BACKGROUND

In November of 2006, a small team at Harvey Mudd modified a Public Missiles Patriot Missile to carry a small video camera and record rocket vibration data with four piezo electric dynamic strain gauges. This rocket, dubbed Mudd I, flew once to 1000 feet; the data received was acceptable and allowed for a series of test rockets for Harvey Mudd College.

The objective of the series of test rockets is to develop and test technologies and construction techniques that will later be used to build fully-instrumented, moderately-powered rockets as a pedagogical tool in an experimental engineering course. For this reason, the optimal rocket would be fitted with dozens of sensors and a data acquisition system. Its design would also need to be simple and robust, such that the rocket may last several years with several launches per year in the hands of students not necessarily familiar with rocketry.

Mudd I's success fueled the creation of a new generation of rocket, called the Mudd II. Graham Orr originally insisted on a rocket that would serve as a testing platform for not only electronic systems, but for high performance supersonic flight. His was to investigate fin flutter and general airframe oscillations in the highly violent portions of transonic flight. This resulted in the decision to build two carbon fiber composite "Mudd II" testing rockets at an estimated material cost of $500 per unit.

Over the course of the next several months, an eight person team including two professors assembled weekly to discuss progress and plans. During this time, a few students researched composite construction techniques and made many failed tubes while others designed signal condition boards and performed diagnostics on the next generation Black Fin fight computer.

The research group became more productive during May because full time work on the rocket had started. Although the rocket had been completed and reviewed in the preliminary design process, it was still not clear whether the team could build the composite airframe tubes themselves. The design required extremely strong tubes with tolerances on the order of thousandths of an inch. The research conducted led the team into a more productive direction but did not outline critical details of the process. It took nearly four months of expensive trial and error to devise a process that produced not only strong but also uniform tubes. This process is outlined in the *Composite Tubes* section.

FLIGHT PROFILE OVERVIEW

The Mudd II was designed as a 54 mm minimum diameter rocket. The booster section was designed to accommodate the largest Aerotech 54mm motor available, which is the 54/2560 casing for a full K motor. Due to the 12 piezo electric sensors that were planned to be surface-mounted on the booster, a complex and delicate process of wire routing was required and is described in the *Scientific Sensor* section.

The high velocity flight anticipated with the design motor would also result in fairly high altitudes. The high ballistic profile of the rocket enables the rocket to coast for a long period of time after a powered boost. In other words, the rocket's drag forces are small compared to the momentum of the rocket. Such a flight characteristic would lead to high altitude flights over 18,000 feet. Because of this, a dual recovery system was built into the rocket. The 18 inch drogue parachute, deployed at apogee by the flight computer, would result in a very high rate and stable descent for the rocket. The 48 inch main parachute would be fired at a user specified altitude, typically at approximately 500 feet. This two-parachute design would allow for rapid recovery allowing for a shorter flight turn-around time.

AIRFRAME TUBES and COUPLERS

The airframe tubes were made of a 5.4 oz. carbon fiber and Kevlar composite, while the couplers were carbon fiber. Both the airframe tubes and couplers were wrapped in 3 to 4 layers of 1.4 oz. s-glass for added strength and for the protection of the surface mounted sensors. A non-glassed airframe tube could be completed in three days. On the first day, one would prepare the adequately-sized mandrel with non-stick plastic to perform the first layups. A long enough section of carbon fiber cloth would be cut out in order to wrap twice around the mandrel. Once the cloth is substantially wet with long set epoxy resin, at least two people would wrap the cloth around the mandrel tightly and make sure that there are no creases or ridges. On the second day, the same procedure would take place with the carbon fiber and Kevlar hybrid cloth. The Kevlar would run in the transverse direction. Finally on the third day, the same procedure as the first day would be repeated. The only variation in this procedure that occurred was in the manufacturing of the booster section of Mudd II. Since this section is the one that would experience the most stress and general wear, the layups would cure under vacuum on the second and third days for added strength. The reason there was never any vacuum bagging on the first day is that the non-stick bag between the first layup and the mandrel would create ridges in the first two layers of carbon fiber, thereby compromising the shape of the resulting airframe tube. One of the major challenges in the manufacturing process of the airframe tubes was removing the composite tube from the mandrel. It was usually done by hammering out the mandrel but in the case of the booster airframe, liquid nitrogen had to be used in order to temporarily decrease the diameter of the mandrel. The team believes this was necessary due to the extra compression caused by the vacuum bagging on the last two days of the tube manufacturing.

The coupler tubes would undergo a similar process except that there was no vacuum bagging or hybrid cloth. Non-glassed coupler tubes could be completed in three days, laying up 2 layers or 5.4 oz. carbon fiber each day. Upon completion of all the tubes, they would be cut to size using Professor King's abrasive saw.

BULKHEADS

Like the airframe, the bulkheads of the rocket were fabricated from fabric composites. Because it is not a good idea to thread directly to fiberous materials, we designed the bulkplates to incorporate either graphite or aluminum inserts depending on the device. For shock chord attachment points, the bulkplate design was extra difficult due to the need to pass signal wires through the shock-chord's inner wire tether and terminate them on each end of the shock chord. In addition, the system would need to hold the tubular nylon shock chord in place while permitting the wire bundle inside to move freely, should the system violently kick or twist during descent. Because of this, we called the mechanism that did this on each bulkplate an SRM or Stress Relief Mechanism. The SRM would prove to be a challenge incorporating since embedding it in the composite bulkhead structure would require a sort of "positive retention" on the bulkplate.

The team did not want to rely on epoxy to hold the 7075 aluminum to the carbon fiber; but wanted a mechanical barrier for it to push against. Because of this, we designed double-thickness bulkplates that had specific hole patterns cut into them to suit their function. When bonded, the resulting bulkplate would have two "levels" on it, in which the inserts would sit. These ensured forces were transmitted directly to at least one bulkplate while the other provided a positioning template and reinforcements.

The fabrication process of the bulkplates consisted of sandwiching carbon fiber, carbon-kevlar hybrid cloth, Kevlar mesh, and a Nomex honeycomb core with a high-strength epoxy laminate. The resultant sandwich was compressed at 1 psi while vacuum-bagged. After 24 hours, the resulting plate was exceptionally stiff and strong and ready to be sent to a local precision waterjet. The parts were cut with an abrasive waterjet using our Solidworks models as the NC template. Because of the composition of the plates a 50,000 psi jet with 0.030 inch diameter was used.

The composite parts were cleaned and prepped for embedding the machined 7075 aluminum and graphite inserts. The bulkplate layers were JB welded together and compressed together while curing. The inserts were then JB welded in their proper locations and allowed to cure overnight creating recovery and data transmission subassemblies. After a strong bond was established, the subassemblies were sanded, fit, and "epoxied" into their respective coupler tubes and reinforced with epoxy fillets.

FINS

The fins were also manufactured out of fabric composite materials bonded by epoxy resin. The core of the fins was made of a Nomex honeycomb pattern sheet, which was shielded on both sides by a light layer of Kevlar matte. Over the light layers of Kevlar on each side were two layers of heavy hybrid cloth; one direction was carbon fiber and the other was Kevlar. The two layers on each side were perpendicular to each other in directionality. Over these layers was pure carbon fiber cloth, completing the fin. The composition of the fins was exactly the same as the bulkheads and the avionics bay. For better aerodynamics, the leading and trailing edges of the fins were fitted with 7075 aircraft grade aluminum inserts. The cross section of these inserts was shaped like an arrow. The tail of the arrow was JB welded into a milled slot in the fin and the arrowhead served as the leading or trailing edge.

Bonding the fins to the airframe was done in the following steps: Template lines were drawn around the rocket to mark the position of the fins. 220-grit sandpaper roughed out the area around the template lines. Each fin was then tacked in place with Super-Glue gel and optically checked for alignment. After the Super-Glue dried a small fillet (of radius 0.1 inch) of JB Weld was applied to the joint and allowed to cure. From here, scientific sensors and wiring was laid down as outlined in the *Scientific Sensors* section. Strips of Kevlar reinforcement tape (0.005 inch) were applied across the joint with high strength laminating epoxy. After the Kevlar strips had set it was noted that the edges of the Kevlar had an undesired ridge, most likely due to how the fabric was woven. Because of this, chopped carbon fiber and epoxy filler was applied to the fins to create a smooth transition around the edges of the tape. When the filler started to set 5.4 oz carbon fiber cloth was cut out in the shape of the fins. The final reinforcement layer spanned from tip-to-tip from one fin to the airframe and across the adjacent fin. This would ensure a strong, yet smooth, final layer for the fin section. After all reinforcements were complete, the aluminum inserts were brazed of all unwanted epoxy and the section was sanded by hand to ensure a smooth finish.

The fin geometry was designed to meet several operation criteria. To increase the durability of the rocket the trailing edges of the fins were swept forward and offset an inch from the aft of the rocket. This design would prevent the fins from directly impacting the ground during descent touch-down. We were prompted to look into this after the Mudd I rocket suffered significant damage during a standard touch-down due to poorly designed fins. The leading edge of Mudd II's fins were designed to accommodate supersonic flight and thus were swept with an angle of 50 degrees from the airframe. This design allows for passive stability to at least Mach 1.3 with a decrease in performance in the higher Mach number regions. The rocket, however, is structurally designed to withstand high loads that may occur around the Mach 2 region. Further testing will be necessary to verify this, however.

One of the objectives of integrating sensors on the surface of the rocket was to take temperature readings at various points on the rocket. Since the leading and trailing edges were machined from aluminum insert would work well conducting heat for thermistor temperature measurement. Two thermistors (root and tip) were integrated into one of the leading edges on a fin. Inspection of thermal gradients across these two points could provide evidence as to the boundary layer conditions across the fin. However, during installation, the tip sensor's 40AWG lead was severed. However, the remaining fin root sensor was not damaged.

AVIONICS SECTION

The avionics section contained an avionics bay consisting of an electronics bed and disks to hold all the avionics in place. This avionics bay was constructed out of the same material as the fins. The avionics bay housed the on-board cameras, video transmitter, RDAS Tiny, the conditioning board, two batteries, and arming switch and two power switches. The cameras were secured onto a movable card that could be adjusted with a set screw. The camera card was extendable in order to increase the field of view and retractable in order to fit inside the airframe. Once inside the airframe, the camera card would extend the cameras to their flight positions.

The avionics airframe was different from the rest of the rocket sections in that it had three shroudings, offset of the fins and 120 degrees apart. They were made of carbon fiber layers shaped onto a basic spyder-foam mold, which were then vacuum bagged and left to cure overnight. Once the resin had solidified the carbon fiber, acetone was used to melt out the spyder-foam, resulting in a hollow shrouding to attach to the airframe. Since the cameras would protrude out of the rocket body, the incorporation of these shroudings was necessary. The shroudings would keep the cameras safe from wind forces as well as keep the rocket aerodynamically viable. In order to balance the aerodynamic forces, the camera shrouding had to be balanced with two others, all spaced at 120 degrees similar to the fins.

RECOVERY SYSTEM

The Mudd II employed a dual-recovery electronically fired parachute system. The pyrotechnic charges were controlled by the RDAS Tiny board, where the 18" drogue parachute was fired at apogee and the 36" main parachute was fired at a programmed 400-500 ft. Separation of the rocket was achieved by electrically firing black powder charges with the use of low-current (0.4 Ampere) electric matches located at the bulkheads on the coupler tubes of the parachute sections. These bulkheads were fitted with the SRMs in order to hold the tubular nylon shock cord. Due to the electronics between the booster and the avionics section, the shock cord that attached these sections together had to be a wire tether. In other words, signal wires were braided and bound by heat shrink tubing, which passed through the inside of the tubular nylon shock cord in order to electrically connect the two sections. Such a tether was not required for the second shock cord connecting the upper sections of the rocket to the nosecone as there were no sensors in either of those sections. All attachment points for the shock cords were at SRMs on the bulkheads with the exception of the nosecone. Two slots were cut into the bottom of the nose cone in order to route the shock cord in and out of it. This design was used in order to insure that the nosecone would not break at its attachment point with the shock cord and in order to not compromise the recoverability of the rocket.

Once the shock cord was routed through the two slots, its end was sowed to the rest of the shock cord at a point near the nosecone with malleable steel wire to insure recovery.

MOTOR RETENTION

Motor retention in Mudd II consisted of two primary challenges: Because the rocket is minimum diameter, there exists no aft bulkplate or centering rings to mount hardware directly to. In addition, the motor retainer would have to be "low-profile" as the team desired the part to introduce little drag. These two constraints led to the design of an aft retaining ring that would be held in place by three 4-40 bolts threaded into three stainless steel pieces at the base of the fins. These mounting points (stainless steel threaded rods) conform to the root-diameter of the fin and replaced a small segment of the fin's trailing aerodynamic inserts. The rods extend from the trailing edge of the fin to the aft of the rocket (a total distance of 1.00 inches). Once the rods were tacked in place, JB weld was applied to both anchor and fillet the parts.

The aft retaining ring was designed to conform exactly to end of an Aerotech 54mm aft closure. Three protrusions along the circumference of the ring provided an area for the mounting fasteners to pass through. The ring was cut from 7075 aluminum using a CNC waterjet cutter.

SCIENTIFIC SENSORS

The body of the rocket was fitted with 14 dynamic strain gauges as well as three thermistors. Though the signal conditioning board was not designed to read thermistor data, the thermistors were permanently embedded for future use once an adequate signal conditioning board is available. Two of the three thermistors are located on the forward end of the booster airframe. The remaining one is located at the root of one of the fins. The data from the dynamic strain gauges were recorded at a 200 Hz sampling rate and stored on the RDAS. It was later downloaded upon recovery of the rocket from the RDAS via USB.

The dynamic strain gauges were laid out in a predetermined manner such that the team would see interesting modal behavior. The sensors were self adhesive and stuck well to the exposed carbon fiber. They were electrically connected with conductive epoxy to 32 gauge copper wire that was surface mounted on the rocket. The wire was then passed through a common hole at the forward part of the booster, where all the wire was bundled for connection to the tether. To reduce the number of surface-mounted 32 gauge wire on the booster and due to the fact that carbon fiber is conductive, the whole rocket booster was used as the common electrical ground.

ONBOARD VIDEO

Preparation for RocStock, June 8-9, 2007

In preparation for Mudd II's first flights at RocStock, the test onboard video system 2.4 GHz BoosterVision camera and the 900 Hz mini-camera were dual-mounted onto a specially cut carbon-fiber board that could be extended and retracted from the avionics bay of Mudd II to look through windows of a mounted shrouding piece. The camera-mounting board extended and retracted by an axially-fixed machine bolt screwing and unscrewing a threaded hex standoff attached to camera-board. On either side of the camera board, there were spacers with dowel pins glued in that were designed to act as bearings. This design did not perform well in practice because of the following reasons: the parts for the scratch-made bearings could not be ordered with tight enough tolerancing; it was very difficult to assemble the mechanism accurately; even with JB welding and epoxy, the apparatus was too fragile. The apparatus would frequently jam during use and would have to be screwed and unscrewed. There was also significant risk of the apparatus breaking while it was retracted causing the avionics bay to be stuck inside the avionics section. It is recommended that future onboard video designs do *not* incorporate moving parts as they are hard to manufacture and assemble and usually present unforeseen complications.

The Mudd II avionics section was constructed out of a hybrid carbon-fiber and Kevlar composite. Due to the conductive nature of carbon fiber, the resulting tube surrounding the radio transmitter acted as a Faraday Cage and prevented any signal from being transmitted long-range resulting in no onboard video footage for these launches. Non-conductive airframe material needs to be used to not block live radio-broadcast video feed.

Preparation for LDRS, July 13-16, 2007

After RocStock, new onboard video system concepts were designed with the goals to be simplified and less prone to failure and to achieve two views (i.e. horizon and ground) with only one camera, as the E80 class rockets (Mudd III) will have at most one camera. Three designs (with variations) were developed. Alternative Design 1 involves having the camera mounted to the avionics bay looking out the side of the rocket with its field of view (FOV) split by an angled mirror attached to a shrouding piece. The mirror would provide a view looking down at the ground. To not block the cameras view but also to prevent bulkiness of the shrouding, the mirror would be exposed to the outside, with the risk of being scratched, broken on recovery, etc.

Alternative Design 2, or the "periscopic prism" design, involves a shaped piece of polycarbonate that would utilize internal reflection to achieve split vision. The motivation behind this design was to not expose a mirror to the environment while at the same time keeping the manufacturing process simple, as it was thought that the surfaces of the polycarbonate could be polished if scratched. Because of the camera's inability to protrude from the airframe, the size of the polycarbonate prism would be too large to adequately cover the camera's FOV. There are also issues with the fact that while most of the reflected part of the camera's FOV would be full (i.e. total internal reflection), a significant percentage would not.

A concern about the two previous concepts mentioned was how assembly and usage of the rocket would affect alignment between the mirror or prism internal surface and camera. With this, Alternative Design 3 was developed where the camera would mount inside the shrouding and would be coupled to the mirror (i.e. the camera and mirror as one unit) via a specially cut polycarbonate board, similar to the previously mentioned camera card. The camera would look straight down while the mirror was angled to reflect a view of the horizon. A further advantage is that the mirror is mostly submerged in the airframe. This design was pursued as the proof of concept for split vision in rocket flight. Even after inaccuracies from the machining process, the design was very effective in achieving split vision, as can be seen in the short in-flight video of the Mudd II at LDRS.

The 900 MHz camera was used for the split vision proof of concept at LDRS with avionics section made out of polycarbonate. The 1-watt transmitter was mounted on the previously used carbon fiber avionics bay with the antenna orientated towards the nosecone for positioning constraints. While there were moments of interrupted transmission, it is unclear whether these were due to the conductivity of the avionics bay (e.g. Faraday cage effects) and not just the orientation of the rocket as it was being handled. For the most part, the signal was very clear until the rocket reached about 4000 ft. If the transmitter antenna could have been pointed down towards the ground, the signal might have been clearer to a higher altitude.

Onboard Video with CCD Cameras

After LDRS, a design was developed to accommodate the much larger BoosterVision CCD camera for split-vision onboard video. This BoosterVision CCD camera included a large square base that prohibited it from being incorporated into an AD3-type design because it is simply too large to reasonably fit inside a shrouding. Instead, AD1 was further developed to accommodate it. But as opposed to the original concept of AD1, the mirror is not attached to the shrouding but instead mounted to a piece that attaches directly to the camera lens by a set screw gaining the advantageous camera-mirror coupling feature of AD3. The shrouding attaches the airframe and partly houses the mirror holding piece, but is not mechanically fastened to it, to prevent complication in the manufacturing process.

A problem not solved in with this design (or currently any other) is sealing off the area directly behind the shrouding as that during flight this will be a low-pressure region and will possibly adversely affect the accuracy of the altimeter inside the airframe if the opening is not sealed during flight. A smaller CCD camera available from OEM Cameras will be compatible with AD3 and it is anticipated that AD3 will more easily incorporate a sealed feature.