SUBSONIC GLIDEBACK ROCKET DEMONSTRATOR FLIGHT TESTING

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1.0 INTRODUCTION

For the past two years, Cal Poly's rocket program has been aggressively exploring the concept of remotely controlled, fixed wing, flyable rocket boosters. This program, embodied by a group of student engineers known as Cal Poly Space Systems, has successfully demonstrated the idea of a rocket design that incorporates a vertical launch pattern followed by a horizontal return flight and landing. Though the design is meant for supersonic flight, CPSS demonstrators are deployed at a subsonic speed. Many steps have been taken by the club that allowed the evolution of the StarBooster prototype to reach its current size: a ten-foot tall, one-foot diameter, composite material rocket. Progress is currently being made that involves multiple boosters along with a second stage, third rocket.

2.0 BACKGROUND

The first step was taken in the fall of 1999 with the construction of several 1-ft tall models. These were simply made and familiarized the club with the unusual design of the Starcraft Boosters, Inc. StarBooster rocket. The ascending qualities were then assessed with a 2-ft model, and the wind-waning tendency due to the main wing was revealed. The flying characteristics were analyzed by the use of a 3-ft model and then a 3 ½-ft model that was remotely controlled with both ailerons on the main wing and flaps on the canards. This model, the first intended for vertical launch and horizontal fly back, employed the construction technique of using a foam core wing with a skin covering. It also housed a parachute recovery system. Flights of the 3 ½-ft model caused the implementation of water ballast in the nose cone for a variable center of gravity. The design improvements were pushed onto the next rocket in the StarBooster evolution, a 5-ft model. This model flew three times, the last of which included a 30 second horizontal flight, the first real milestone of the StarBooster project. With this momentum, CPSS took the next step began development of a 10-ft model.

The first 10-ft model was constructed with phenolic tubing, 11 ¾-in. outer diameter and reinforced with two layers of laminated composite fabrics. The inner layer was a twill cloth with carbon and arimid fibers woven both the length and width of the cloth. Arimid was used to help with abrasion resistance while the carbon was used for its high tensile strength. The outer layer was a standard satin fiberglass cloth that could be sanded to a smooth surface. The wings, totaling a span of 117 inches, had a blue foam core hot-wire cut using NACA 0012 templates, basswood spars, and composite fabric skin. The skin consisted of fiberglass, Kevlar and carbon cloth that were all vacuum bagged over the wing to increase structural integrity. The wings had a saddle cut out of them that allowed the body tube to rest inside such that the leading and trailing edges came in contact with the tube. This reduced the frontal area and thus drag, and it increased the bond strength between the two pieces. Four hard points built into the wing allowed it to be bolted to the body after assembly while still offering a breakaway feature in order to preserve the wing. Both the two fins and the two canards were hot-wire cut from blue foam, and then vacuum bagged with layers of Kevlar and fiberglass. The nose cone was formed with layers of fiberglass, Kevlar, and carbon fiber placed over a foam mold that had been turned on a makeshift lathe and cut to the desired shape. With the watertight volume inside and the holes cut around the tip, 3 gallons of water could pour out in about 24 seconds. Only 1 gallon, however, was used for launch. The parachute chamber in the rear of the rocket extended two feet into the body cavity. A wooden door was held in by shear pins that allowed the door to break away and the parachute to eject once the ejection charge was fired. The chute was a store-bought "Rocketman" parachute that was 18 feet from one side to the other, and made from a rip-stop nylon. Control of the 10-ft StarBooster was accomplished by the use of four servos, one for each aileron and each canard.

The 10-ft rocket was launched only once with an AeroTech L-1120W motor. The launch occurred at a Tripoli Rocketry Association sponsored event in Fresno, California. They conduct a monthly High Power rocket launch with an FAA waiver to an altitude of 10 to 20 thousand feet and operate in accordance with Tripoli safety procedures. At take-off, the weight was 70 lb., which put the maximum expected altitude at 1900 ft. The launch proceeded as planned with a stable climb during motor burn. The pilot nosed the rocket over slightly before apogee putting the max altitude at about 1700 ft. Without enough altitude to gain speed from freefall and pitch up and fly horizontally, the rocket hit the ground before achieving nose up flight and just as the parachute ejection charge fired. Too much weight, too little power, and a center of gravity too far forward were blamed for an unsuccessful glide. This event marked the end of Cal Poly Space Systems for the 1999-2000 year.

3.0 DESIGN DEVELOPMENT

In the fall of 2000, Cal Poly Space Systems reconvened and began construction of a new 10-ft tall model of the StarBooster rocket. It was the flight of the previous 10-ft model that dictated new construction techniques. The goal was a lighter structure in order to reach a higher altitude, in conjunction with a more powerful motor. It was decided that composite materials would be used for the manufacture of the entire rocket. Instead of a phenolic tubing body, carbon fiber would be used, and fiberglass and carbon fiber would replace the kevlar skin on the wing, canards, and fin surfaces.

During the summer of 2000, a nosecone mold was built that incorporated the complex geometry as proposed by the StarBooster blueprint. This mold was used to fabricate a nosecone entirely out of thick layers of carbon fiber cloth. The mold included a slightly smaller diameter bottom section such that it could be easily slid into the main body section.

The body tube was formed using a phenolic tubing mold. Three layers of a medium thickness carbon fiber cloth were laid around this mold, and then held in place with a large, smooth Mylar sheet. The Mylar allowed the finished surface, once dried, to be smooth and not necessary to sand. The bottom section of the aft airframe tube was cut such that the wing could fit underneath. The wing tip and trailing edge were each in contact with the surface of the tube. Figure 1 shows the individual pieces of the StarBooster rocket in an early stage of construction. Shown are the phenolic tube mold (striped), the mid and tail sections of the body tube, the wings (blue foam, uncovered), the nosecone, vertical fin and canards (covered with composite skin).

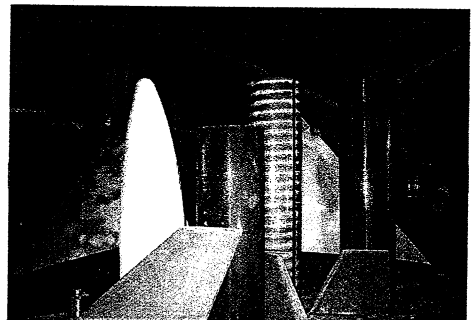

Figure 1 - Individual StarBooster Parts

The wing, canards and vertical fin were constructed from foam cores hotwire cut to the appropriate shape using templates. These cores were then covered in one layer of carbon fiber and one layer of fiberglass, the fiberglass used on the outer layer for ease of sanding. Figure 2 shows this process being done for one side of the main wing. They were all dried while inside of a vacuum bag in order to increase their individual strength and provide a smooth surface. The wing, once situated underneath the body, was attached with a thick epoxy mix - a long-drying epoxy with generous portions of microballoon glass spheres. This additive increased the volume of epoxy as well as its strength without increasing its weight. Once bound with the epoxy mix, strips of carbon fiber were used along the joints that extended several inches on either side of the joint. The vertical fin and two canards were similarly attached.

Figure 2 – Composite Skin Covering Process

Four bulkheads mounted inside the body at various points increased the compression strength of the carbon tube. These bulkheads, about 1-in. thick, consisted of two layers of carbon fiber with a foam center. One bulkhead was placed in the nosecone and was heavily epoxied to enforce a watertight characteristic. Another was used as a centering mount for the motor in the rear. A hole in the center of the bulkhead was precisely cut such that the motor casing would fit snuggly. The two other bulkheads were epoxied into the center section of the body tube, spaced out by the electronics board.

The electronics board was perpendicularly sandwiched by the center section two bulkheads, and slid into place with wooden rails on the inside of the body tube. The board was outfit with an altimeter, the parachute ejection charge circuit, and the radio receiver for remote control by the pilot. Zip ties and thin foam sheets kept the electronics and batteries carefully in place.

The extensive use of the lightweight foam and the composite materials decreased the overall weight of the vehicle. What did increase the weight was the new motor mount. It was designed by CPSS and then machined on campus. The mount was made of a thick aluminum and designed to distribute the tremendous forces exerted by both the motor and the parachute while at the same time allowing sufficient space for the parachute compartment.

The parachute compartment extended about three feet into the rear of the body tube, above the motor mount, as shown in Figure 3. A thin sheet of epoxied fiberglass was rigid enough to keep the parachute within its designated area and not touch the potentially damaging hot motor casing. A door sealed the cavity, made of a thick canvas and held in place by two shear pins. One thick Kevlar line extended out and around the nozzle of the motor, attaching the main chute to the drogue. The drogue, housed in a small, cardboard tube container, was held in place with a thick, snuggly fit wooden door. The ejection charge, when fired during flight, pushed the drogue out of its compartment, which in turn pulled out the main chute.

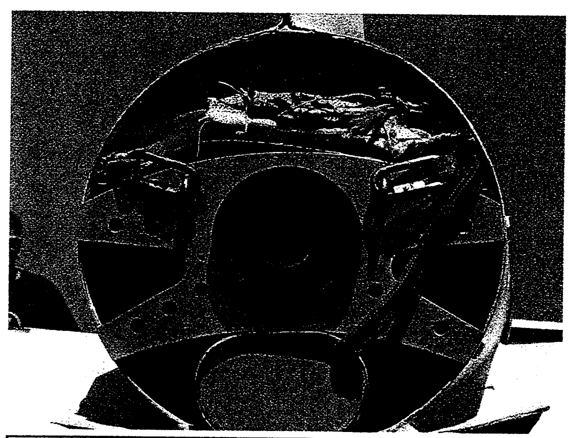

Figure 3 – Rear End of the StarBooster
From top to bottom: parachute compartment, motor mount and motor casing, drogue compartment.

The rocket was completed with a contrasting color scheme applied, white on top, black on bottom, for easier identification of orientation while in flight. Several logos, displaying the club's title as well as the StarBooster name gave the finishing touches.

3.1 R/C POWERED GLIDER

To aid the Cal Poly Space Systems standard testing environment of vertical launches, a test platform StarBooster powered R/C airplane was designed, built and tested by the CPSS Pilot, Paul Barthel. The main purpose for the R/C airplane, named the XTM (experimental takeoff model) was to better understand the horizontal flight characteristics of the StarBooster configuration. Figure 4 shows Paul preparing the model for its test flight. A gas powered propeller engine was used to fly the model. One successful flight was made with the XTM, which showed that the stability of this configuration is very dependent on cg location. The airplane flew, but was somewhat unstable in both pitch and roll. It was determined that the cg for this R/C plane, as well as the 10 ft rocket was not necessarily the same as that specified for the full scale StarBooster.

Figure 4 – R/C Powered StarBooster Model

4.0 FIRST LAUNCH – MARCH 2001

Initially, the first 10-ft tall, composite material StarBooster rocket was ready for launch in February of 2001. The Tripoli launch for that date was cancelled due to rain in Fresno, CA. A second launch date was then perused at a different location, but it too was cancelled for bad weather. It wasn't until March 18th that sunny skies finally reached Fresno.

The rocket had a pre-launch weight of about 80 lbs., including 16 lb. water ballast in the nosecone and a 19.6 lb. AeroTech M-1939W solid rocket motor. Given the power of our motor and the size of our rocket, we had initially estimated a maximum altitude of about 4000 feet. Electronics on board the vehicle consisted of an Emanuel Avionics IXA-96 integrating accelerometer to collect acceleration and altitude during flight. In addition, a Missile Works WRC Wireless Recovery Controller was used as a backup control for ejection of the parachute.

Figure 5 shows the initial ascent of the StarBooster. The rocket launched vertically and flight during motor burn was excellent up until the moment of greatest aerodynamic force. Then, the left canard ripped off of the nosecone and the rocket suffered an immediate perturbation in its vertical flight. Once it reached apogee and pitched over, the water poured out of the nosecone. The water streamlined the body of the rocket and re-entered the tube through various holes made for pressure equalization for the onboard automatic ejection circuit. Subsequently, the electronics became soaked with water and immediately became useless. Without radio contact and having no way of jettisoning the parachute, nothing could be done as the 60 lb. rocket (having had lost the weight of the water and the propellant) tumbled through the air. Fortunately, due to the lack of a canard and a misdistribution of weight, the vehicle went into a perfect flat spin after falling from apogee for only a few hundred feet. Spinning on a completely horizontal plane, the rocket landed on the ground directly on its belly and suffered only minimal damages. The rocket was easily repairable for another launch attempt in April.

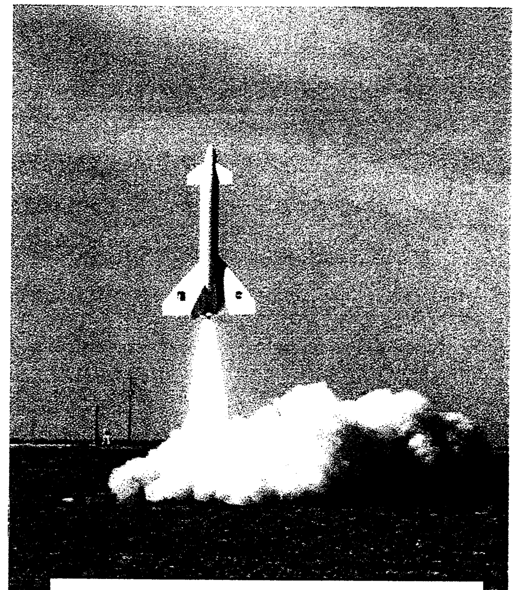

Figure 5 – March StarBooster Launch

4.1 DESIGN ALTERATIONS

Post-launch analysis revealed that the center of gravity was much too far aft. The rocket was repaired and improved before the next launch date in April. An additional permanent weight was added to the nose by an appropriately sized lead weight bolted to the inside of the water ballast volume. Though it increased the overall weight by about 6 lbs., weight was not available for removal anywhere else on the structure. Further mathematical analysis suggested that no water ballast at all would be necessary, so having a watertight bulkhead or sealing up the problem pressure holes was not an issue. The rocket would not shift its cg aft during flight.

Both of the canards were re-constructed. They were attached to the nosecone with the addition of a copper tube spar that ran from inside one canard, through the nose and into the other. A thick microballoon epoxy mix was used to adhere the spar to the canards. Also, two layers and a few wider strips of carbon fiber were placed along the joints on the outside of the nosecone.

The parachute recovery system, although never used during this launch, had weak areas of its design exposed. Upon initial burn of the motor while the rocket was still on the launch pad, the canvas door and some parts of the chute were burned and melted. This resulted in a three-layer thick Kevlar door to be implemented with Kevlar braided threads attached to the shear pins.

5.0 SECOND LAUNCH – APRIL 2001

One month for repairs was more than enough to have the StarBooster ready for launch in April, again in Fresno. This time the electronics consisted of a Missile Works RRC Remote Recovery Controller and a WRC Wireless Remote Controller. In addition, a WWC 900 Hopper - 1 Watt - 900MHz transmitter and receiver with a 6dB gain Yagi antenna were installed to transmit the data to the ground.

The same motor was used and thus a 4000-ft maximum altitude was our pre-launch estimation. The ascent was good, and this time undisturbed. Once it reached apogee, the smoke plume had grown so enormous that our pilot lost visibility. After about ten seconds of erratic downward flight, the pilot regained visibility and then attempted to maneuver the StarBooster into a nose-up horizontal position. This occurred for not more that a few seconds, and then quickly digressed into a vertical descent. Once the rocket was at about 1000 feet, the parachute was ejected but detached from the rocket immediately. The parachute deployed but the rocket continued its dive until it hit the ground.

What remained of the rocket revealed useful stress analysis information. The enormous forces imposed by the chute attempting to open at such a high velocity straightened the eyebolts that attached the main chute to the motor mount. The motor mount itself sheared all twelve bolts that attached it to the body. This exposed the lack of strength for the size of bolts that was used as well as the strong nature of the carbon fiber. The motor casing, having slid halfway through the mount and through the center of the electronics board, was undamaged and reusable. Figure 6 shows the main area of the crash site, though some of the debris extended another 15 to 20 feet out. Though the bulk of the structure was not intact, four pieces remained usable and found themselves within the assembly line during the construction of the next StarBooster: the launch lugs, the motor mount, motor casing, and the Kevlar parachute compartment door.

Figure 6 – Crash Site After April Launch

5.1 MORE CG TESTING

The decision was made to build a new 10-ft rocket and fix the design weaknesses. While construction began for the new rocket, tests were done in order to re-assess the issue of the center of gravity. After observing the second launch, it was thought that the nose was too heavy for a successful glide. Two small, easily manufactured models resolved the issue.

First, a one-foot tall model was constructed out of a cardboard tube and balsa wood fins. The center of gravity was left variable by the use of a foam insert and a few coins. After dozens of flights, the placement of minimum height for the center of gravity was nailed down. Any further towards the rear and a stable ascending rocket flight was not possible. Because of these tests, water ballast was implemented again in the new 10-ft rocket construction.

Second, a three-foot long, ¼ scale of the rocket was fabricated out of blue foam that was hotwire cut into every shape and surface needed. Mylar tape around every surface made the vehicle sturdy as well as smooth. This particular model was used in order to qualitatively pinpoint the center of gravity for optimal flight. The center of gravity was varied through a range of locations on the model over a period of nearly fifty flights, and the CG with the best performance was found. These tests nailed down exactly where the center of gravity should be for the 10-ft rocket.

5.2 FURTHER DESIGN ALTERATIONS

One month to construct an entirely new rocket was difficult but manageable with only a few nights of no sleep. Six new changes were made to the rocket design and its construction:

1) A larger vertical fin was made. The new fin was 20% larger and thought to decrease its roll sensitivity. Though it had not been a problem up to that time, flight tests with the ¼ scale model encouraged the change to be made.

2) The centerpiece to the body tube, a 4-ft section that housed the electronics, was made out of eight layers of fiberglass as opposed to the three layers of carbon fiber. This was in response to the idea that electrical interference may be problematic with a semi-conductive carbon fiber in-between the radio receiver onboard and the pilot on the ground. The fiberglass added slightly to the overall weight.

3) The motor mount was re-drilled with larger bolts at the connection points to the body and four U-bolts, two ½ inch thick and two ¼ inch thick, were used to attach to the parachute.

4) The parachute deployment system was also assessed. In order to reduce the energy that the main chute must absorb, four 25-ft Kevlar cords were folded up and taped in such a way that when chute did open, the cords would absorb some of the energy as the tape was ripped away. The use of a drogue did not change as it too absorbed some of the energy and required little explosive charge to deploy.

5) The main wing, once it was foam cut and covered with layers of carbon fiber and fiberglass, was cut to fit the body tube, as opposed to cutting the body tube to fit the wing. This increased the surface area in contact between the two and was easier to accomplish.

6) The color scheme was also changed. A flight-test orange top and black bottom was done with the thought that it may help distinguish its orientation better than white and black did.

6.0 THIRD LAUNCH – MAY 2001

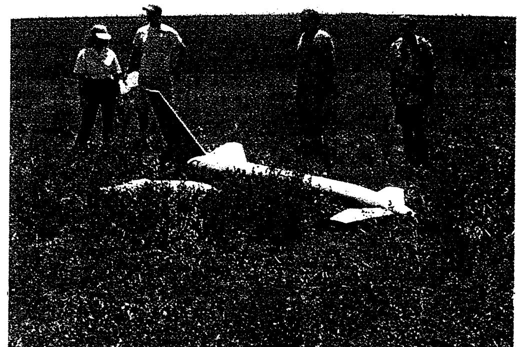
Figure 7 – Smooth Landing After Successful May Launch.

The third and last launch of the season ended with enormous success. The ascent was beautifully unperturbed and its 3500 ft altitude allowed for enough room to gain speed for a spectacular pull up into horizontal flight. The StarBooster made two turns and flew two very long (an estimated total of 1500 feet) horizontal paths. The parachute was deployed at the end of its last flight path, while the rocket was still horizontal. This allowed for the least amount of stress on the chute. The landing did damage the tip of the nose and the edge of a wingtip, but the structure was essentially unharmed. Figure 7 shows the rocket after it was recovered by the successful deployment of the parachute.

7.0 SUMMARY & RECOMMENDATIONS

Two all composite 10-ft tall rockets were built and flown a total of three times during the 2000-2001 academic year. In addition, a 3-ft powered R/C airplane was built and flown to test cg. The experience with the powered R/C plane led to the development of an unpowered foam glider that was subsequently used for cg testing and was much more successful.

In March, the 10-ft StarBooster model was flown for the first time, but lost a canard during ascent, went into a flat spin, and suffered minimal damages. The second launch in April had a successful ascent, but the parachute failed to stop the rocket upon its quick descent. The rocket for the final launch of the year in May is shown in Figure 8. The launch was a major success in that the rocket finally achieved nose-up flight. The rocket reached a sufficient altitude and then upon descent had two long horizontal flights that were under complete control of the pilot. A key factor in the success of this flight was that the pilot did not attempt a pull up of the vehicle at apogee, but only after it made a dive to gain speed. This second rocket, constructed in May, still exists and awaits its next launch in the near future. Cal Poly State University and the CPSS team are currently negotiating placement of a high power rocket launch facility at Vandenberg Air Force Base, which would make an excellent location for a second launch of the 10-ft glider.

Figure 8 – Cal Poly Space Systems StarBooster Team, May 20, 2001

Cal Poly Space Systems has reconvened in the fall of 2001 in order to take the StarBooster project one step further. The plan is to construct two models of the StarBooster rocket as well as an upper stage rocket that will be carried by the boosters. This launch sequence – two StarBoosters lifting off simultaneously, detaching after burnout and gliding back to the ground while the second stage engine lights and then ascends another some-odd feet – is exactly what would happen if the StarBooster project were implemented on a full-sized scale. New challenges await CPSS as we begin this multi-tasked objective. For one, the mechanism that detaches the StarBoosters from the upper-stage will be a little tricky. Precise timing with either mechanical or pyrotechnical devices will be essential to a successful glide-back. Also, with a second glider comes the demand for a second pilot, a skill that is currently being developed by several CPSS members. The group plans to collect flight data for the entire trajectory of the booster rockets, including data for flare and landing the StarBooster.