Human-powered Flight

Human-powered aircraft exploit a little-understood flight regime. Aircraft that can negotiate it are fun to fly and may turn out to have uses in reconnaissance and planetary science

by Mark Drela and John S. Langford

During all the centuries in which people dreamed of human flight it was supposed the flier would provide the power, as a bird does. Yet only in the past 25 years—after the development of the propeller-driven airplane and the jet engine as well as the achievement of supersonic flight and space flight—has the human-powered aircraft come into its own. Its arrival is due to the development of a combination of crucial technologies: aerodynamic, propulsive and structural. Equally important was a somewhat earlier achievement: making the craft adequately controllable by a pilot for whom the task of generating a large amount of mechanical power is distracting. The craft have now reached a stage where some applications for the technology can be envisioned.

Human-powered aircraft probably would not have reached this stage without the stimulus supplied by a series of competitions sponsored by a few organizations and individuals. The first one, which took place in France between 1912 and 1922, was a project of the Peugeot company. It resulted in aircraft that were really only jumping bicycles: the operator pedaled hard to get up speed on the ground and then the winged craft would glide through the air for about 12 meters. Once the craft was airborne it had no means of propulsion.

In 1935 the German aircraft *Mufli* went a step further: the pilot was able to drive a propeller after a catapult takeoff. Apparently the power requirement for level flight was more than the designers could achieve. The pilot could produce only enough power for an extended glide, the longest of which was 712 meters. *Mufli* competed for a prize of 5,000 marks offered by a group in Frankfurt for the first human-powered flight around two pylons 500 meters apart. Similar prizes were also offered in Italy and the U.S.S.R.; all went unclaimed.

The most famous competitions, and the ones that have led to genuine technological progress, have been sponsored by Henry Kremer, a British industrialist. In 1959 he offered a prize of £5,000 to the first entrant who could fly an aircraft around a one-mile, figure-eight course under human power alone. Eighteen years had passed and the prize money had increased tenfold when Bryan Allen of the U.S. successfully flew *Gossamer Condor* around such a course.

Kremer subsequently offered the largest prize in the history of aviation: £100,000 for the first human-powered flight across the English Channel. Again the winner was Allen, who pedaled *Gossamer Albatross* across the 21-mile strait between Folkestone and Cape Griz-Nez on June 12, 1979.

Both *Condor* and *Albatross* were large, fragile craft that became unmanageable in all but the gentlest breezes. Their success did not lead to widespread activity in human-powered flight. Four years after the Channel crossing Kremer responded by sponsoring another competition intended to make human-powered aircraft faster and thereby smaller and more practical. This time the goal was to achieve a relatively high speed around a triangular course of 1,500 meters. The prize was £20,000 to the first contestant who could complete the course in less than three minutes—a pace that implied a speed of about 32 kilometers (20 miles) per hour. Frank P. Scarabino of the U.S. won this prize in May, 1984, flying *Monarch*, a craft designed and built at the Massachusetts Institute of Technology. Prizes offered by the Royal Aeronautical Society are now available for flights that better the existing record by at least 5 percent; three such prizes have already been awarded.

Discounting stunts and turn-of-the-century winged bicycles, some 60 human-powered aircraft have been built. Most of them were inspired by the Kremer competitions. The designs can be grouped roughly into three generations, according to characteristic sets of aerodynamic and structural concepts [*see illustration on page 125*]. The

HUMAN-POWERED AIRCRAFT completes a speed trial at Hanscom Field in Massachusetts. The craft is *Monarch B*, designed and built at the Massachusetts Institute of Technology. The pilot is Frank P. Scarabino,

craft of the first generation were conceptually based on sailplanes (motorless gliders). They could make only straight-line flights, few of which exceeded one kilometer.

The second generation includes the first vehicles capable of sustained and controllable human-powered flight. *Gossamer Condor* is the best-known of them. It was built in California by a team led by Paul MacCready, Jr., and now is on display in the Smithsonian Institution's National Air and Space Museum. A lesser-known but somewhat more rugged craft is *Chrysalis*, a biplane built by students at M.I.T. in 1979. Second-generation craft have unusual configurations because the designers went beyond conventional ideas of what an airplane should look like.

Third-generation aircraft have been built for the speed competition and so are much smaller. Externally they look something like the first-generation craft, but they incorporate modern structural and aerodynamic technology and reflect the experience accumulated through the design and operation of the second-generation machines. Because of a provision in the rules of the speed competition, some of these machines also have an energy-reserve capability. Such a system enables the pilot to store his own energy in the craft for a short time before a flight (usually by pedaling a generator to charge batteries) so that he can draw on it during the flight. The machines are also considerably more sophisticated than their predecessors. For example, the pilot of the M.I.T. *Monarch* can tune the propeller electronically, thereby modifying the requirement for the speed of pedaling or the output of stored energy.

Although the specific tasks have differed in each Kremer competition, the designers of all three generations have faced a common problem: how to reduce the power required by the aircraft to the amount available from a human being. The second major problem of human-powered flight has been stability and control.

The power available from a human differs widely according to the person's age, training and motivation. A well-conditioned athlete can produce up to one kilowatt for short periods of time or a few hundred watts for several hours. Surprisingly in view of the many studies made, little conclusive evidence is available on such basic factors as whether it is better for the pilot to be vertically seated or recumbent. In the absence of sound physiological data the design decision is usually made for reasons of aerodynamics, structure or weight distribution.

The power required by an aircraft is the product of its aerodynamic resistance (drag) and its velocity. Low power can therefore be obtained by building a craft with low drag; flying slowly is also a way of reducing the power requirement.

who in 1984 won with this craft a prize of £20,000 offered by Henry Kremer of the U.K. for completing a 1,500-meter triangular course in less than three minutes. The rules of the Kremer competition and succeeding ones sponsored by the Royal Aeronautical Society stipulate that the craft must be at an altitude of at least two meters at the start and finish; the orange streamer being held by two members of the ground crew is two meters high. The crewman at the right also holds a stopwatch, as does an official judge (appointed by the Royal Aeronautical Society) standing in the near background. In winning the Kremer prize *Monarch B* averaged 21.5 miles per hour.

To achieve equilibrium in flight the lift (vertical force) produced by an aircraft's wings must equal the gross weight of the vehicle. Wing area is the most useful variable for the designer. In theory arbitrarily low flight speed and power requirements can be obtained with sufficiently large wings. In practice the wing area is limited by considerations of structural rigidity, weight, sensitivity to wind and the size of the buildings available for storing planes on the ground.

Drag at subsonic speeds has two components of comparable magnitude. One component arises from friction with the air. It is roughly proportional to the exposed area of the plane. The second component is an unavoidable consequence of generating lift and is known as induced drag. Friction drag can be reduced by decreasing the exposed area and employing aerodynamically efficient shapes. Induced drag can be diminished primarily by increasing the wingspan and by flying close to the ground. Both theoretical and practical factors limit the amount of reduction in each case.

Sailplanes have long represented the epitome of low-drag design, and so it was only natural that the first generation of human-powered aircraft resembled them. Designers essentially sought to reduce the weight of a sailplane by a factor of 10 while adding a propeller and allowing no compromise of aerodynamic principles. All the framework and bracing was internal. One can now see that the task was beyond the capability of the available structural technology. The resulting aircraft were heavy and small compared with the machines of the second generation. The low drag and relatively high flight speed created a power requirement that left the pilot little margin for maneuvering the vehicle.

Second-generation craft embodied the low-speed approach to power reduction. The low-drag advantage of the sailplane was abandoned in favor of external bracing. The resulting increase in drag was offset by substantial increases in wing area and large reductions in weight. A low power requirement was achieved by the resulting low flight speed (approximately 16 kilometers per hour).

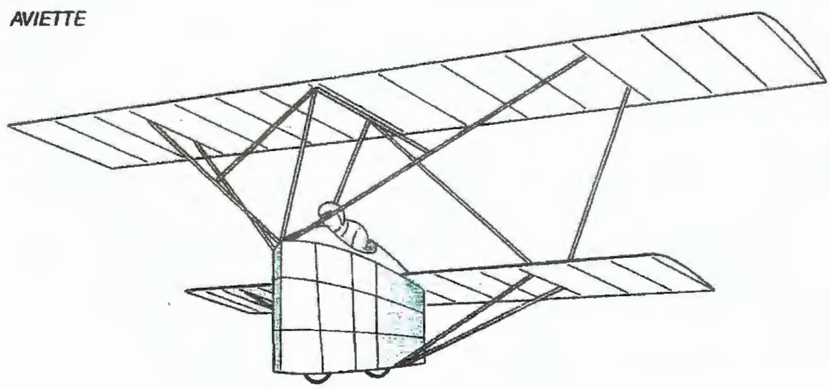
The machines of the second generation also incorporated the first workable solutions to the problem of stability and control. This achievement meant the designers had coped successfully with several effects that are normally not significant in conventional aircraft.

An example is acceleration. To accelerate an aircraft (when, say, it is making a banking turn) some of the surrounding air must also be accelerated. The craft is said to have an "apparent mass" in addition to its own mass. In conventional aircraft this additional component is negligible. In a human-powered aircraft it can be very important. As a result conventional control surfaces cannot generate the forces needed to deal adequately with the apparent mass, and so designers had to take a new approach.

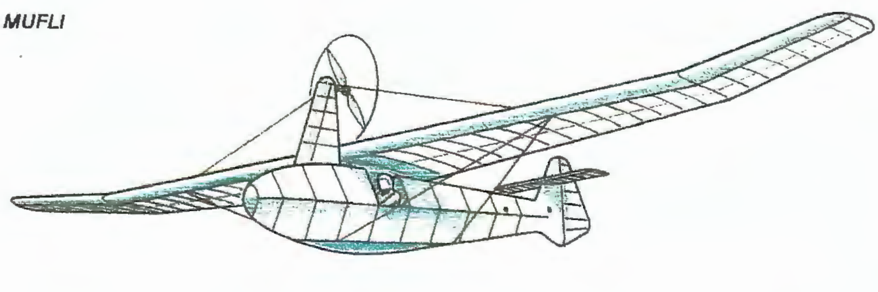
An aircraft must be controlled on three axes: yaw, pitch and roll [*see illustration on page 126*]. Usually a vertical rudder on the tail governs yaw, a horizontal elevator on the tail establishes pitch and horizontal ailerons on the wings determine roll. To begin a turn the pilot rolls the craft by means of the ailerons. This action tilts the lift vector of the wing, providing the side force needed for the turn. The rudder is then employed to "coordinate" the turn, keeping the nose pointed into the airstream. The ailerons control the roll rate, so that they are centered when the turn has been initiated and are used in the opposite direction to roll the aircraft out of the turn.

When ailerons are deflected, they impose on the wing a torque that tends to twist it along the axis of the span. The resulting change in the angle of

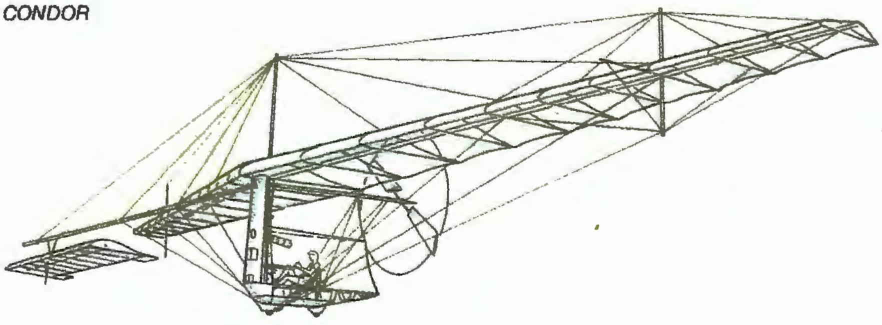
AVIETTE



MUFLI

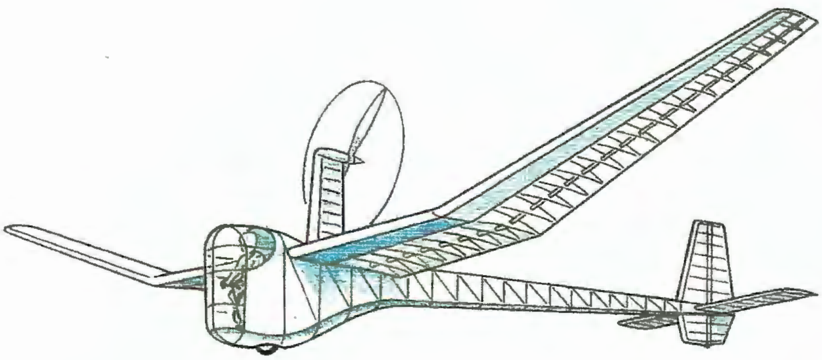


CONDOR



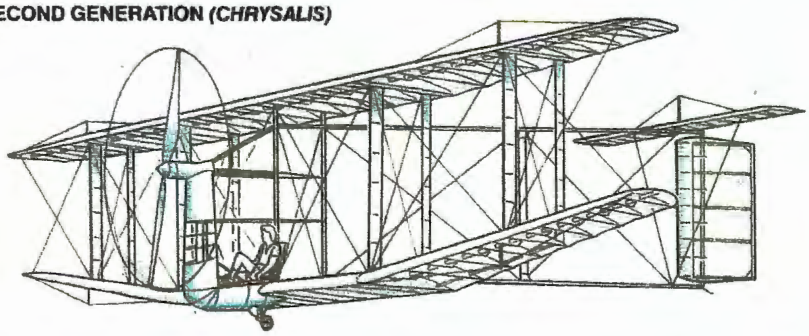
ADVANCING TECHNOLOGY of human-powered aircraft is marked by *Aviette, Mufli* and *Gossamer Condor*. *Aviette*, the winner of a competition sponsored by the Peugeot company between 1912 and 1922, was basically a jumping bicycle; it had no source of propulsion after it left the ground and so merely glided for a few meters. *Mufli*, a German craft operated in 1935, had a human-powered propeller, but the pilot could generate only enough power for an extended glide (712 meters was the longest one). *Condor* represents the class of human-powered craft that can fly indefinite distances and are fully controllable. In 1977 *Condor* won the first Kremer competition by completing a one-mile, figure-eight course.

FIRST GENERATION (*JUPITER*)



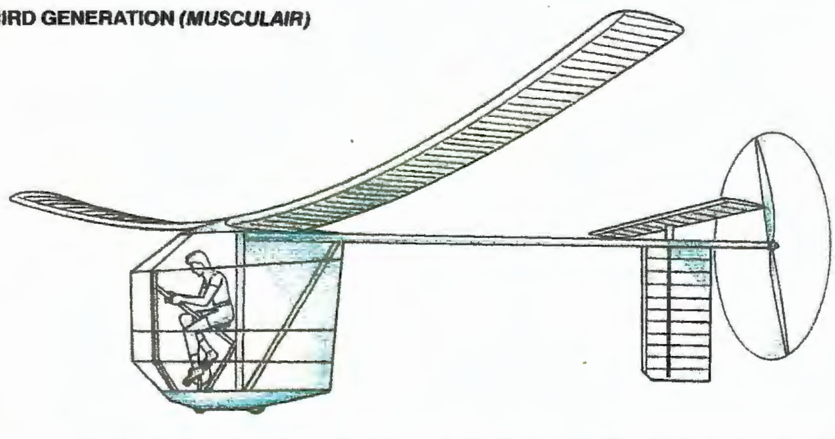
NAME	ORIGIN
MUFLI	GERMANY
PEDALIANTE	ITALY
SUMPAC	U.K.
PUFFIN I	U.K.
McAVOY	U.S.
VINE	S. AFRICA
MAYFLY	U.K.
PUFFIN II	U.K.
LINNET I	JAPAN
RELUCTANT PHOENIX	U.K.
LINNET II	JAPAN
MALLIGA	AUSTRIA
SM-OX	JAPAN
LINNET III	JAPAN
LINNET IV	JAPAN
MERCURY	U.K.
OTTAWA	CANADA
WRIGHT	U.K.
JUPITER	U.K.
TOUCAN I	U.K.
LIVERPUFFIN	U.K.
EGRET I	JAPAN
EGRET II	JAPAN
EGRET III	JAPAN
BURD I	U.S.
AVIETTE	FRANCE
EGRET IV	JAPAN
DEDAL III	POLAND
TOUCAN II	U.K.
STORK I	JAPAN
BURD II	U.S.
BLIESNER	U.S.
OLYMPIAN ZB-1	U.S.
ICARUS	U.S.
SKYCYCLE	U.S.
STORK II	JAPAN
NEWBURY MANFLIER	U.K.
PHOENIX	U.K.
PHILLIPS	U.K.

SECOND GENERATION (*CHRYSALIS*)



GOSSAMER CONDOR	U.S.
CHRYSALIS	U.S.
GOSSAMER ALBATROSS	U.S.
GOSSAMER PENGUIN	U.S.
MILAN '82	JAPAN

THIRD GENERATION (*MUSCULAIR*)



MONARCH	U.S.
HVS	W. GERMANY
BIONIC BAT	U.S.
PELARGOS	SWITZERLAND
MUSCULAIR	W. GERMANY
MONARCH B	U.S.
MAN-EAGLE	U.S.
SWIFT B	JAPAN

GROUPING OF CRAFT into three generations reflects major differences in the technology of human-powered flight. Aircraft of the first generation had internal wood trusswork; they were both heavy and fragile and could make only straight-line flights. Aircraft of the second generation had an aluminum-tube framework and external wires for bracing. These were the first fully controllable craft. Aircraft of the third generation are smaller and speedier. Modern materials such as graphite make cantilevered construction possible.

attack (and hence the lift) at each tip partially negates the effect of the aileron itself. For adequate control of roll the wing must therefore have enough rigidity to resist the twisting torque of the ailerons.

In the first two generations of human-powered aircraft the combination of large apparent mass and torsionally weak wings made ailerons ineffective. The problem was solved for *Gossamer Condor* by means of a canard: a control surface mounted on the fuselage to ride in front of the wing. On *Condor* the canard was tilted, producing a sideward force like that generated by a rudder, thereby achieving the desired yaw. The yawing motion produced a higher airspeed and a higher lift on the outside wingtip and a lower airspeed and lift on the inner one. The lift differential made the craft roll.

To keep the craft from banking too much a pilot flying *Condor* had to pull on the external bracing wires in order to twist the wings, much as the Wright brothers did on their *Flyer* of 1903. The maneuver increased the angle of attack (and hence the lift) on the inner wing and decreased it on the outer one. This action made sustained controlled turns possible.

Because human-powered aircraft of the third generation are smaller, their apparent-mass effects are smaller and the wing can be made considerably more rigid. Ailerons have proved practical for these machines.

We turn now to the three technological developments that have proved crucial to successful human-powered flight. They are high-lift airfoils, efficient propulsion systems and lightweight structures.

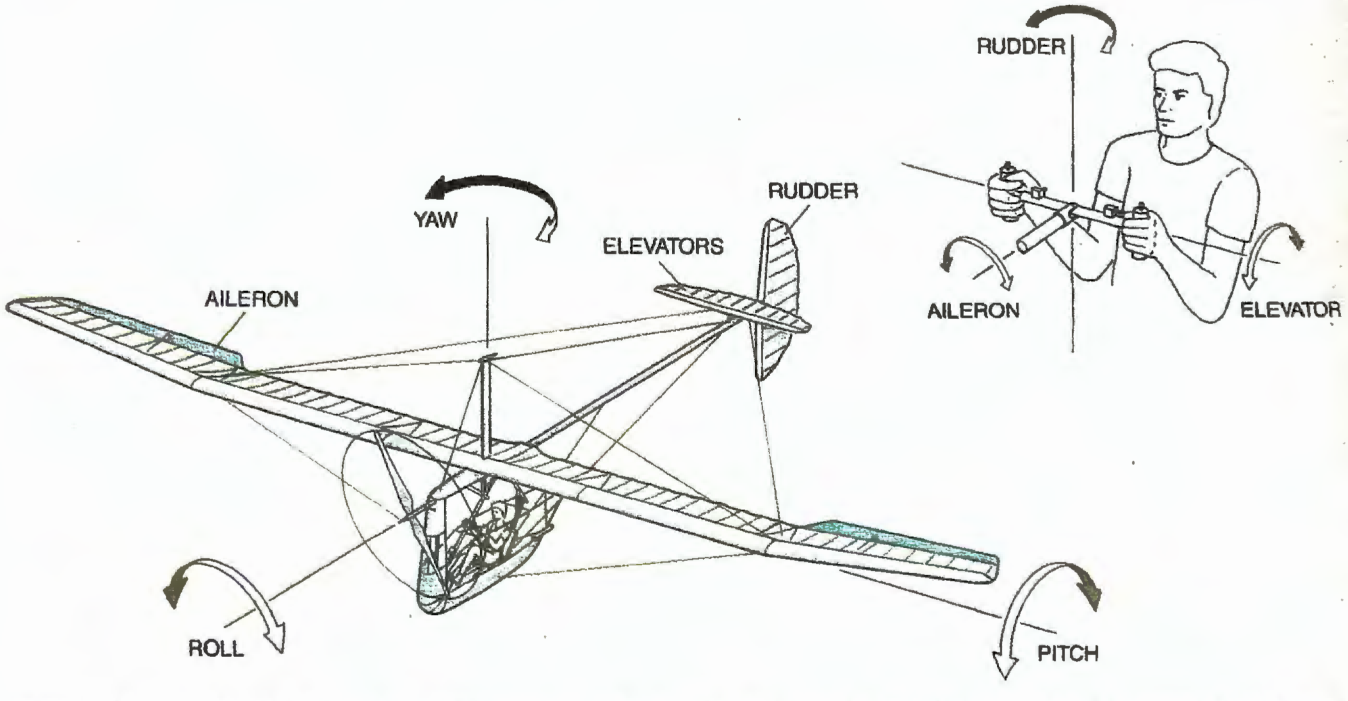
The main aerodynamic surface is the wing. Because it creates most of the drag, its cross-sectional shape (the airfoil) must be as efficient as possible. One measure of an airfoil's efficiency is the ratio of lift to drag ($L:D$). Another performance measure is the "power parameter," which is similar to $L:D$ but gives more emphasis to high lift. The higher the power parameter, the lower the power needed to sustain flight. Because low power is the primary concern in human-powered aircraft, a large power parameter is more important than a large $L:D$. To attain a high power parameter an airfoil must be capable of high lift but must not induce excessive drag.

The airfoil must also have a small pitching moment, meaning that it should tend to remain level along the axis of flight. A large pitching moment generates the same torques about the axis of the wingspan as ailerons do. (This is another reason the wings must be made torsionally stiff.) Higher stiffness invariably adds to the weight of the wing. In addition a high pitching moment destabilizes the aircraft and requires larger tail surfaces, which add weight and drag.

A factor that complicates the design of human-powered aircraft is that they operate in an unusual aerodynamic regime, normally the province of large birds and model airplanes. The regime is formally characterized by its relatively low Reynolds number, a dimensionless figure of merit that takes into account the speed, density and viscosity of the air together with the length of the body aligned with the flow. Typical aircraft operate at Reynolds numbers of between two million and 20 million; a vast store of information on that kind of flight has been built up since World War I. Human-powered aircraft operate at Reynolds numbers of less than one million, a poorly understood region of flight.

The low Reynolds number and the need for high lift, low drag and low pitching moment have required the designers of human-powered aircraft to adapt existing airfoils or to design new ones. The task is to tailor the distribution of pressures on the airfoil's surface. Loosely speaking, two types of airfoil could serve in human-powered aircraft: rear-loaded and front-loaded. The terms reflect the fact that the distribution of pressure on the top and bottom of the wing tends to be uneven, so that most of the load is carried either on the rear of the wing or on the front according to the choice made by the designer.

A typical rear-loaded airfoil offers a large lift-to-drag ratio that prevails through a fairly wide range of speeds and angles of attack. This type works well on sailplanes but not nearly as



THREE-AXIS CONTROL of a typical third-generation craft is achieved solely with the pilot's hands. (His legs are pedaling to provide the power for flight.) He controls roll by means of the ailerons, pitch by means of the elevator and yaw by means of the rudder.

well on human-powered aircraft. Its main disadvantage is its high pitching moment. This disadvantage and others, however, become less severe as the size of the aircraft decreases. The German *Musculair*, a successful third-generation craft, employed a rear-loaded airfoil.

Front-loaded airfoils offer high lift-to-drag ratios and also the highest power parameters, but only over a relatively narrow range of speed and angle of attack. Although those disadvantages make the airfoil unsuitable for sailplanes and most airplanes, it is ideal for human-powered aircraft, which perforce have a narrow speed range because of their limited power. Moreover, the airfoils have low pitching moments; hence a wing with a front-loaded airfoil can be built with a lower structural weight than can a wing with a rear-loaded airfoil.

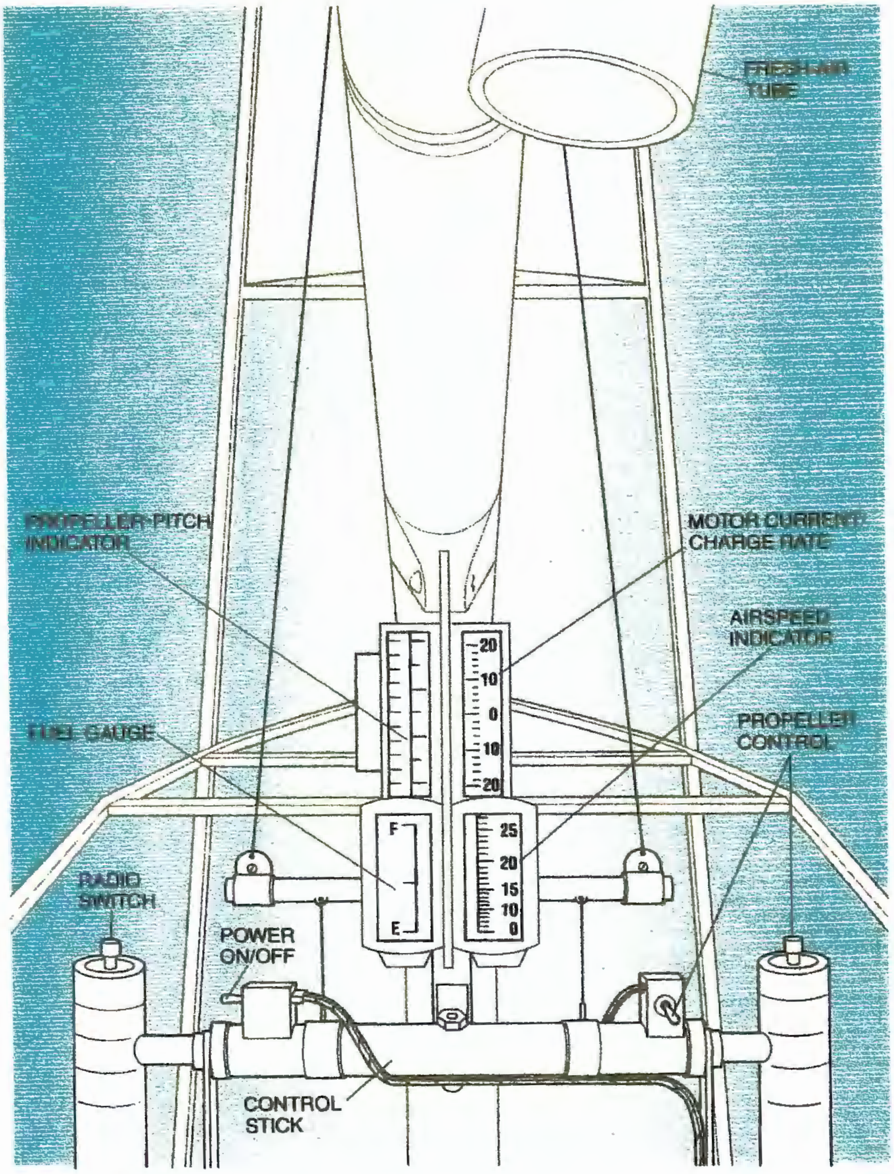
Propulsion is another area where high efficiency is important in human-powered aircraft. A propeller is by far the most effective means of transforming the mechanical power generated by the pilot's legs into a thrust sufficient to overcome the drag of the machine. One can conceive of other means of propulsion for human-powered aircraft, including flapping wings and jets of compressed air, but they have not yet been successful.

Any propulsive device (with the exception of a rocket) that generates thrust takes in air at flight speed and expels it to the rear at a higher speed as a jet. In the case of a propeller the jet is the slipstream: the air pushed aft of the propeller. A flapping wing pushes back an amorphous mass of air with each stroke.

In every case the jet carries kinetic energy that has been added by the propulsive device and that cannot be recovered; it is eventually dissipated as heat. As the jet velocity increases, the loss from wasted energy goes up faster than the gain in thrust. Thus efficiency dictates a device that takes in a large mass of air and adds to it only a small increment of velocity. This goal calls for a propeller that has a large diameter or for flapping wings that have a large span. (A compressed-air jet is inherently inefficient at the speeds of human-powered aircraft because of its high jet velocity.)

Although the flapping wing can in theory be made quite efficient, it has never been applied successfully to any aircraft powered by a human or carrying human passengers. To achieve high efficiency the wing must be twisted in one direction along the axis of its span on the downstroke and twisted in the other direction on the upstroke. Birds execute the maneuver quite well, but in a machine the combination of flapping and twisting creates severe mechanical and structural problems that get worse as the size of the craft increases. Hence a propeller is currently the only practical propulsive device for a human-powered aircraft.

The ideal of a large-diameter propeller faces certain constraints in a human-powered aircraft. A large propeller adds weight, which is something the designer is trying to avoid. Beyond a certain size the propeller tips are likely to strike the ground when the aircraft is taking off or landing. Thus the designer cannot achieve maximum efficiency by merely increasing the diameter of the propeller. Instead he must seek to reduce the efficiency-robbing kinetic energy in the slipstream of the propeller by careful attention to the distribution of the load on the blade. Air friction on the blades also influences the design of the propeller. An ample diameter and an optimum de-



CONTROL DEVICES of *Monarch B* are shown as the pilot sees them. The current/charge gauge records the rate at which the craft's battery is being charged or discharged; the charging takes place before the flight, when the pilot pedals a generator to store power. In flight he can draw on the stored power by means of the power switch, which actuates an electric motor. The fuel gauge records the amount of charge in the battery. The propeller-pitch indicator reflects the angle of the propeller blades, which the pilot can control by means of the propeller-control switch. By pushing the radio switch the pilot can talk to the ground crew; he can hear the radio at all times. *Monarch's* control stick bears a message of encouragement for the hardworking pilot: "You have great physical powers and an iron constitution."

sign enable a propeller on a human-powered aircraft to attain efficiencies approaching 90 percent.

Structural technology is the feature of human-powered aircraft that has changed the most since the vehicles of the first generation. In those early aircraft intricate trusswork made chiefly of wood provided form and strength. The truss is an efficient structure: it has high ratios of strength to weight and of stiffness to weight. Wood is easily obtainable, easy to work with and relatively inexpensive. Moreover, most of the people who build human-powered aircraft are or were model-airplane enthusiasts, experienced in working with wood.

On the other hand, the wood truss presents several drawbacks. It has so many individual pieces and joints that building one is a labor-intensive project. Mending a broken one is difficult. Moreover, if one truss member fails, the nearby members are put under unusual stress and the entire structure is put in jeopardy. For these reasons the wood truss was abandoned in the second-generation aircraft. Designers relied instead on a primary structure of aluminum tubing that had a large diameter and thin walls; wires provided external bracing.

The tubing was sized primarily to resist compression. External wires took all major bending and torsional loads. (At low flight speeds the drag created by the wires is more than offset by the saving in weight.) The advantage of such a structure is that it has a high ratio of strength to weight and provides excellent rigidity. The absence of wood trusses also made the second-generation craft much easier to repair than their predecessors.

Because third-generation craft are smaller and strong materials such as graphite and graphite-epoxy have become available, designers were able to turn to cantilevered structures that eliminate external wires. Mylar film as a covering skin has also contributed to structural improvement.

The combination of low speed, low altitude and limited power makes piloting a human-powered aircraft a challenging task but one that is within the capability of almost anyone. General-purpose craft such as *Condor* and *Chrysalis* have been flown by men and women ranging in age from the teens to the 60's.

The pilot usually begins by shedding clothes. A jogging outfit and a bicycle helmet constitute the proper attire: extra weight calls for extra power, and sunlight on the transparent covering makes the cockpit uncomfortable when the craft is not moving.

It is hard to get into the aircraft without damaging it. There are few places solid enough to bear one's weight, and so the pilot normally uses stepping platforms and is helped in by members of the ground crew. After running through a preflight checklist the pilot signals to the crew members holding the wingtips and begins to pedal.

The takeoff is surprisingly smooth. Most people flying for the first time are unaware that the craft is airborne until they hear the cheers of the ground crew. The cockpit is noisier than one would expect because of the whirring of the bicycle chain and the cyclic whooshing thump as the blades of the propeller pass the fairing.

In the air the pilot's main task is to concentrate on maintaining a steady attitude and airspeed. If the craft has been correctly trimmed for his weight, only small adjustments of the rudder are necessary. To climb the pilot pedals harder; to come down he or she reduces the pedaling rate.

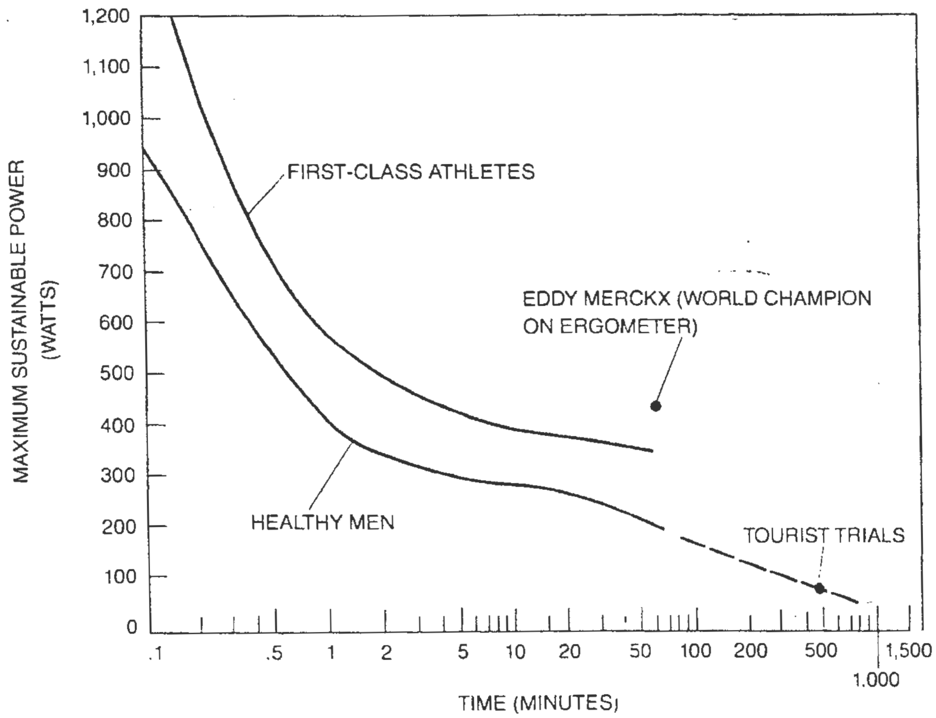
A human-powered aircraft reacts quite slowly to its controls; consequently inexperienced pilots are likely to overcontrol. Even more confusing is the tendency for the aircraft to respond differently on different axes. The pitch response is relatively fast, the roll response agonizingly slow. Making turns around a specific course, as is required in the speed competitions, calls for careful coordination and much practice.

The two primary dangers in flight are stalls and gusts of wind. The craft stalls when the airflow separates from the surface of the wing. The separation usually occurs because the pilot has let the craft's speed fall too low.

The inherently low flight speed makes gusts a special problem. Because the relation between wind speed and the speed of the aircraft is crucial, a gust of only five miles per hour is equivalent to one of 30 miles per hour or more on a small conventional airplane. Striking from the front, such a gust can overload and break the wing; from the rear it can cause a stall. A gust can also change both the flight path and the plane's attitude. Fortunately the low speed and the low altitude combine to make a human-powered aircraft fairly safe; crashes that demolish the airframe usually inflict only cuts and bruises on the pilot.

To land the pilot aligns the craft with the runway and reduces his rate of pedaling. The vehicle glides gently in and touches down softly.

Human-powered flight has been pursued mostly for its own sake, greatly spurred by the incentive of the various competitions. Nevertheless, the technologies that have evolved can be expected to have practical applications in at least three areas: human-powered flight itself, ultralight aircraft and a variety of reconnaissance and observational tasks.



HUMAN POWER varies according to the age, condition and motivation of the person. The range is indicated on this chart. The "tourist trials" line shows values deduced from cross-country bicycle races. One kilowatt (1,000 watts) is the equivalent of 1.3 horsepower. The data are derived from *Bicycling Science*, by Frank Rowland Whitt and David Gordon Wilson.

In human-powered flight the speed competition as it is now set up will continue until 11 more awards of £5,000 each have been won. The result will certainly be faster aircraft, perhaps attaining speeds of as much as 85 kilometers per hour. Such a speed will be difficult to achieve, however, even with highly efficient schemes for storing energy. It remains to be seen whether the proposed prizes will be sufficient to elicit the necessary investment of money and thought.

The Royal Aeronautical Society is examining the possibility of staging additional competitions. They would probably be aimed at making human-powered aircraft more practical and more rugged. At the other end of the spectrum it is now possible (in our view) to build a large, low-power craft that could turn the legend of Daedalus into reality, flying the 96 kilometers from Crete to the Greek mainland at about 22 kilometers per hour.

The relation between human-powered and ultralight aircraft (which are powered by small gasoline engines) is that the former, as they are increasingly designed for speed and utility, become more like the latter. Human-powered aircraft of the third generation cruise on about .5 horsepower and climb splendidly at two horsepower. The engines of today's ultralight aircraft produce from 30 to 50 horsepower. Improvements in the technology of human-powered aircraft can be expected to reduce this gap so that human-powered aircraft can perform some of the tasks now calling for ultralights and ultralights can function at lower power.

The final application has to do with high-altitude operations. High-altitude craft capable of prolonged flights are now being considered as unmanned platforms for reconnaissance, communication relays and sampling work in the stratosphere. A high-altitude craft operates at the low Reynolds numbers characteristic of human-powered aircraft. Hence the technologies developed to increase the structural strength and reduce the weight of human-powered craft will also benefit the high-altitude vehicles.

Eventually these technologies might find application in space. For example, the atmosphere of Mars, even though it is much less dense than the earth's atmosphere, could support winged flight at Reynolds numbers similar to those of human-powered aircraft. A winged, unmanned vehicle (an airborne analogue of *Lunar Rover*) would be an effective platform from which to examine the terrain and sample the atmosphere of Mars.