly over the past few years and has spawned a burgeoning hobby industry for indoor and microflight model airplanes. Radio-controlled flight vehicles with spans of 10 cm, helicopters with all-up flying weights of 6.9 g, and solar airplanes powered by pager motors have been developed in the last year [23].

Figure 14. Matt Keenon's 1.7g solar-powered aircraft.

As the scale of flight vehicles is reduced, the importance of viscous aerodynamics increases, the importance of structural loads generally decreases, and the relative importance of atmospheric turbulence changes. The possibility that small flight vehicles could extract energy from gusts and wind gradients of many sorts has been suggested for years and dynamic soaring, as practiced by birds and insects might well provide significant performance advantages for these vehicles.

The feasibility of very small aircraft also suggests the possibility of using several, or even large numbers, of these platforms to accomplish missions that would normally require a larger vehicle. Swarms of micro air vehicles for atmospheric sensing or planetary exploration may become possible with continuing development in microelectronics, computational power, and battery or micro fuel-cell technology (figure 15). The use of multiple vehicles or collectives of individual agents to accomplish a shared task is the final area for potential innovation highlighted in this paper.

Figure 15. Swarms of very small aircraft might someday be used for 4-D observation, and multi-resolution imaging, providing a robust approach to atmospheric sensor platforms.

Collectives, Multiagent Systems, and Systems of Systems in Aeronautics

The development of aeronautical systems has focused on the design of individual vehicles, which are then sometimes assembled into a fleet, to become the air transportation system, for example. As the complexity of these systems grows, however, this approach to system design becomes more difficult and less optimal. New theories of collective behavior, an improved understanding of emergent system properties, and new approaches to the design of multi-agent systems promise to significantly change the way that aeronautical systems are developed.

Whether the system of interest involves network routing (of aircraft or data packets), the distributed design of a complex system by multiple disciplinary design teams, or the coordination of multiple air vehicles for performance enhancement or air traffic management, the science of multi-agent systems can be applied to create a system of systems whose performance may greatly exceed that of an ad-hoc aggregated system.

Although the theory of collectives and strategies for the design of complex systems are still in their infancy, several striking examples of the potential for this approach have been described recently [24] and further progress is likely to spur innovation in aeronautical systems for decades to come. The following examples are intended to provide only a suggestion for how this science could change future aeronautical design concepts.

Miniature Trailing Edge Effectors (MiTEs)

An unconventional application of the idea of collective systems to vehicle flight control is illustrated by the distributed control system shown in figure 16. The MiTE concept involves replacing or augmenting conventional control surfaces with a large number of simple and small trailing edge devices as shown below.

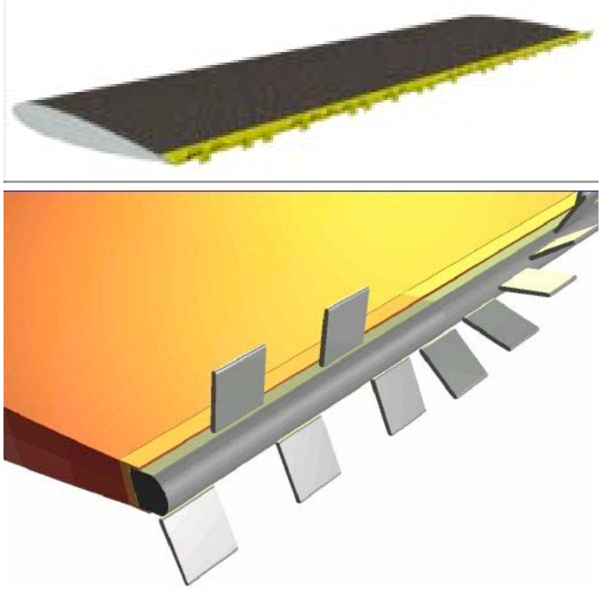

Figure 16. Distributed control using small trailing edge effectors.

The small surfaces (1% to 4% of the chord) are deflected in one of three states: neutral, up, or down, eliminating the need for servo feedback to accurately position the surfaces. Because of their small size, MiTEs provide very high bandwidth control and have been used successfully for flutter suppression. One difficulty with these devices is that they exhibit very nonlinear behavior due to the manner in which they are deflected, causing vortex formation near the trailing edge as shown in the time sequence of figure 17. This represents a difficulty when synthesizing control laws for a group of perhaps hundreds of the devices.

The approach described in [25] uses reinforcement learning and the theory of collectives [24] to optimize the performance of the system as a whole, while individual flaps make local decisions based on local information. The idea was implemented in a wind tunnel test, in which MiTEs were fabricated and a distributed control law was created to maximize the flutter speed of an elastically tailored wing. This approach successfully suppressed flutter, increasing the allowable dynamic pressure by almost 50% [25].

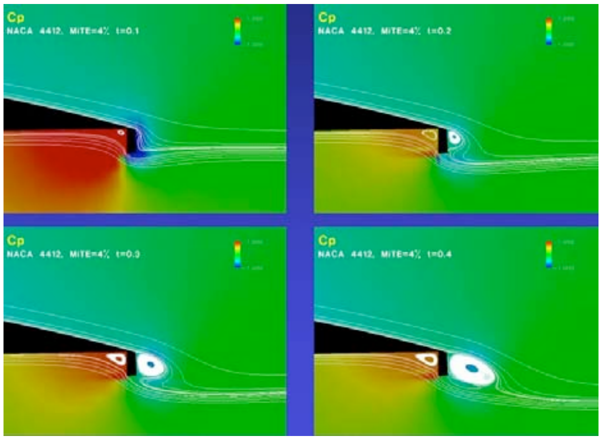

Figure 17. Flow near trailing edge after deflection of MiTE. Sequence from Navier Stokes simulation showing development of separation and shedding of vortex.

Formation Flight

Perhaps a more obvious example of the potential advantages of group behavior is that of formation flight. As illustrated in the flocking behavior of many migratory birds and as is well-known to aerodynamicists and pilots, substantial reductions in vortex drag may be achieved by exploiting favorable interference between two wings. Figure 18 (computed based on simple linear theory [26] and subject to roll trim constraints) shows that when the two wing tips are separated laterally by a small distance, a vortex drag savings of about 40% may be achieved. Since the longitudinal spacing does not affect the total vortex drag, this close spacing does not require a dangerously close proximity between the tips. A similar savings is produced by a wing flying in formation with its own image (ground effect), when the distance above the symmetry plane is about 20% of the wing span.

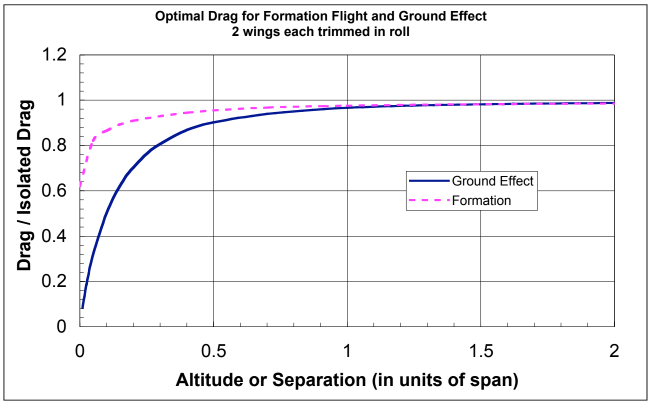

Figure 18. Potential reductions in induced drag due to favorable interference between two wings.

When more than two aircraft fly in formation, the potential savings is much larger, with a very simple analysis suggesting that the average lift-to-drag ratio scales as the square root of the number of aircraft in the flock. Thus, the potential savings associated with even three or four aircraft in formation may far exceed that of wing configuration features such as winglets, which, although capable of reducing vortex drag, involve a structural weight penalty that sometimes offsets much of the advantage [27].

One of the outstanding problems with formation flight is maintaining the correct relative position of the aircraft in the formation. The success of good pilots in achieving precision formation flight shows that this is not a completely intractable problem, however, and recent work at NASA has investigated some of the critical aspects of autonomous formation flight [28]. This fundamentally different approach to aircraft operation could be enabled by recent advances in precision navigation and increasingly capable and reliable automatic flight control.

Figure 19. Two F-18's fly in formation as part of NASA's Autonomous Formation Flight Program.

Techniques for the design of multi-agent systems and collectives may be applied in this example as well. With a large number of interacting air vehicles (or birds), simple rules can be created that lead, not just to the interesting looking emergent behavior described by Reynolds [29], but to a desired optimal system behavior. Figure 20 shows a top view of the time-based evolution of a group of 25 birds that start out with a random longitudinal distribution and by following a single simple rule and local measurements are able to efficiently and robustly find the desired solution. This approach, described in [30] may also be applied to the more interesting problem of inhomogeneous formations for which the weights, geometry, or mission capabilities of the individuals vary.

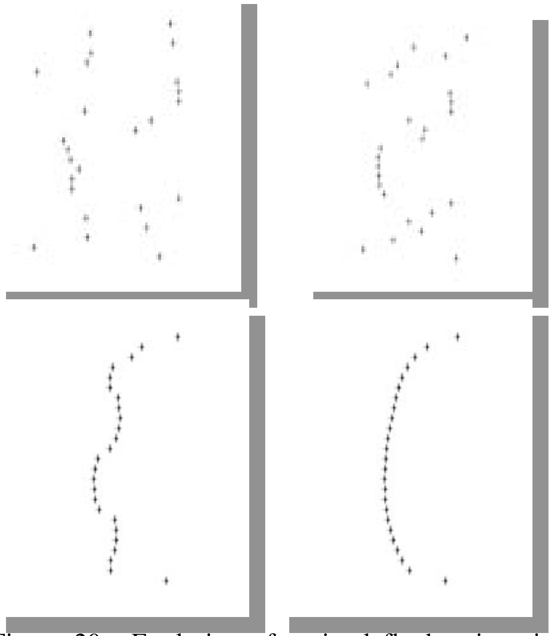

Figure 20. Evolution of optimal flock using single policy control strategy (clockwise starting from upper left).

In addition to applications of this concept using UAV's, researchers have discussed its application to efficient cargo transportation and as a possible approach to more environmentally friendly aircraft. Further research is required in flight control, in aircraft design to maximize interference and reduce position sensitivity, and in system operation to best exploit the potential advantages of the concept.

Figure 21. "Artist's" concept of formation flight for low cost cargo transportation. Use of configurations especially tailored for formation flight can amplify potential savings.

Conclusions

Although the pace of vehicle development over the second fifty years of aeronautics appears to have slowed in comparison to the breakthroughs that led from Kitty Hawk to LAX, many opportunities exist for future innovations in aeronautics. Changing requirements associated with air transportation capacity and security as well as environmental sustainability will likely motivate new concepts in aeronautics even in the relatively near future, while continuing major advances in computational capabilities, electronics miniaturization, and complex system understanding may make these possible.

Lack of future innovation, however, could be a major problem for the aerospace industry and the nation, both directly and because of the indirect effect on the workforce. A sustained period of stagnation may lead potential future innovators to other fields and since innovation is, by its nature, not something that can be predicted, sustained, consistent support for research and development is critical.

Acknowledgements

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