The MIT Monarch and the Kremer World Speed Competition

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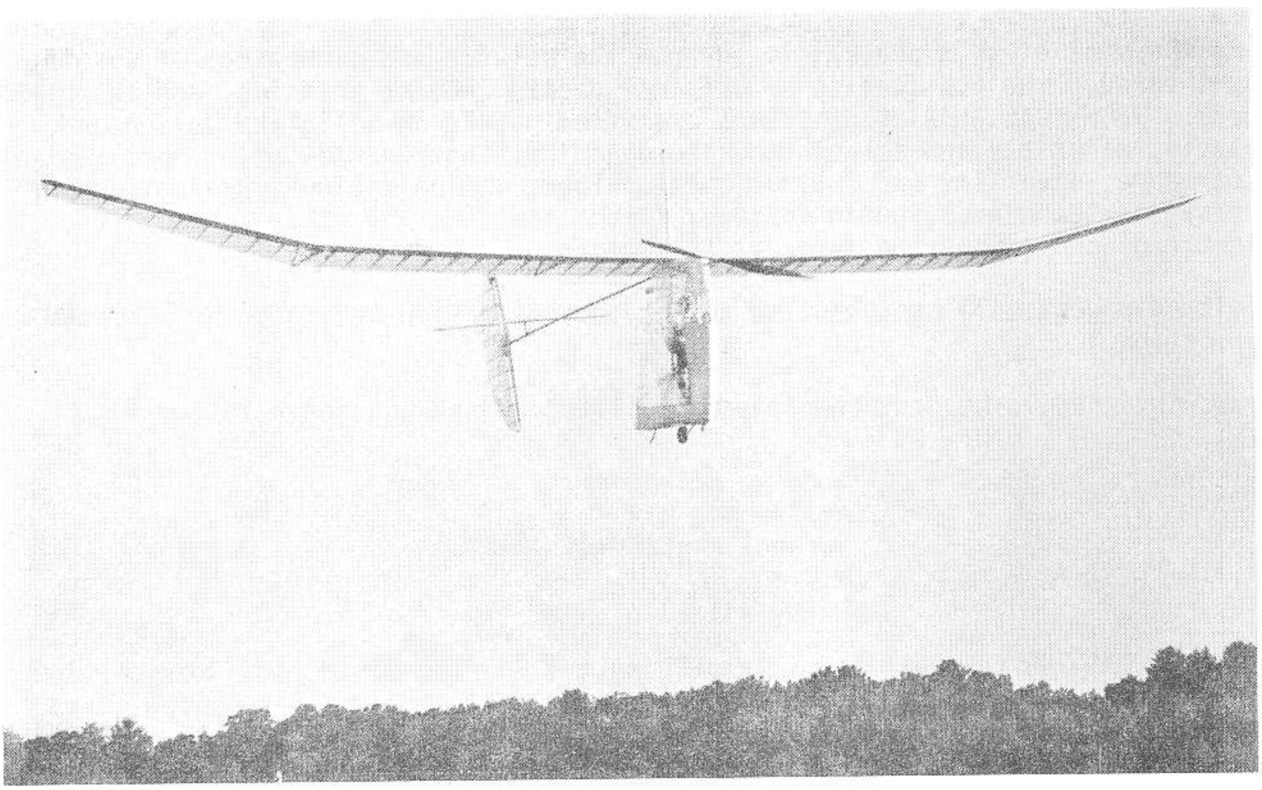

ABSTRACT

The race for the Kremer World Speed Record was the closest human powered aircraft competition yet. Throughout the summer of 1983, teams in Massachusetts and California worked to construct aircraft capable of completing the 1500 meter Kremer Course in less than three minutes. Between August 14 and September 23, the MIT Monarch successfully demonstrated all of the components of the Kremer course and began making record attempts. On September 23, the Monarch was damaged in a landing accident, and subsequently disassembled due to pressures of the academic term. This paper traces the design and development of the Monarch.

INTRODUCTION

In May of 1983, the Royal Aeronautical Society (RAeS) announced the third in its series of human-powered aircraft (HPA) competitions. Known as the Kremer World Speed Competition, this new contest offered a £20,000 prize to the first entrant to fly a 1500m closed course in less than 180 seconds (requiring a speed of roughly 20 mph). In a significant departure from previous HPA competitions, this one allowed the use of energy storage. During a ten minute period before the flight, the pilot(s) could store his own energy via whatever means the contestants devised. The rules (Reference [2]) also included provisions for official observation, minimum and maximum altitudes, a qualifying flight, and follow-on prizes each time the record is broken.

Upon announcement of the competition, a small group of students at MIT (including the authors, Scott Clifton, and Steve Finberg) began to examine the feasibility of winning the prize. Three other HPAs had previously been built at MIT, including BURDs I and II, designed for the original Kremer Figure-of-Eight competition, and the Chrysalis, flown some 350 times in 1979 as the precursor to a hoped-for entry in the Kremer Cross-Channel competition. Two of the authors were involved with Chrysalis, and much of the technology was transfered from that experience into the newest aircraft, known as the Monarch.

At first glance, the new competition appeared to be almost too easy. Assuming a 10% increase in course length (to 1650m), a lift-to-drag ratio of 20, andaircraft weight (with pilot) of 950N (210 lbs), the energy required to climb three meters and fly the course is approximately:

$$E = (d \times W \times D/L) + (m \times g \times h)$$
$$= (1650 \times 950 \times 1/20) + (950 \times 3)$$
$$= 81.2 \text{ kJ}$$

Allowing for a propeller efficiency of 90%, approximately 90.5 kJ would be required at the propshaft. The power available from the pilot depends on age, training, and motivation. Whitt and Wilson [3] indicate that 250W (.33 HP) could easily be obtained for the 13 minute duration involved, and levels up to 400W (.54 HP) might actually be available during the flight. Thus the total energy available would be:

$$E = (P_c \times t_c \times \eta_c) + (P_f \times t_f \times \eta_f)$$

where:

P_c = Power produced during charge = 250 W
t_c = time of charge = 540 s
η_c = charge efficiency
P_f = Power produced during flight = 250 W
t_f = time of flight = 180 s
η_f = efficiency in flight = 90%

With these baseline assumptions, the efficiency required for the energy storage system was only about 30%. This efficiency could be achieved by a variety of systems, including electrical (batteries), mechanical (flywheel), and strain (rubber) energy storage.

Based on these encouraging initial calculations, we set out in late May to design and build an aircraft for the competition. Primary design considerations included the understandings that a) the project (both facilities and manpower) had to be completed before the Fall 1983 academic semester began; and b) only limited funding would be available. Through July 1, individual students provided all the project funding; after July 1, the Department of Aeronautics provided most of the funding. Total costs ran to about $4300.

These considerations, coupled with the belief that Paul MacCready would not be entering this competiition, led to the selection of a 'minimum' design that could set the record (but not break it), could be built quickly near MIT, and would have a minimum cost. The final design was that of a tractor monoplane, with aft tail, vertical pilot seating, and a wire-braced aluminum tube structure. Somme 3600 man-hours were required in construction, with the final design shown in Figure 1. The actual design process was too lengthy to detail here, but is documented in Reference

[1]. The remainder of this paper describes the basic construction of the aircraft and some of the highlights from the flight program.

AERODYNAMIC SURFACES

The wing was a 62 foot span, wire-braced monoplane. Since neither the project's schedule nor budget allowed the use of graphite-epoxy, the primary structure was entirely 6061-T6 aluminum tubing. A single 2.5 in. o.d. spar located at 29% m.a.c. carried the lift loads. The spar had .035 in. walls in the center panels, but tapered to .018 in. at the tips (the spar was tapered by chemical milling, which we performed in a one-day special operation). Designed for an ultimate load of 2.0 g's, the outer 12' panel of the spar was fully cantilevered. A single .043 in. diameter steel wire attached at the dihedral break carried the main lift loads. A single wire from the top mast was designed for 1.0 g downloads. The wing was warped for roll control by top and bottom wires attached at the trailing edge of the dihedral joint. The trailing edge wire was sized to carry the forward loading at high lift conditions, and a leading edge wire carried aft bending loads.

The airfoil was a modified Lissaman 7769, similar to the airfoil on the Gossamer series of aircraft and on Chrysalis. Ribs were constructed from 2.0 lb/ft^3 foam, bought in blocks and sliced using a machine designed by Bob Parks. Each rib has top and bottom cap strips of graphite epoxy, donated by and fabricated in MIT's Technology Lab for Advanced Composites (TELAC). To prevent debonding, each cap strip was secured by a layer of .75 oz. fiberglass cloth. The leading edge was wrapped with 3/16 in. foam. The ribs were reinforced near the spar with 1/64 in. plywood. Special angled ribs at the panel joints took both compression and covering loads. The wings were covered with half-mil tensilized Mylar, donated by DuPont.

Construction of the all-flying rudder and stabilizer were similar, except that these surfaces were fully cantilevered. The tail surfaces were covered with third-mil Mylar.

FUSELAGE

The fuselage was built of aluminum tubing, with each joint machined to fit and then lashed with Kevlar yarn. The pilot was seated upright. In his right hand was a two-axis stick controlling the rudder and the elevator. His left hand normally rested on a fixed handlebar, with a thumb switch for motor control. To enter or exit a turn, the pilot was required to reach down and grasp the wing warp lever, which was a set-and-lock control. Initially the landing gear was designed as a tail-dragger, but a combination of problems resulted in a nose-over on the first rollout, and the aircraft was modified with the addition of a small nosewheel. Both wheels of the landing gear were castoring and shock-absorbing.

PROPULSION SYSTEM

After briefly considering flywheels (too complicated) and rubber (too heavy), we elected to develop an electrical energy storage system. In our judgement, the relatively low efficiency (about 33%) was more than offset by the low development time and cost. The final system (shown in detail in Figure 1) consisted of: 1) standard bicycle cranks, driving a flexible chain; 2) a minimum induced loss tractor propeller, disconnected via a clutch during charging; 3) a 62.2:1 three-stage gearbox; 4) a 700W DC motor normally used for electric model aircraft; 5) a power controller; and 6) a bank of 1.2 A-hr NiCad batteries.

The key concept in this system was the idea of splitting the battery pack during charging. This allowed us to use the flight motor as generator, and to do so without changing the gearing between charging and flying (the conversion could be accomplished in less than 10 seconds). We traded mechanical complexity for electronic complexity; a key element in the system was the power controller. Designed and built by Steve Finberg, the controller performed a variety of functions, including: 1) splitting the battery pack, automatically cycling between the two subpacks every 10 seconds during

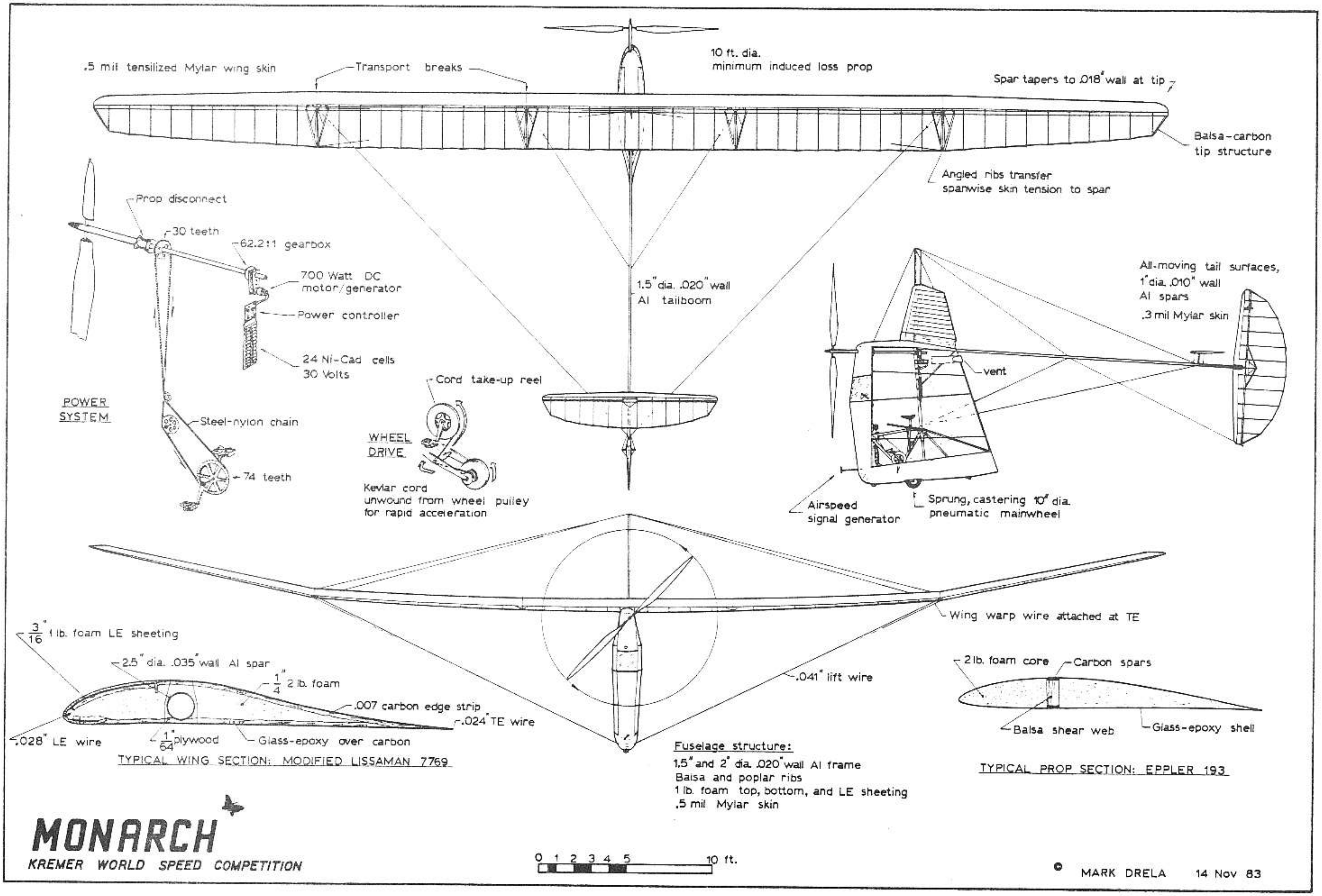

FIGURE 1. the MIT Monarch Human-Powered Aircraft. September 1983 Flight Version.

charging; 2) providing visual confirmation of charge cycling via LEDs; 3) providing a direct current path between batteries and motor (the pilot controlled the on/off via a relay, and the pilot's amperage readings were provided via a Hall Effect Device, without the losses of a shunt); 4) use of a current-sending system to act as a no-loss diode; and 5) sensing battery pack voltage and providing an audible low-voltage alarm.

Performance of the propulsion system is illustrated in Figure 2. Curves of motor performance (power produced versus rpm and voltage) are plotted along with propeller performance curves (power absorbed versus prop pitch and rpm) for a given flight speed. If the pilot produced no power, the system would operate at the intersection of the appropriate voltage and prop pitch curves. Once the pilot pedals faster than the corresponding rpm, he adds power to the system. At the design point, the pilot and the motor were each expected to produce approximately equal power.

Figure 2 also reveals a serious deficiency in a system where prop pitch and voltage are variable only on the ground. When the pilot increases his output power, only about half is delivered to the propeller, while the remainder serves to unload the motor. Thus, the pilot has only a limited control on the power output in flight. This could have been solved with the introduction of a variable pitch propeller, but time did not permit its inclusion once we realized the full magnitude of the problem.

FLIGHT PROGRAM

Monarch made its first flight on August 14, 1983 with Rick Sheppe as the pilot. A CFI and active member of the SSA, Rick was never intended to be the record attempt pilot and was not in training for such. Unfortunately, the pilot/athelete who had been training was not an experienced pilot, and he crashed the aircraft on his second flight on August 19. The aircraft was repaired and flying again by September 2 and on September 23 Scarabino made 25 flights, including several attempts with observers to fly the qualifying course. During this period the aircraft demonstrated all of the components necessary for the Kremer course, including unassisted take-offs, long-endurance flights, speeds exceeding

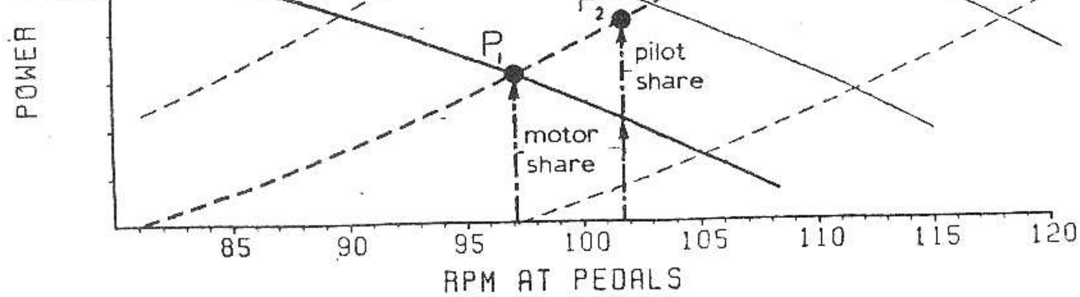

Figure 2. Operating curves for motor (solid line)and propeller (dashed) at various voltage and pitch settings at a flight speed of 23 mph.

24 mph, battery charging, and turns. MIT resumed its classes on September 12, however, and the pace of the program tapered rapidly after that. On September 23, the aircraft rolled into the grass after landing and nosed over, damaging the fuselage. MacCready's Bionic Bat claimed the record on September 25 (although this claim was subsequenty rejected by the RAeS), and the Monarch was disassembled on October 14.

SUMMARY

The Monarch was an educational experience for all those involved with it. Although we lacked the resources to sustain the project, it was a technically successful aircraft and it came very close to accomplishing its initial goal. It provided all those involved with it a refreshing opportunity to apply an engineeering education to a hands-on project.

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