Taking Off:
A Century of Manned Flight

Presented at the 2003 American Association for the Advancement of Science Annual Meeting

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AIAA

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To Alexander and Caroline Coopersmith,
Kara, Heather and Brooke Launius, and
Haley Yates,
for whom the dream is still alive

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Introduction

On any day in 2000 in the United States, 25,000 commercial airliners carried 1.6 million passengers—over one-third of the 4.4 million passengers worldwide. An additional 30,000 business jets and over 200,000 private airplanes can travel among 15,000 airports. Meanwhile, more than 1000 aircraft of the four armed services of the United States protected the nation's security. Predictions are for an average annual growth rate in passengers and cargo of 5% over the next decade; the number of passenger aircraft will increase from over 10,000 in 1999 to nearly 15,000 in 2009 and 19,000 in 2019.

All this activity began with two brothers, Wilbur and Orville Wright, who, after years of experimentation, became the first people to fly a powered heavier-than-air airplane on 17 December 1903. In a century of amazing technological accomplishments, the four flights that day still stand out, whether viewed in terms of consequences, dreams, or simple perseverance. Not until 1906 did Alberto Santos-Dumont become the first European to fly, and it was 1908 before Glenn Curtiss become the next American pilot, demonstrating how far ahead of everyone else the Wright brothers were. In 1908, the Wrights could fly and turn for two hours while the rest of the world could only manage hops of a few minutes. Only in that year did the Wrights receive a belated—but tumultuous—public recognition of their pioneering efforts when they demonstrated their improved plane outside Washington, DC, in hopes of winning a military contract.

The triumph of the Wright brothers has resonated strongly in American society, culture, and the economy. By starting the ascent of humanity into the skies, they fulfilled an age-old universal dream—but that was not the only reason. The two bicycle mechanics embodied the essence of the Yankee tinkerer and inventor, working alone. As Peter Jakab demonstrates, the Wrights were much more than casual tinkerers; they were engineers in the best sense of the word. But, as Janet Bednarek shows, the Wrights continued the tradition of individuals working independently to design and build their own aircraft. The Experimental Aircraft Association has institutionalized this tradition, best displayed at its annual airshows. Perhaps the penultimate realization of this dream was Paul McReady's 70-pound *Gossamer Condor,* on 23 August 1977 became the first plane powered by a person to take off, fly a mile in level flight, turn and land.

The Wrights demonstrated the importance of aeronautical engineering, but, patent battles notwithstanding, they lost control of their invention as other people and organizations became involved. World War I was a major turning point in the history of aviation, turning it from a technology of esoteric interest shared by hundreds to an industry and military service populated by tens of thousands. The demands of war accelerated technological developments and manufacturing while the "knights of the air" captured the attention of a public numbed by the massive carnage of trench warfare. Hereafter, aviation—"the high ground"—was an essential part of any modern military, and the military, as Charles Gross demonstrates, was a key promoter of aviation research.

In comparison with the skepticism that met news of the Wrights' 1903 accomplishment (but not their 1908 demonstrations), Charles Lindbergh's nonstop solo flight from New York City to Paris in 1927 sparked extraordinary, sustained excitement that immediately spread across continents. Lindbergh bested several rival pilots to attain one of the many aviation prizes offered in the 1920s, a strong demonstration of how much had changed since 1903. The Lone Eagle truly was an international hero and met a popular reception unequaled until the first cosmonauts and astronauts returned to Earth after breaching the barrier of space. the excitement was not confined to Lindbergh: flying in general benefited from the greater attention, including a wave of investment in aviation stocks that climbed until the crash in October 1929.

The Wrights' flight was a world-shaping event, but not by itself. The popular image of aviation is the individual pilot. The reality is that the pilot and the airplane are the apex of a huge supporting infrastructure that has grown over the last century to research, develop, diffuse, and support aviation. As Michael Gorn shows, the university has long been a major contributor, although not the only player. From the wind tunnels of the National Advisory Committee for Aeronautics (NACA) at the Langley Memorial Aeronautical Laboratory in Hampton, Virginia, to the overnight service airports of Federal Express and UPS, from the military and private pilot training schools to air traffic control, millions of people, and thousands of institutions enable flight.

The government had to play a large role to support civil as well as military aviation. Airplanes proved costly to develop, build, and operate. Nor was the supporting infrastructure—airfields, weather forecasts, radio and teletype communications, trained crews, mechanics, and other staff—inexpensive. As Roger Launius illustrates, aviation probably best demonstrates the contradiction between the U.S. profession of faith in free markets and the government's need to shape the evolution of a technology for national security and economic goals. The concept of industrial policy clashes with the choices generated in a market economy. Only the military, using the aegis of national security, has had the ability to create markets although the Post Office tired. Not coincidentally, in the mid-1920s Boeing's dependence on government contracts was sufficient to merit a five-person staff in Washington, DC.

Not every promotion by government succeeded. Efforts in the 1920s and early 1930s to promote commercial aviation via airmail and other incentives fell far short of backers' hopes. Not until the development of the Douglas DC-3 did airliners prove to be profitable as well as effective technologies. World War II further accelerated the growth of aviation as manufacturers produced tens of thousands of planes and the military trained hundreds of thousands of pilots, mechanics, and other essential personnel.

Aviation became further embedded in the economy after the introduction of jet travel in the late 1950s. The number of planes and passenger is just the tip of the iceberg. More important is the role of air travel in enabling just-in-time delivery of parts and products. The success of Federal Express, UPS, and other express services depends on their cargo planes that fill the skies at night, delivering parcels to central airports, where they are sorted and then sent out on other airplanes for delivery later that day.

Indeed, future historians may well characterize successful human flight, and all that followed in both air and space, as the most significant single technology of the twentieth century. Has it fundamentally reshaped our world, at once awesome and awful in its affect on the human condition? Has it made easy, even luxurious, movement about the globe an afterthought? At the dawn of the twenty-first century, crossing the American continent or Atlantic Ocean demands less than one day. That stands in striking contrast to the experience before 1903, when Jules Verne's *Around the World in Eighty Days*, published originally in 1873, accurately described travel times.

Without question, aviation has been a powerful technology, but it has been greatly influenced by other technologies; indeed, it has often been the initial recipient or market for technologies that flowed into other areas. Materials and electronics are probably the two best examples. Planes have moved from wood to metal and, in recent decades, to composite materials. The results have been lighter, stronger, more capable structures.

Electronics extend far beyond the actual aircraft. The most exciting and technically challenging task facing civil aviation is the creation of an automated air traffic control system. The importance of electronics shows no signs of decreasing. Increasingly, airplanes are defined by their electronics, especially military planes.

As we enter the second century of human flight, we should remember and understand what has not happened as well as what has. Airpower has not made war too horrible to contemplate. There is not an airplane in every garage, nor do supersonic and hypersonic transports effortlessly zip passengers from continent to continent. Financially, the economics of airlines and air travel continue to be unstable, following boom-and-bust cycles.

Like airline routes, aviation inventions and innovations span the globe with the United States and Europe, reflecting their economic and technical base, dominating. This book focuses on the United States, but anyone who neglects the many contributions of European aerospace community does so at their peril. It is easy to take the U.S. leadership for granted, but nine decades of European aircraft show that creativity and ingenuity are not the monopoly of any one continent or country. The Airbus A380, planned to carry over 500 people when it begins operation later this decade, may revolutionize flying as much as the Boeing 747 did. Aviation in the United States has benefited considerably from the huge size of the country, a single national government, and a political preference for state-supported private enterprise instead of state-owned firms.

What does the next century hold? It is easy to be pessimistic. On 18 November 2002 the congressionally mandated Commission on the Future of the United States Aerospace Industry issued its final report, warning that this nation may well lose its aviation leadership in the twenty-first century unless government, industry, labor, and primary and secondary education cooperate to rejuvenate the aerospace industry. The Commission called for sweeping changes including promotion of mathematics and science education as well as lifelong learning, cooperation among different parts of the federal government, sustaining and supporting the economic viability of the industry, and sustaining long-term investments in long-term research and infrastructure.

The United States finds its manufacturing dominance increasingly challenged with success by Airbus. The post-Cold War consolidation has reduced the industry from over seventy major suppliers in 1980 to five prime contractors today. Ideas for new technologies exist, but huge research and development costs (the Airbus 380 is expected to cost $8–12 billion to develop) ensure that most, regardless of merit, will not leave the computer screen (formerly known as the drawing board). Boeing in December 2002 abandoned its Sonic Cruiser, announcing it intends to develop a new plane with a focus on reduced operating costs, not increased speed. Perhaps the most exciting and technically daunting challenge facing civil aviation, the creation of an automated air traffic control system, is more a challenge in organization, computing, sensing, and communications than actual aviation. The North American share of traffic is increasing absolutely, but decreasing relative to the rest of the world as it, especially Asia, approaches North American levels.

Perhaps most important, a sense of technological stasis coupled with financial pressures, hovers over U.S. aviation. The most exciting technological fields—those attracting the best and brightest—are information technologies, biotechnology, and space. Much of the challenge facing aerospace consists of applying these technologies. The challenges and opportunities exist, but their execution seems measured in decades, not years.

The Commission was optimistic, heralding that, if its recommendations are carried out, "Aerospace will be at the core of America's leadership and strength in the 21st century." In short, we have come a tremendous way from the accomplishments of the Wright brothers a century ago, but, as in other areas of science and technology, the rest of the world will not allow the United States to rest on its laurels. What the Wrights began continues. Where it will go and how is the challenge for us today and tomorrow.

The Wright Brothers and the Invention of Aeronautical Engineering

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Introduction

On 17 December 1903, Wilbur and Orville Wright inaugurated the aerial age with their historic first flights in a powered airplane at Kitty Hawk, North Carolina. On that chilly, wind-swept morning, humans took wing for the first time. The triumphant moment of success was dramatically captured by Orville's camera. The graceful image of the Flyer lifting off its launching rail, Orville onboard with Wilbur trailing behind, is one of the most famous photographs ever taken. It is forever etched in the mind of anyone with an interest in aviation.

However, the Wrights' achievement encompassed far more than the singular act of getting an airplane off the ground. Wilbur and Orville defined and solved all of the essential technical problems of heavier-than-air flight. The Wrights are important not simply because their airplane was the first powered, heavier-than-air craft to leave the ground and maintain sustained flight. They are the watershed figures in aviation history because every successful airplane that has followed is rooted in the Wright Flyer. Moreover, the research and design techniques that the Wrights developed and used in the course of building their flying machine became, and in rudimentary form have remained, the standard approach to aircraft design. In short, not only did the brothers invent the airplane, they also pioneered the practice of aeronautical engineering.

In many key respects, aircraft design today mirrors the basic concepts and techniques developed and employed by the Wrights nearly a century ago. In other ways, however, the analytical tools modern practitioners use, the design parameters within which they work, and the institutional settings that define the direction of their research programs are quite different. This paper will trace in broad strokes the evolution of the practice of aeronautical engineering, focusing predominantly on the tools and settings that emerged to perform research in aerodynamics. This history can be usefully divided into three periods: the birth of modern aeronautical engineering practice in the work of the

Wright brothers, the emergence of the institutional entities and facilities in which the field grew and matured in the 1920s and 1930s, and finally the influence of the computer revolution on aerospace engineering from the 1970s to the present. On some levels this is a very simplified historical framework. But in stepping back for the long view, it does in great measure reveal the fundamental historical dynamics that have governed the evolution of aerospace engineering, particularly with regard to aerodynamics.

The Invention of Aeronautical Engineering

What distinguished the Wright brothers, and in large measure explains why they were successful in inventing a practical airplane, was their method.[1] They did not apply uninformed trial-and-error techniques like so many of their contemporaries, nor did they tackle the problem as theoretical scientists, trying to discover the underlying principles of flight. Instead, the Wrights were the first to truly engineer an airplane in the modern sense. The goal was less to understand why the forces of flight behaved the way they did than to learn how in actual practice they acted with respect to one another, and in turn to use this information to construct a successful flying machine. They described a set of design and performance parameters and then developed research tools to generate specific pieces of data that were required to implement the design. This was engineering in its most basic form and the supporting foundation of all aspects of the Wrights' inventive method.

Of course, the Wrights' aeronautical work embodied numerous original conceptual breakthroughs that enabled them to quickly leap ahead of others working on the problem of mechanical flight. Their adaptation of three-axis control featuring their wing-warping system for lateral balance, their understanding of the movement of the center of pressure under the wing, and the development of an aerial propeller, among other creative insights, were central to their invention of the basic technology of flight. However, in the course of taking these seminal steps the brothers employed and adapted basic engineering methods that are recognizable by any present-day practicing professional engineer. It is this engineering methodology of the Wrights, rather than their admittedly towering conceptual accomplishments, that is the focus for this discussion.

The approach taken by the Wright brothers included many elements common to all fields of engineering, techniques that were not specific to aeronautics. For example, they began by conducting a literature search. They familiarized themselves with the state of flight research and experimentation as it stood when they entered the field in the late 1890s. They took note of the useful ideas of their predecessors, and perhaps more importantly, discovered fruitless avenues to avoid. This is the typical first step taken by any engineer. Once immersed in the project, the Wrights' revealed a number of other approaches and capabilities that characterize standard engineering method.

First, they recognized that they had to think in terms of technological systems. The airplane was not just one invention, but many discrete elements, all of which had to be developed independently and then brought together to operate in unison for the craft to fly. Aerodynamics, control, structures, propulsion, and other areas all presented distinct technical and design challenges that had to be met. Failure to conquer any one of them meant the whole system would be unsuccessful. The Wrights understood this and pursued their inventive work with this mindset at all times.

The brothers also saw the advantage of continuity in design development. Their path to practical flight took them through an evolving series of gliders and powered machines derived from a single basic design, each incorporating what was learned from the previous craft. They shunned the rarely productive haphazard, mercurial approaches to flight research that were common among their contemporaries.

Technology transfer is also evident in the Wrights' work. Certain obvious examples, such as the sprocket-and-chain drive transmission system on the Wright Flyer that connected the twin propellers to the engine crankshaft, clearly were drawn from the bicycle and a knowledge of basic mechanics. More subtle examples stemming from the brothers' familiarity with bicycles included concepts of stability and control. Knowledge that a bicycle is a totally unstable yet entirely controllable technological system gave the Wrights confidence to pursue this idea with the airplane, an approach that was very much counter to mainstream aeronautical thinking at the time. As is generally the case, successful engineering is the product of merging original concepts with imaginative new ways of adapting existing technology. The Wrights were firmly within this tradition.

Finally, the ability to move with facility from conceptual models and thought processes to practical, functioning hardware is a skill that all good engineers possess. The Wrights were especially adept at this, and it was a major contributing factor to their success. They could visualize technological components, manipulate and refashion them in their mind's eye, and then transform them into a working mechanical device. Perhaps the most dramatic example of this was their creation of an aerial propeller, which they first conceived as a rotary wing turned on its side to generate a horizontal "lift" force, or thrust. Using this concept, they then used the aerodynamic data collected for their wing design to fabricate two extremely efficient propellers. They were unlike any propellers that had come before and all subsequent propellers have been based on the Wright design. The propellers were among the most original components of the Wright Flyer, but the brothers' effective capacity for moving back and forth between the abstract and the concrete is reflected throughout their work.

These aspects of the Wright brothers' engineering method and talents were at the center of their technical achievement. They are in significant measure the reason why Wilbur and Orville invented the airplane rather than some other of the many experimenters who were also working on the problem of heavier-than-air flight. These techniques and skills were part of the foundation that they established for basic aeronautical engineering. However, as noted earlier, they were not peculiar to flight research. All fields of engineering employ them, but the brothers paired these general engineering tenets with two fundamental tools specific to aircraft design that combined with them to define aeronautical engineering practice for much of the century. These core tools were the use of the wind tunnel in aerodynamic research and flight testing as a data-gathering and information feedback resource.

The Wright brothers did not invent the wind tunnel. Nearly a dozen tunnels preceded the one they built in 1901, beginning with the tunnel constructed by Francis Wenham and John Browning in 1871.[2] What made the Wright tunnel the breakthrough instrument was that it was the first to be used to gather specific aerodynamic data to be incorporated directly into the design of an airplane. When the brothers began their aeronautical research, the basic equations necessary to calculate the lift and drag for a given wing surface were in place. They did not have to derive them in any way. Further, aerodynamic data regarding air pressures on wing surfaces at different angles of attack had been collected by previous experimenters, most notably the great German glider pioneer, Otto Lilienthal.[3] Thus, it was a relatively simple matter for the Wrights to substitute the particular specifications of the glider they planned to build into the lift-and-drag equations to calculate projected performance. This is precisely what they did with their first two aircraft in 1900 and 1901.

These first two Wright aircraft were biplane gliders, based on a small five-foot wingspan kite that the brothers built in 1899 to test their method of lateral control that they called wing-warping. By twisting, or warping, the wingtips of their glider in opposite directions more lift would be generated on one side of the aircraft, causing that side to rise, thus banking the whole aircraft. By controlling this twisting, or warping, via cables, the Wrights could balance the wings of their glider and initiate turns when desired. This basic concept of differential lift on opposite sides of the aircraft was central to the Wrights' successful invention of the airplane and is the heart of the method of control of all airplanes that followed.

The Wright brothers flight tested these gliders in 1900 and in 1901 on the sandy, windy beach off the coast of North Carolina, near a fishing village called Kitty Hawk. Actual flight performance was mixed in these first two years of the Wrights' flight experiments. The wing-warping method of control proved sound, but the aerodynamic performance, especially the lift, fell far short of what their calculations suggested it should have been, leaving the brothers in a quandary.

They immediately suspected the air pressure data, or coefficients of lift as they would come to be called, that they had utilized from Otto Lilienthal's published research. All other terms in the equations were directly measured quantities, such as velocity and the surface area of the wings, so they had little doubt about the accuracy of those figures. The next logical step for the brothers was to gather their own coefficients of lift rather than relying on the suspect work of others.

After experimenting with several other devices, the Wrights settled on the wind tunnel as the optimum tool for collecting aerodynamic data. The Wrights' tunnel itself was little more than a crude wooden box, six feet long and sixteen inches by sixteen inches square, with a fan at one end. The significant feature was the sophisticated test instruments they designed that were mounted in the airflow to generate the coefficients of lift and drag. These instruments, or balances[4] as the brothers called them, were cleverly designed mechanical analogs of the lift-and-drag equations. In other words, they operated in such a way as to yield the specific piece of data, i.e., the term in the equations, the Wrights sought, namely the coefficients of lift and drag. The balances were also constructed such that an unlimited number of wing shapes could be tested over a full range of angles of attack, thereby generating coefficients for a wide variety of potential wing surfaces, not simply a single shape as Lilienthal had done. Not only were they able collect a large amount of data with the balances, but modern review of the brothers' coefficients has confirmed them to be quite accurate as well.

The Wrights performed the bulk of their wind tunnel testing in October and November 1901. Armed with this vast array of data, the brothers set about designing a new glider to fly at Kitty Hawk in 1902. The 1902 aircraft was a great improvement over the previous machines. It produced precisely the lift that the Wrights' calculations predicted it should and it did so with a very favorable lift-to-drag ratio, meaning it could sustain itself at very low angles of attack.

As the aerodynamic research was going on, the brothers made other refinements to the glider, most significantly in the control system. They added a vertical rudder, later made movable, to eliminate several problems that emerged with the wing-warping system of lateral control in 1901. The resulting aircraft was the first truly practical airplane. It was fully controllable in all three axes of motion, it had sound aerodynamics based on sophisticated wind tunnel research, and had an ingenious structural design that allowed for strength and was lightweight. Of course, the brothers went on to build and fly a powered version of their design, making history on 17 December 1903, but the solutions to all of the essential aerodynamic, control, and structural problems leading to mechanical flight were embodied in the 1902 glider. Indeed, when the Wrights secured a patent on their flying machine in 1906, it was for an unpowered version, not the famous craft from 1903.[5]

It is not exaggerating to say that the Wright brothers' airplane and their ingenious wind tunnel balances are two halves of a single invention. One cannot understand the craft that lifted off the sand at Kitty Hawk in December 1903 without understanding the little instruments that were churning out data in the brothers' Dayton workshop in late 1901. Not only did the Wrights use their wind tunnel to design an efficient wing shape, but the tunnel also was used directly in the design of the propellers, wings struts, and other features of the airplane. Simply stated, it was the heart of their aeronautical research effort.

Equally significant was the manner in which they carried out their aerodynamic experiments. Unlike most previous wind tunnels, which were used to gather general qualitative information on shapes in a flow, the Wrights' tunnel was designed expressly to yield specific quantitative data to be used in the equations then in place for designing an aircraft. The Wrights were the first to use a wind tunnel in this modern fashion. Of course, the equations have become more complex and include many more terms than in the Wrights' day, but the approach they developed is fundamentally the same. Wind tunnel research was central to the Wrights' aeronautical effort, and it remains at the heart aerodynamic study today.

The other critical tool employed by the Wright brothers that has come to define aeronautical engineering practice was flight testing. This is not simply the building of an aircraft and attempting to fly it, hoping for the best. Flight testing as the Wrights approached it was a slow, systematic, incremental series of field trials, observing and recording performance characteristics, and feeding that information back into the design.

The brothers would typically begin by flying their gliders as kites, unoccupied, to record measurements of lift, drag, and other performance elements. The craft then would be kited with a pilot onboard to give the operator a sense of the flight characteristics and a feeling for how the controls worked. Next, short glides would be attempted, only a few inches off the ground. During these initial flights the lateral balance controls would be fixed so the fledgling pilot need only concern himself with pitch control. Once some experience and, more importantly, flight performance data were gained in this way, the wing-warping controls would be freed to add a further variable to the mix. Progressively, farther free glides of greater duration would be made, all the while gaining more data and piloting experience. The Wrights were not only making qualitative judgments regarding the performance of the aircraft. They were also recording quantitative data in a systematic way to help them understand the behavior of their machines. They measured wind velocities and angles of attack, explored the movement of the center of pressure with actual