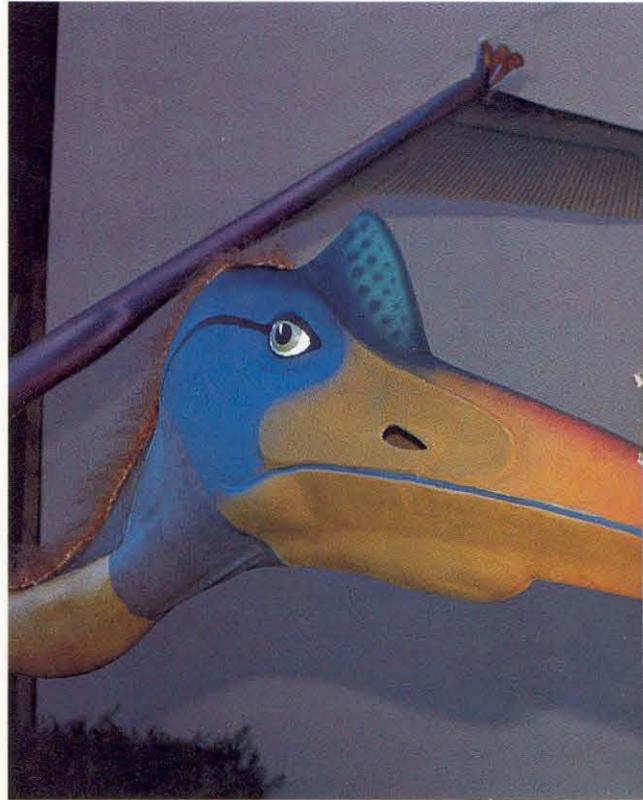


Alan Cocconi (left, BS 1980) and project manager Alec Brooks (PhD 1981) calibrate the angle-of-attack vane on the swing-wing development model of the pterodactyl.



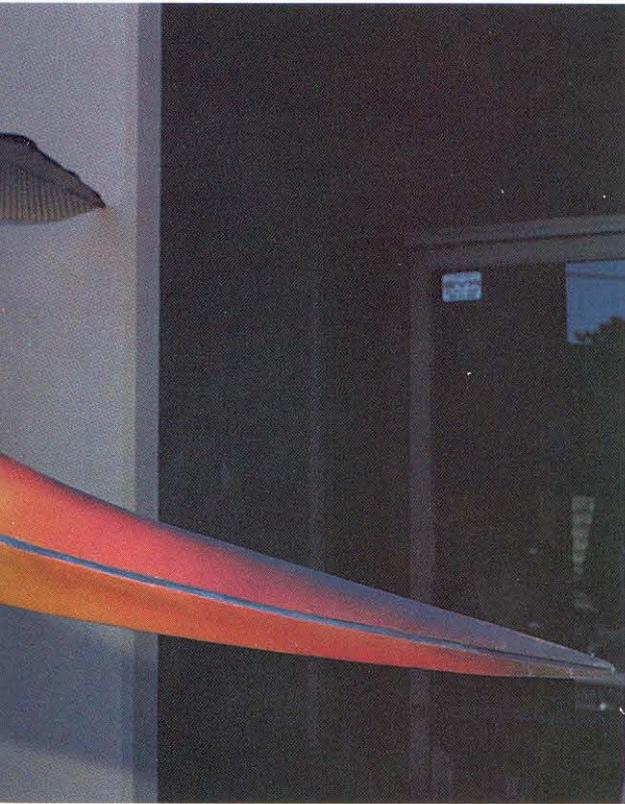
Below — the half-size, lateral-control development model is pulled into the air by ground-based winch. The auxiliary tail is dropped away after release from the tow line. The small bump on the creature's back houses an emergency parachute — just in case.



by Paul MacCready

SOME 65 MILLION YEARS AGO, a gigantic pterodactyl — a flying reptile — lived in the region now called Big Bend National Park in west Texas. By remarkable good fortune, a few of its fossilized bones, which provide clues to its size and appearance, have survived and been found. These clues suggest that the creature, designated *Quetzalcoatlus northropi*, had a wingspan of 11 meters (36 feet) — the size of a four-person airplane. It is the largest natural flier known.

In late 1983 I realized that there had been recent advances in the aerodynamic theory of oscillating airfoils, in the theory and practice of stability and control, in robotics, mechanisms, sensors and servos, and in composite structural materials and techniques — advances that meant that perhaps now a flying replica of *Quetzalcoatlus northropi* would be feasible. So we decided to try it. A primary reason for mounting the project was to give people the chance to experience the awesome grandeur of this natural creation in a manner that could never be matched by looking at a static display or even an animated film. A zoo or nature park lets one



The Great Pterodactyl Project

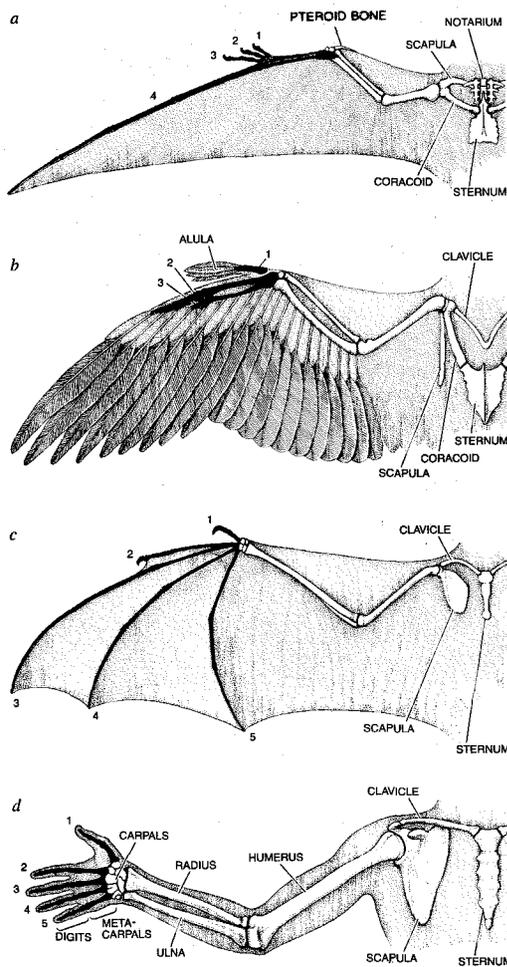
observe modern living creatures; a natural history museum displays inanimate items from prior times. The flight of the pterodactyl replica would combine the "aliveness" of the zoo with the time grasp of the museum.

In April 1984 the Smithsonian Institution's National Air and Space Museum initiated the project to build and fly the replica (called QN™), and subsequently the Johnson Wax company agreed to provide the major funding. The project team is based at Aero-Environment, Inc., with outside consultants helping in specialty areas. One goal of the project is to fly the QN replica on the Mall in Washington, D.C., in June 1986 in conjunction with the opening of the National Air and Space Museum's IMAX film, "On the Wing," also funded by Johnson Wax. The QN replica will play a significant role in the film, which explores the connections between nature's fliers and aircraft.

The fossil remains of *Quetzalcoatlus northropi* had been found in 1972 in west Texas by Douglas Lawson, working with Professor Wann Langston, Jr., at the University of Texas at Austin. Two groups of fossils

were found. The first group contained only fragments of half of the bones of one wing and one neck vertebra. The other group, 50 kilometers away in distance and an unknown difference in time, contained fossil remains of at least a dozen smaller creatures. The common fossils from both groups were nearly identical in shape, differing only in size. Both groups were given the genus name *Quetzalcoatlus* after the Aztec feathered serpent god, Quetzalcoatl. The species of the larger animal was named *northropi* after the Northrop Corporation, which had built several giant flying wings. The smaller animals have not yet been assigned a species name and are referred to simply as *Quetzalcoatlus* sp.

On the basis of rather complete sets of bones and from extrapolations from *Pteranodon*, a somewhat differently shaped pterodactyl, the wingspan of *Quetzalcoatlus* sp. was estimated to reach 5.5 meters. Early estimates of the span of *Quetzalcoatlus northropi* wings ranged from 11 to 21 meters, but as we kept reviewing the subject, with inputs about the engineering limits of muscles, tendons,



The wings of a pterosaur (a), a bird (b), a bat (c) and the arm of a man (d) indicate evolutionary variations on a theme. Adaptation to successful flight took several different routes.

From "Pterosaurs" by Wann Langston, Jr. © February 1981 by Scientific American, Inc. All rights reserved.

and delicate hollow bones, the estimates edged toward the lower end of the range.

Roughly 85 known species made up the order *Pterosauria* of flying reptiles. A sub-order, *Rhamphorhynchoidea*, appeared 200 million years ago. They were rather small, some the size of sparrows, and featured short heads and necks and long tails. The other suborder, the *Pterodactyloidea*, emerged 50 million years later. These had long heads and necks, were almost tailless — and large. The *Quetzalcoatlus* species were pterodactyls, as was *Pteranodon*, whose wingspan reached seven meters. Many pterosaurs had crests on their skulls; in *Pteranodon* the crest reached an extreme size, doubling the length of the skull in some cases. In other fossils the crest was apparently lacking. If the lack arose from the animal not having a crest, rather than from the imperfect preservation of fossils, this casts doubt on the use of the crest for some operational function — such as to balance the head, to reduce loads on the neck, or to add to yawing forces or drag during maneuvering. The large pterodactyls had,

relative to size, bigger brains than did the smaller, more primitive pterosaurs and reptiles; nature apparently found it an efficient tradeoff to increase brain size at the expense of eliminating the tail.

Similarities between the wings of a pterosaur, a bird, and a bat, and the arm of a human bespeak their common ancestry. The adaptation of biological flight, wherein the laws of aerodynamics and muscle strength and the structural realities of tendons and bones must prevail, designs the configuration. From different starting points there are a variety of routes leading to successful flight.

The pterodactyls were apparently dying out toward the end of the Cretaceous period, the last portion of the Mesozoic. This was a time of substantial changes in climate and habitat. *Quetzalcoatlus northropi* may have been the last to depart. The timing of the final disappearance of the pterosaurs may well have coincided with the great extinction about 64 million years ago. Whether or not this event was attributable to a large meteorite striking the earth, the catastrophic consequence of some special event is unquestioned; half the species of flora and fauna disappeared, including all land and flight animals larger than about 23 kilograms. Some birds and pterosaurs occupied equivalent ecological niches a hundred million years ago. The pterosaurs died out after evolving some extremely large forms. The birds proved to be more adaptable to the changing world, and they survived. Much later a huge bird emerged — the Giant Teratorn. This vulture-like bird, with a wingspan over seven meters and probably weighing well over 80 kilograms, was found as a six-million-year-old fossil and may represent the heaviest creature to have flown. Some extinct flightless birds were much heavier still.

The physical laws of aerodynamics determine the minimum power required for a flying device, animal or man-made, as a function of its shape, size, and weight. In comparing many large birds, we find that the muscle power available per kilogram for propulsion actually decreases with increasing weight. However, the power required per kilogram increases slowly with increasing weight. This is a consequence of the fact that for flight vehicles of the same shape and density, the larger ones fly faster because they have to carry more weight per square meter of wing area. If you double the dimensions of such a vehicle, the wing area goes up by a

factor of 4, weight by a factor of 8, and the speed and the power required per unit of weight both increase 1.4 times.

Birds that are primarily soarers do not have much margin of power beyond that needed for takeoff and brief climbing and cruising to locate upcurrents in which to soar. Power required and power available are closely matched. Therefore a bird that grows much larger will end up with inadequate power unless there are some refinements not yet considered. There are three refinements available: (1) as size and/or speed increases, an aerodynamic scale effect comes into play and yields slightly more efficient wings; (2) the creature can alter its configuration to be more efficient, becoming, say, more like a sleek sailplane; and (3) the weight can be kept below that which would be expected if the density stayed constant as the bird grew in all three dimensions. We suspect that *Quetzalcoatlus northropi* needed all three approaches, with the lighter weight effect being especially important. The thin walls of the wing bones indicate a very light structure. They are delicate tubes, and other parts of the creature were fashioned with comparable delicacy. Thus, in spite of its large size, its wing loading and power required per kilogram might have been about the same as for some modern vultures.

There has been speculation that *Quetzalcoatlus northropi* was a poor flier and could take off only by launching from cliffs or trees and fly by gliding. Paleontologist Kevin Padian of UC Berkeley, who has studied pterosaurs extensively, suggests that the legs of pterosaurs were more like those of birds and dinosaurs than was previously assumed. For *Quetzalcoatlus northropi* the takeoff and flight characteristics and behavior are envisioned as those that might appear if one combined various features of a frigate bird, an albatross, a pelican, and a stork or crane, and then increased the size about sixfold, decreased the density somewhat, and cut the wing flapping rate down to one cycle every two seconds. The original was deemed to be able to walk and take off from flat ground without wind, climb weakly, and stay aloft for long times and distances by soaring on upcurrents. It did not land and take off from water, although it may have been able to snatch fish from near the surface while it remained flying. In spite of its gargantuan size, its wing loading and hence flight speed were comparable to those of existing large

soaring birds. It did not have teeth, although many of the smaller pterosaurs did. Perhaps it hunted small aquatic creatures as it wandered the shallows. Its full diet and many other aspects of its life style are unknown. We look forward to the discovery of further fossil evidence, which can augment our present knowledge and support or correct our conjectures.

Before the giant pterosaur's discovery, the size limits for biological flight were assumed to be much lower than an 11-meter-span flier. But nature is no respecter of performance limits assumed by man for biological creatures. To arrive at a consensus about the size, shape, and operating features of *Quetzalcoatlus northropi*, as well as to assess the overall feasibility of building and flying the QN replica, we convened a workshop at Caltech in July 1984. The workshop brought together experts in paleontology/paleobiology, ornithology, aerodynamics, vehicles/mechanisms, and other disciplines. We arrived at a design consensus amicably but without great confidence because the fossil record was so sparse. The consensus configuration that emerged had the following physical specifications:

Span	11 m (36 ft)
Wing loading	8 kg/m ² (1.6 lb/ft ²)
Area	8 m ² (86 ft ²)
Weight	64 kg (140 lbs)

The version we will actually be building will weigh 15 to 20 percent less, and hence have a 15 to 20 percent lower wing loading. This gives it a 7 to 10 percent lower flight speed and helps to provide for gentler landings and easier flight testing, while still being in a possible range for the specific original creature.

There was general agreement at the workshop that, among the many technical challenges, two in particular stood out: (1) obtaining stability/control around all three axes for a gliding QN replica, and (2) adding propulsion via wing flapping, sufficient for a gentle climb, to the gliding version.

The stability/control challenge arises for several reasons. First, *Quetzalcoatlus northropi* had no horizontal tail to help with stability and control in pitch. Also its wing appears to be unstable in pitch, inasmuch as it has undercamber and little sweep; so the wing can be considered more a part of the problem than part of the solution. Second, there is no vertical fin or rudder to help with yaw trim, and it has a long neck and large

head (large when viewed from the side, especially if a crest is assumed), which are destabilizing. Roll control via wing twist does not pose a basic problem.

Adding propulsion via wing flapping presents many mechanical and structural challenges. However, the details of wing flapping, with the associated twist magnitudes and phasing, are not considered critical. If the flapping is done inelegantly, propulsion efficiency will be low, but this can be compensated for by installing more power. The bigger question involves the interaction between wing flapping and pitch stability and controllability. Will the flapping upset the vehicle in pitch? Perhaps, but there are various approaches to solutions. We have confidence in our ability to achieve a final satisfactory result because nature provides so many successful role models. The albatross, with essentially no tail, is certainly stable in pitch during its efficient cruising flight. It is reported that some moulting birds can fly and maneuver without a tail by moving the wings forward and back. Active control presumably permits stable flight; small fore-and-aft movements of the wing continually adjust the position of the center of lift relative to the center of gravity, just as a person on a bicycle is unstable and remains upright only because of continual steering corrections, which quickly become automatic.

Questions remain about the airfoil shape and the aeroelasticity of the wing of the replica. The airfoil behind the spar may be

primarily a membrane, as with a bat, hang glider, or sailboat. Aerodynamically, a reflexed trailing edge (upward camber) could be best for helping pitch stability, but this would require ribs or battens or even a more solid structure. There are some rare clues about the flesh and membrane portions of pterosaurs for small specimens, suggesting that the membrane does have some rigidity, opening up the possibility of an airfoil with "nice" characteristics, but the extrapolation of such structures of giant pterosaurs is subject to question.

Recreating *Quetzalcoatlus northropi* involves designing, building, and testing a number of flight models of increasing size, complexity, and accuracy of reproduction of pterodactyl features. We are also continuing to search the literature and to talk with people who have built wing-flapping models and gliding pterosaur replicas. The relative lack of literature on birds' pitch stability and control forced us to mount some actual bird flight investigations with still and video cameras.

This latter research has gotten us more acquainted with the evolution of the structure and control of biological flying devices and given us a healthy respect for the elegant way nature has solved all the operational problems. Nature has been designing birds and other flying creatures for at least 150 million years. The task has obviously been well done. Design features meet a survival purpose, some by way of aerodynamic efficiency,

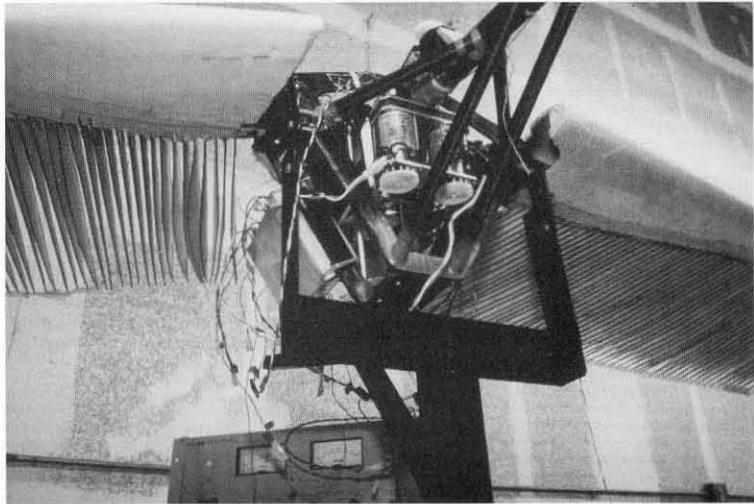
The project team includes (from left) Martyn Cowley, Adam Curtin, Mark Hawker, Tyler MacCready, Peter Lissaman, Alec Brooks, Ray Morgan, Paul MacCready, Henry Jex, Lance Inoue, Bob Curtin, and Les King. Not pictured are Dave Busch, Parker MacCready, and Alan Cocconi.



others by way of biological adaptability or sexual selection. Thus a bird has elegantly handled the aerodynamic problems such as boundary layer control, stability, and sensors. Basic study of bird aerodynamic features may be expected to yield valuable dividends to both research aerodynamicists and engineers.

After the workshop a series of small (two-meter-span and less) gliders were tested that had configurations analogous to *Quetzalcoatlus northropi*. These gave initial clues as to reasonable sweep, twist, and airfoil compromises. Some 1-meter and 2-meter-span wing-flapping models were also flown. Next a 3.7-meter-span model was constructed. It was made flexible and extremely strong so that it could survive the expected (and achieved) rough landings and crashes inherent in a development program. It was finally equipped with radio control and launched by tow line. The conclusion drawn from its testing was that, with a bit of sweep forward to the wings, with some trailing edge reflex, and with appropriate twist, static pitch stability could just barely be achieved with a configuration having poor but perhaps adequate efficiency. But the pitch control operated with too little authority to be practical. The inescapable conclusion was that pitch control had to come from wing sweep movement. The head and neck are too slender in planform to permit their use as a forward control surface the way a canard stabilizer (forward horizontal surface) operates on some aircraft.

We then built a 2.5-meter-span, radio-controlled glider. It had a standard configuration but incorporated a mechanism for sweeping the wings, in flight, forward and backward from the root. During initial flights this provided the sole pitch control, while a normal horizontal stabilizer at the rear was in place to help with stability and damping. Then the stabilizer was replaced with smaller and smaller ones, and the glide tests continued to the "almost-no-tail" configuration. During these flights the "brain" on the vehicle was an autopilot incorporating a pitch-rate gyro and an angle-of-attack vane as sensors. The autopilot characteristics were developed by Henry R. Jex (MS 1953) of Systems Technology, Inc., using advanced aircraft computer analyses utilizing the dynamics of the flight vehicle, the sensors, and the servos. All in all, theory agreed with experiment and set the stage for the next vehicle — the half-size (perhaps youthful) version of *Quetzalcoatlus*



with a 5.5-meter wingspan.

The first version with a pterosaur configuration had a semi-rigid wing (for gliding only) and was aimed at demonstrating lateral control. A sensor detects vehicle yaw, the head is turned to produce a correcting yaw force, and a hand (spoiler) half way out on the leading wing can create drag and reduce lift. It has ailerons on the trailing edge of the wing. Launched by electric winch, this rudimentary pterodactyl was flown successfully in August.

The final wing-flapping version, the same size as the lateral-control development model and weighing more than 15 kilograms, was recently completed and is currently being flight tested. The flapping mechanism requires three independent motion controls: besides flapping, wing twist is to be used for achieving the appropriate flapping lift distributions as well as for controlling roll; wing sweep is to be used for controlling pitch. The replica has an actuator system powered by nickel-cadmium batteries, but will still be

Top — the wing-flapping mechanism consists of two one-horsepower samarium-cobalt DC motors (the round objects in foreground), which drive the flapping through a gear box and ball screw drive. The mechanism is normally powered by six lbs. of nickel-cadmium batteries, but for testing here a 50-amp power supply is used.

Bottom — The finger motions of the hand halfway out the wing act as spoilers and drag breaks and operate on only one wing at a time to provide yawing moments. Each finger is driven by a small model-airplane servo.

launched by electric winch. For landing, it glides gently down to land on a skid on its stomach. The head is tilted upward just before touchdown, so if the pterodactyl pitches forward on contacting the ground, the rounded, rugged front of the neck coasts along the ground, protecting the vulnerable head and its actuating mechanism.

This version also looks like a realistic *Quetzalcoatlus northropi* (at least as far as anyone knows). The wing structure uses carbon fiber and foam with latex covering. This structure is strong and flexible and, when painted, looks very "biological." The 5.5-meter replica was chosen as a stepping stone toward the final replica because it's small enough to keep construction costs low, large enough to model the dynamics, structure, and autopilot of its larger relative, and actually could represent a younger version of *Quetzalcoatlus northropi*. The final goal is to produce the QN replica with its 11-meter wingspan. We do not expect the doubling in size and six-times increase in weight to affect its efficiency and controllability significantly.

Will the recreation of the flight of *Quetzalcoatlus northropi* be accurate? The paleontological evidence will always be too sparse to give us all the answers we want about config-

uration, flight mode, and appearance. However, the requirement that the replica fly like the original introduces aerodynamic and structural constraints that should tend to move the reconstruction toward reality.

We will be satisfied if the replica, viewed from 50 to 100 meters away, can be mistaken for the real thing as it flies. We don't intend to have it take off unassisted. The complexity of developing a leg mechanism for stable running is far beyond the scope of this project. The battery and motor systems for controls and wing flapping will be capable of permitting climb and level flight for five minutes, and of course for longer flights if soaring is used.

Everyone has daydreamed about being a time traveler, able to observe at first hand events of long ago. We cannot physically go back in time, but we can create mental images of the past and make the images stronger through books and art and moving reconstructions with film or replicas. In making its journey over tens of millions of years, a time period we can quantify but scarcely comprehend, QN — The Time Traveler,TM will allow us to look more openly and appreciatively on nature's engineering of flora, fauna, and the earth and cosmos. □