CALTRANS Bridge Inspection Aerial Robot

Division of Research
& Innovation

Final Report

Report CA08-0182
October 2008

Caltrans Bridge Inspection Aerial Robot

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Report No. CA08-0182

October 2008

Prepared By:

Advanced Highway Maintenance and Construction Program (AHMCT)
University of California at Davis
Davis, CA

Prepared For:

California Department of Transportation
Division of Research and Innovation, MS-83
1227 O Street
Sacramento, CA 95814

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16. Abstract

The California Department of Transportation (Caltrans) project resulted in the development of a twin-motor, single duct, electric-powered Aerobot designed of carrying video cameras up to 200 feet in elevation to enable close inspection of bridges and other elevated highway structures. The Aerobot designed to perform that mission, the model ES20-10, is a forty-pound vehicle employing two electric motors with power, control commands, and sensor images transmitted through a thin-wire and fiber-optic 200-foot cable. Aerobot is a ducted-fan vehicle utilizing a unique computer-aided stabilization and control system. The vehicle is capable of vertical takeoff, translation to horizontal movement as commanded by the pilot, hover at a point in space as commanded, rotation about its vertical axis (yaw control), and controlled descent to a vertical landing. This control permits extensive mobility for positioning the inspection camera to view elevated structures close-up from any angle. The system is designed to be very safe to operate in that it allows a video camera to be placed close to the structure being inspected while the operating personnel remain safely on the ground. The ducted fans are encased deep within the duct and the duct inlet can be fitted with a safety screen. Onboard computer controls stabilize the Aerobot at all times. Due to a number of implementation issues, the device did not perform as expected within the initial or extended schedule of events and was not deployed.

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CALTRANS Bridge Inspection Aerial Robot
Contract number UCD02-02371
Final Report
October 2008

DISCLOSURES AND DISCLAIMER

1. ACKNOWLEDGMENTS: The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology Program, with the Department of Mechanical and Aeronautical Engineering at the University of California, Davis, the Division of New Technology and Materials Research at the California Department of Transportation and the Federal Highway Administration. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities.

2. The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA, the FEDERAL HIGHWAY ADMINISTRATION or the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

3. This report was prepared in accordance with the terms of Research Agreement Number UCD02-02371.

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1. OVERVIEW

BACKGROUND

The normal aging of bridges and other elevated highway structures coupled with large increases in vehicular traffic have made it very important that elevated highway structures receive timely inspections. Present systems for inspection require complex equipment, disruption to traffic flow, and risk to inspection personnel. The advent of a small, vertical takeoff and landing (VTOL) aerial vehicle with the ability to carry a video camera in close proximity to the underside of elevated highway structures offers the capability to conduct inspections quickly, safely and effectively.

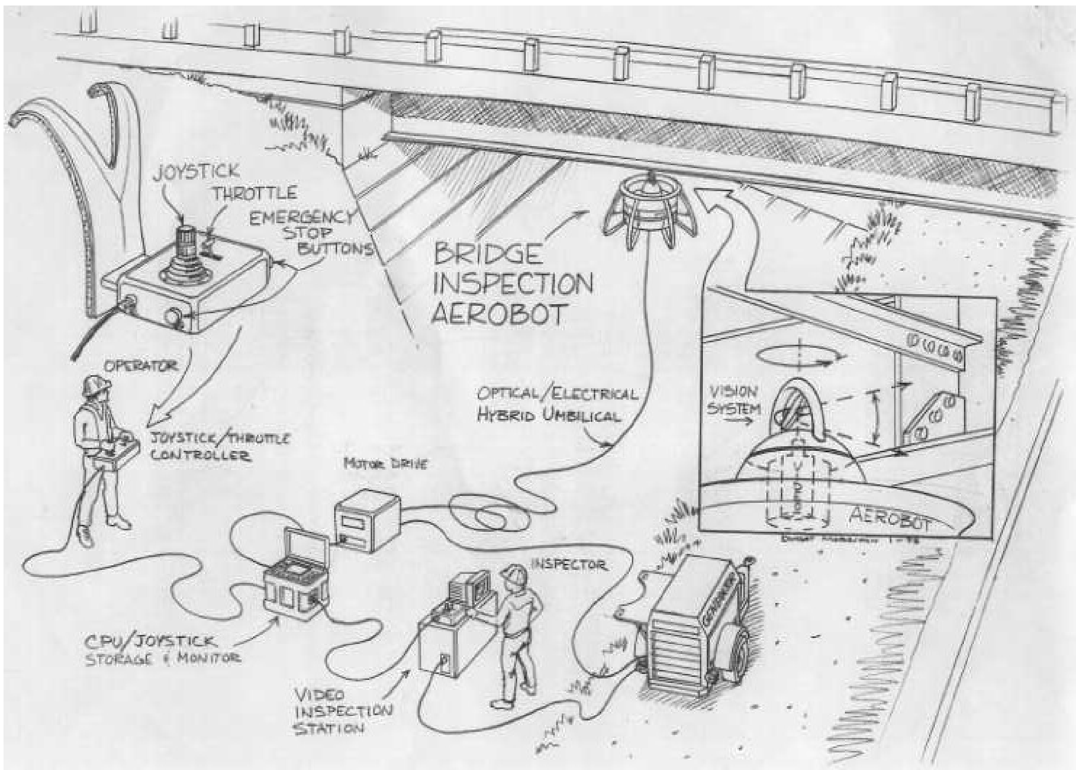
Aerobotics Incorporated, a wholly owned subsidiary of Moller International, has designed, fabricated and tested an aerial system for video inspection of bridges and other elevated highway structures.

PURPOSE

Previous work was accomplished under Research Agreement CAL94-6 and resulted in a remotely controlled aerial inspection robot with specific characteristics. The purpose of UCD02-02371 was to extend the work initiated under the previous agreement and create a new Aerobot with improvements in performance and utility.

SYSTEM DESCRIPTION

The new system consists of a vertical takeoff and landing (VTOL) aerial platform called an Aerobot®, which is approximately two feet in diameter and two feet tall with mounting provisions for video cameras and other sensors. The system includes a ground control unit that contains pilot controls, power supplies, and electric motor drives. Provisions are included for a video downlink and processing



and storing of video images.

This Aerobot is an electric motor driven, ducted fan structure utilizing Aerobotics' unique, patented computer stabilization and control system that facilitates hover, translation, and rotation in flight. Pilot commands, video signals, and electric power are transmitted through a light-weight umbilical of wires and fiber optics, permitting extensive mobility for positioning the inspection camera to view bridge details from many angles. Aerobotics Inc. is very familiar with the technology required to fabricate and assemble this system.

The system is designed to be very safe to operate by permitting personnel to be safely on the ground during inspections. The ducted fan has no exposed moving parts and can be fitted with a safety screen over the inlet. Onboard-computerized controls stabilize the Aerobot at all times.

The previous development contract resulted in an Aerobot that demonstrated the capability to perform basic VTOL flight and carry a video camera to the underside of an elevated structure.

STATUS

This contract resulted in the creation of an advanced model of the Aerobot with enhanced flying capabilities and the added features necessary for a fully operational system although, due to a number of implementation issues as described below, the device did not perform as expected within the initial or extended schedule of events and was not deployed.

The project was divided into two phases starting with the design-build-test and demonstration tasks for the new Aerobot, and then moving into tasks that added functionality to the basic vehicle. Phase I consisted of designing and manufacturing an improved Aerobot with better aerodynamic design, an improved stabilization and control system and more powerful electric motors. These tasks were accomplished and we moved into the final events of Phase I, the test and demonstration events. During this portion of Phase I, significant issues arose which required resolution before proceeding into Phase II. The project was suspended prior to the resolution of these issues.

Phase II was to include the addition of many features which can optimize the utility of the system for its inspection tasks. This phase was not undertaken due the issues identified in Phase I.

Total expenditures for this project have exceeded $962,000. Of this total, Moller International has contributed approximately 66% as cost share.

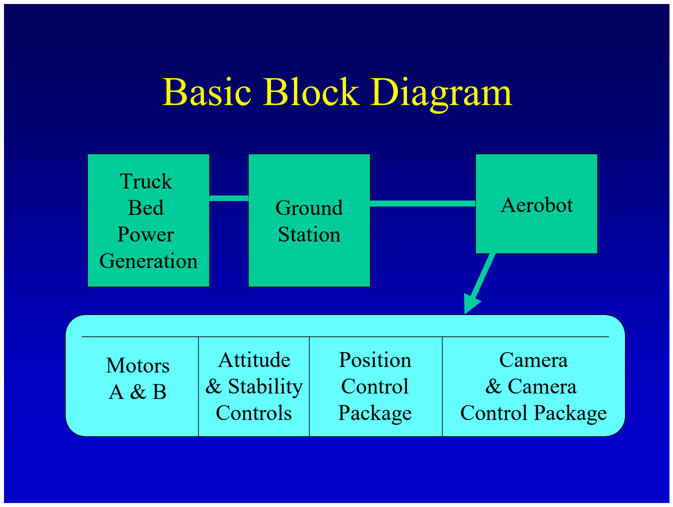
2. VEHICLE SYSTEMS DEVELOPMENT

DESIGN SPECIFICATIONS

The overall objective of this effort was to design and build an improved VTOL Aerobot vehicle and associated equipment to achieve an operational system capable of enabling properly trained personnel to conduct appropriate inspections of bridges and other elevated highway structures to detect, identify and record cracks, corrosion and other visually detectable structural defects.

VEHICLE DEVELOPMENT GOALS

Design, fabricate, test and demonstrate a new VTOL Aerobot that will be approximately two feet in diameter and slightly less than two feet tall and will weigh less than 40 pounds. There will be no exposed moving parts. Two generators will be provided to supply electrical power, approximately 15 KW of DC, through a 200-foot umbilical cable to provide power for operating two electric motors for lift and control. The two generators will be operated continuously to provide power for the electric motors and on-board and ground-based electronics. The second generator will provide instantaneous backup power in the event of failure of a generator. The payload capacity of the vehicle will be 20 pounds during normal operating conditions. The computer-controlled on-board control and stabilization system will allow the vehicle to operate safely in winds gusting up to 20 miles per hour. The design will incorporate altitude, position and heading hold features. The design will prevent inadvertent suction to the structure.



DEVELOPMENT TASKS

Phase I Tasks
-Planning and Design
-Manufacture New Duct Structure
-Procure and Install New Electric Motors
-Manufacture and Install New Landing Gear
-Design, Manufacture and Install Duct Stability and Control System w/software
-Procure Parts and Assemble a 200' Umbilical

Phase II Tasks
-Design, Procure & Install Height Holding System
-Design, Procure & Install Azimuth Holding System
-Design, Procure & Install Inspection Lighting System
-Design, Build & Install a Screen Over Duct
-Test & Demonstrate
-Prepare Operator & Maintenance Manuals
-Train CALTRANS Operations & Maint. Personnel
-Prepare Final Report

3. VEHICLE SYSTEMS – GOALS AND STATUS

Pilot Controls and Emergency Systems

GOAL

The operator will be able to control the Aerobot using a "roving cockpit" containing the pilot controls. A three-axis joystick will enable the operator to command roll and pitch angles and yaw rate. A thrust lever will allow control of vehicle thrust. The roving cockpit will be mounted on a yoke, which fits over the operator's shoulders and places the controls conveniently in front of him or her at waist level, allowing him or her to walk in order to maintain the best vantage point for viewing the vehicle in flight. The control yoke will contain an emergency stop system, which will allow the operator to eliminate all power to the vehicle if necessary. The generators can also be shut down quickly if necessary.

Significant improvements over the previous design include:

- User defined baseline for orientation of controls
- Simple "relative" movement of joystick translates directly to Aerobot
- Altitude and positional holding will be implemented. Potential technologies are GPS, differential GPS, local RF triangulation, and laser triangulation

STATUS

This portion of the system was designed, built and successfully tested. The altitude and position hold capability was successfully developed using an optical methodology by Moller's third party electronics design consultant. It has subsequently been demonstrated on other small UAV, although it was not installed on the bridge inspection Aerobot.

Electric Motor and Fan Design

GOAL

In the initial prototype the cost of the custom-designed and manufactured motors was significant (>$80,000) and therefore would have a significant impact on the price of follow-on units. The goal for this phase was to find a lower-cost alternative using available "off-the-shelf" technology where possible.

STATUS

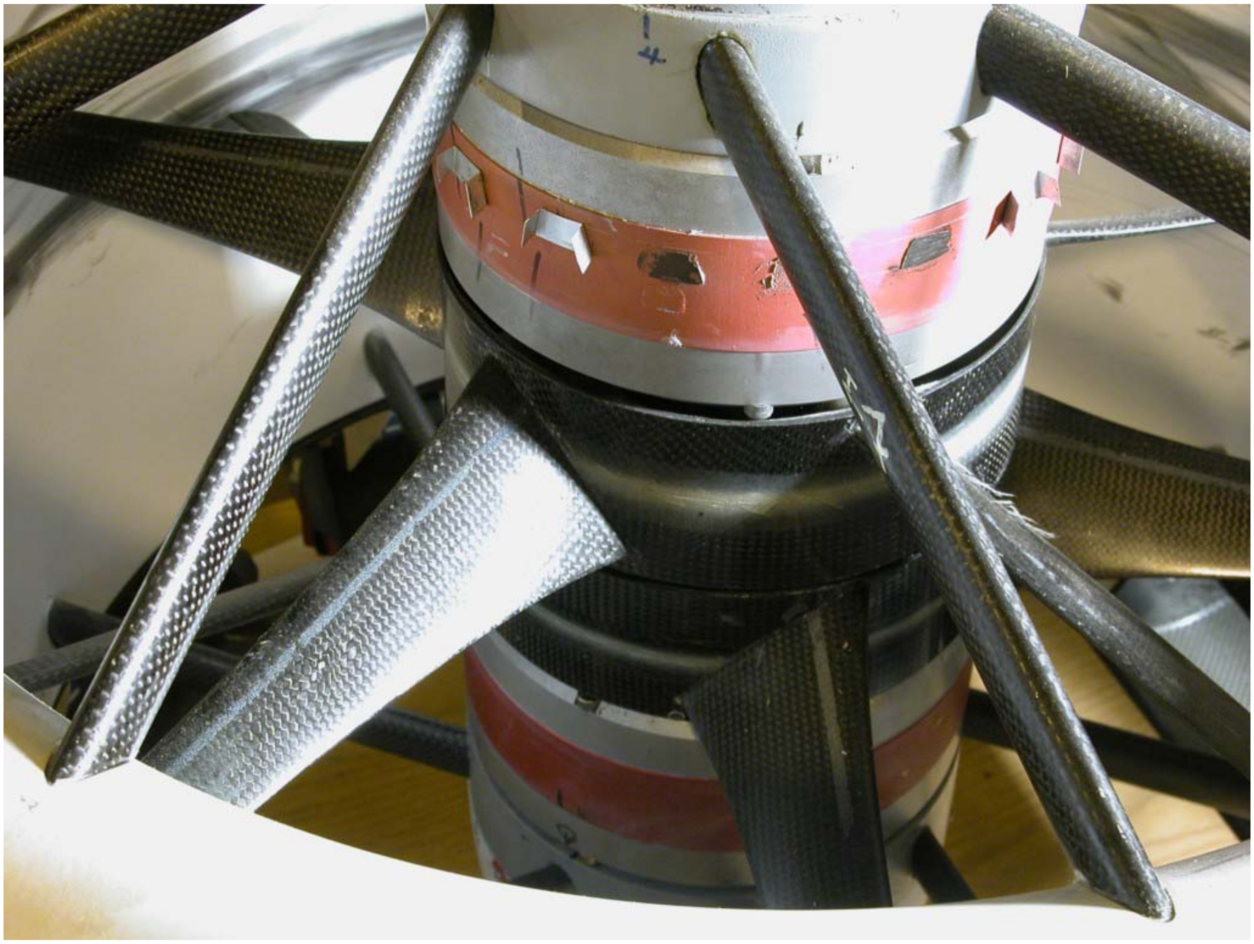
Three companies were identified which manufacture appropriate advanced electric motors. Selection of the Ecycle as the supplier was based on both cost and price-performance. The cost of the motor was less than $1,000 per unit. While we have experienced some difficulties with these motors, the overall cost benefits of going with these ultra-low cost motors are obvious.

The low-cost Ecycle motors posed several challenges that were identified and addressed in consultations with Ecycle during the motor selection process. The standard Ecycle spindle (driveshaft), hub interface, and spindle support bearings were originally designed for standard chain or belt drive, and would be inadequate for the high thrust loads and cyclic (resonant) axial loading imposed by a high speed thrust fan. The solution was for Moller International to re-design the entire Ecycle spindle to dimensionally match the standard Ecycle rotor and also re-fit the Ecycle endplates with a robust ball- bearing that could withstand any foreseeable loading. In addition, the re-designed spindle included a shaft taper feature ideal for Moller International's proven fan hub. With this solution, Ecycle would use their standard parts and not impose additional costs. The "custom" spindle design was relatively simple and inexpensive to fabricate in the MI facilities.

The "custom" spindles passed all functional and interference quality checks and proved successful in motor qualification and static thrust tests. Anomalies in the motor performance were first indicated during flight stability tests where finely tuned control of the motors was required. The problem exacerbated as the motors became warmer. The problem was initially attributed to tuning problem of the closed loop stability control system and/or blade interaction effects between the counter-rotating blades. It was only upon routine internal inspection of the motors that evidence of slight interference between the motor rotor and bearing housing was indicated. This was easily resolved with additional thrust washer.

The second challenge addressed during consultations with Ecycle was adapting a motor controller to the Ecycle Motor. The Aerobot application with a long umbilical required significantly higher voltage than Ecycle's standard controller; hence, a third-party motor controller (Aerotech) was selected. With the additional impedance of the long umbilical, power matching the controller to the motor posed a significant challenge. After many hours of testing and several iterations of Ecycle motor windings, and power chokes, a combination was found that gave the calculated speed-torque characteristic that would exceeded the torque requirements of the thrust fan.

An additional challenge of adapting the Aerotech controllers was interfacing to the Aerotech digital and analog controls. Aerotech engineers were very helpful in providing details and solutions to our application; however, it was well outside of their typical application. The system currently operates well with the exception of one anomaly that causes one controller to "fault" periodically. Fortunately, the "fault" has not occurred during a flight test, and "appears" to be timing bug between the ground station firmware and the Aerotech firmware. This bug has not been resolved and it potentially could occur during a flight and crash the vehicle!



The new motor/fan combination meets specifications, as shown by the table below:

Test	Lower Motor, RPM	Upper Motor, RPM	Thrust, lbs	Current @Max Speed, Arms	Comment
Both	**4775**	**4650**	**88**	**42.5**	
Upper	**2460**	**4600**	**51**	**47.5**	**autorotation on lower**
Lower	**4850**	**2500**	**52**	**45**	**autorotation on upper, Speed decreased after 3-5 seconds**

Structural Inspection System

GOAL

A high-resolution video camera will be mounted on the Aerobot in a manner that allows the camera to be tilted through approximately 45 degrees. Vehicle rotation provides 360 degree panning capability. A ground-based real-time video monitoring station will be provided which will be located independently from the pilot's controls.

STATUS

The desired camera was not provided, nor was one purchased, therefore this system was not install or tested.

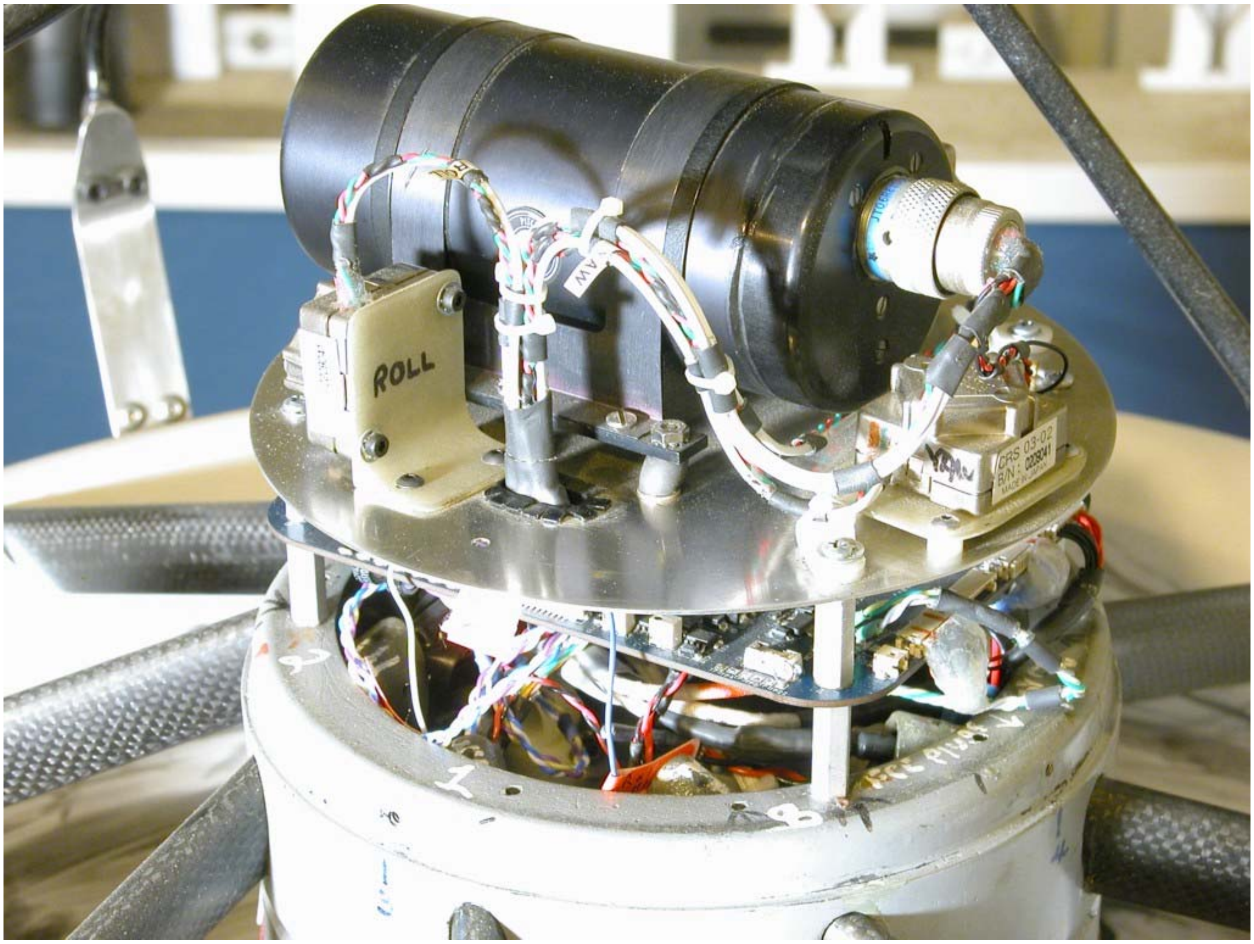
Control System

GOAL

The mission and nature of the Aerobot determines the requirements of its control system. Since the vehicle is essentially a remotely operated sensor platform, the operator must have the ability to control vertical and horizontal vectors, velocities and rotation rates. Therefore, the operator-commanded variables are thrust, pitch and roll angles, and yaw rate. The vehicle thrust is controlled by varying the applied torque to the fans, thus controlling climb, descent and hover. Roll and pitch angles control the horizontal component of thrust and thus horizontal velocities. Yaw control is achieved by varying the relative torque of the two motors to produce the desired torque force to rotate the vehicle to the intended heading.

The control system is based around a high performance 16-bit micro controller. This micro controller contains an on-board analog-to-digital converter, a timer, a serial communications unit, as well as a DSP unit capable of implementing control-type algorithms.

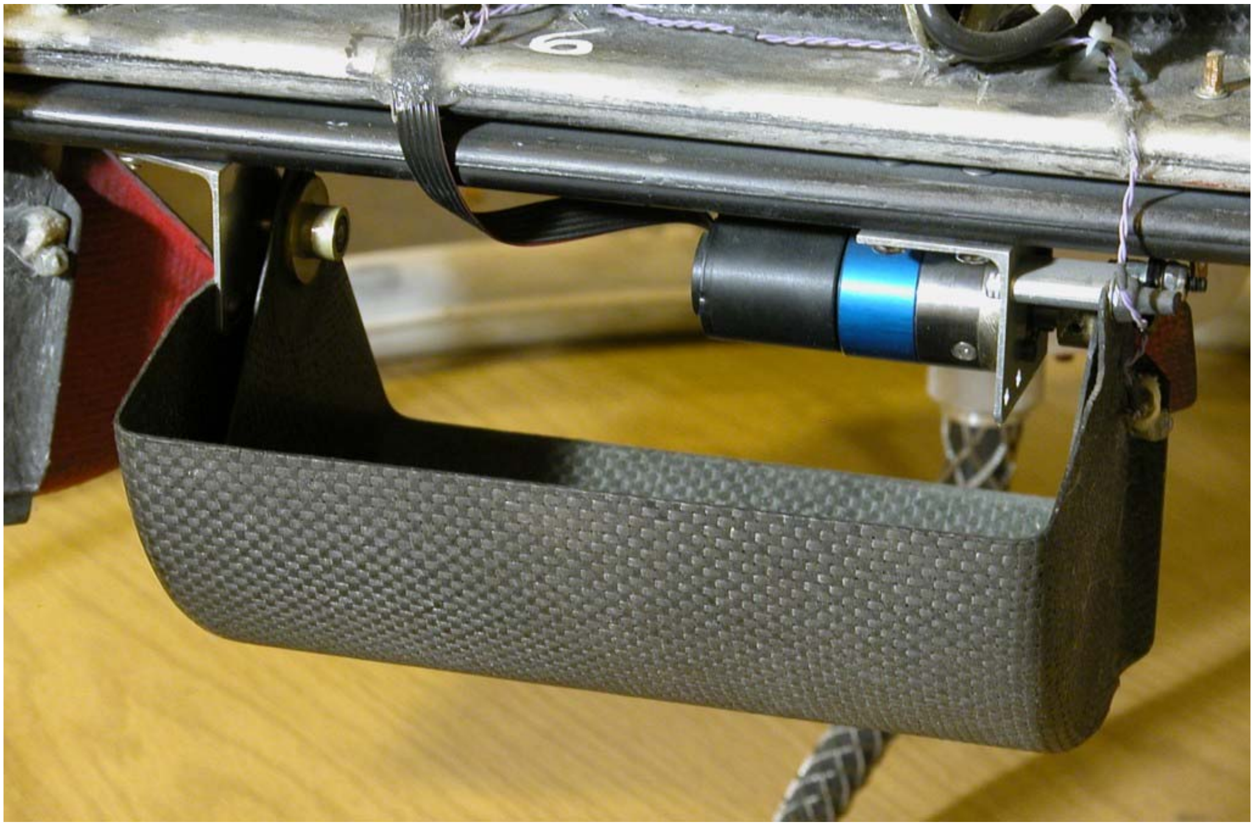
The micro controller receives vehicle roll and pitch attitude information from inertial sensors mounted on the vehicle. These inertial sensors consist of a vertical gyro, quartz angular rate sensors and servo angular accelerometers.



The sensor signals are passed through low-pass filters before entering the micro controller to reduce the effects of high frequency noise that could provide a false signal down into the control system bandwidth due to the limited sampling rate of the micro controller.

Pilot commands and telemetry are sent between the micro controller and ground control unit via a bi-directional asynchronous serial interface over fiber optic cable.

A set of eight servos are commanded by the micro controller, based on information from the sensors and from operator commands. These servos control a set of eight thrust deflectors, which stabilize, and control the vehicle.



Thrust deflector and servo

STATUS

The control system was designed, fabricated, installed and successfully tested.

Central Processing Unit

GOAL

A Central Processing Unit (CPU) is provided as a stand-alone station separate from the pilot controls. The CPU will provide the interface among the pilot, the Aerobot, and the flight motor drives and the video monitoring and recording system and will contain an LCD video screen to display the vehicle status when power is applied to the CPU. The CPU will contain a PC-based computer to control all communications and store data obtained during flight on easily removed tape or disks.

The primary improvements over the old system are:

- Software control of both primary and emergency stabilization systems
- Failsafe “limp home” mode for critical flight control in case of hardware failure
- Design improved to reduce single point of failure susceptibility

STATUS

The CPU was designed, fabricated, installed and successfully tested.

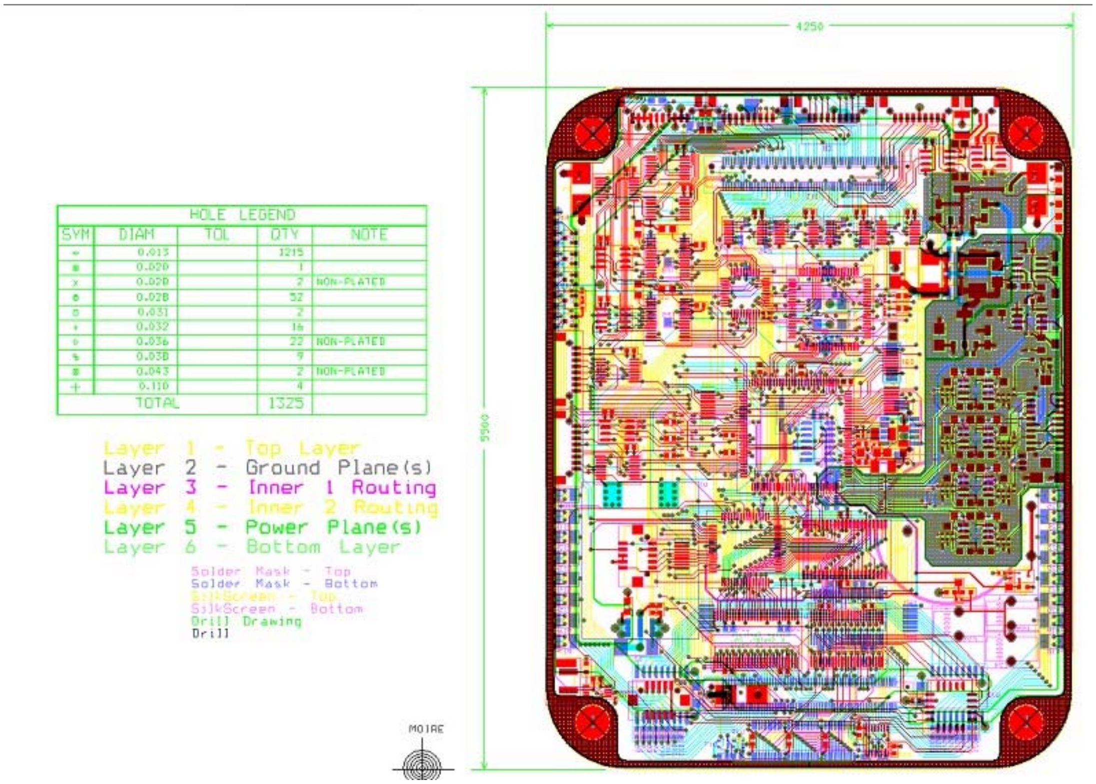
Flight Control Computer (FCC)

GOAL

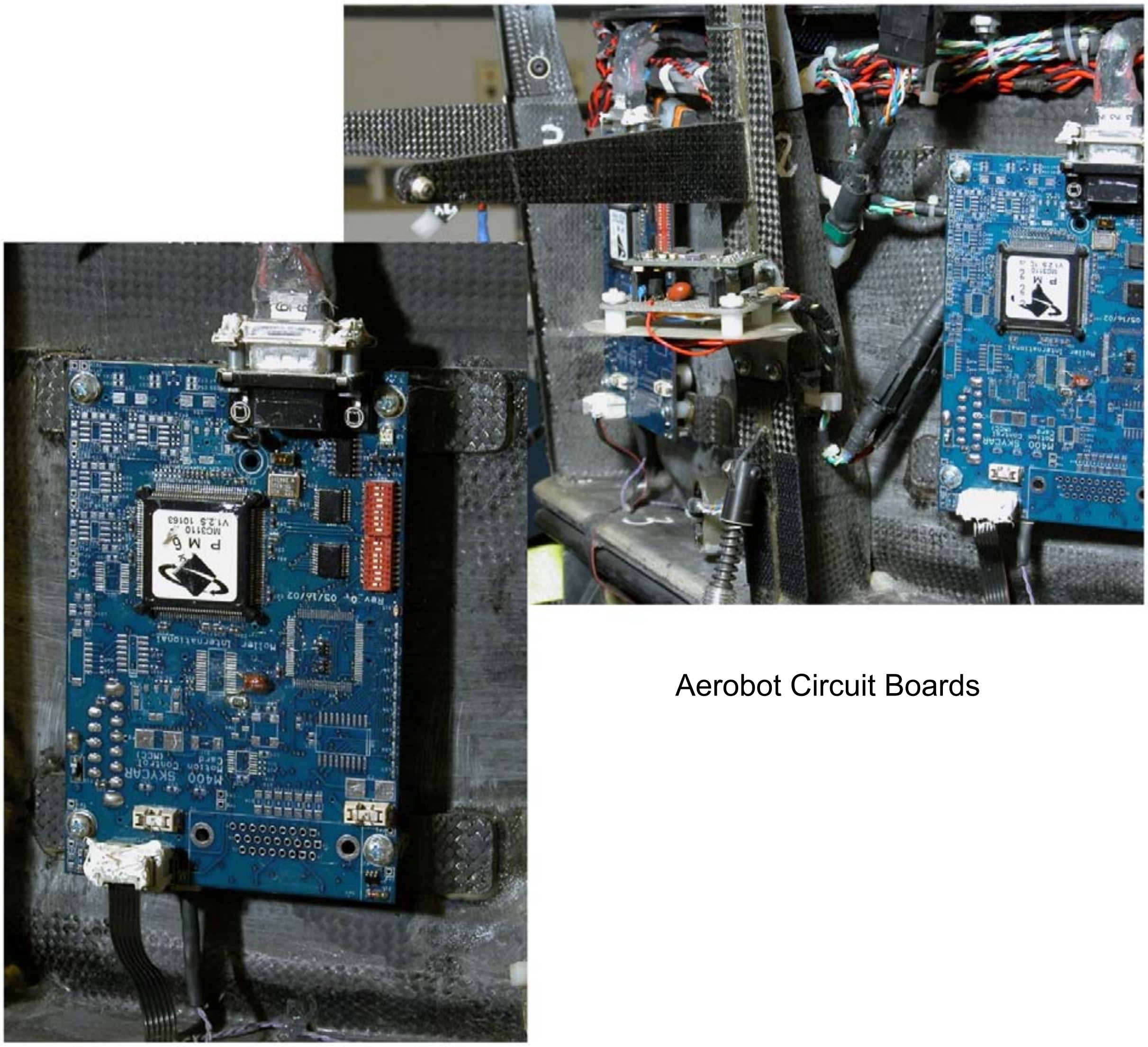
The goal for the new Flight Control Computer (FCC) was to effectively provide a redundant high-speed communications link to manage the stability controls, and specifically the 8 scoop command channels. In addition it would monitor attitude and rates of change for the unit and provide roll and pitch information to the flight controller in order to keep the vehicle oriented.

STATUS

The Flight Control Computer was designed, fabricated and tested. The FCC base configuration includes Power Supply, System Clock, MCU, SRAM and FPGA. It internally stores necessary decode logic as well. The circuit board for the FCC is shown below.



The FCC features a dual-channel high speed communications chip, an 8-Channel Octart chip (controls scoop command channels), 512 K Byte SRAM, 512 K Byte Flash program/parameter storage, programmable logic & decode, 8 K Byte program variable SRAM, and Analog signal conditioning circuits.



Aerobot Circuit Boards

The vehicle attitude sensors consist of a vertical gyro, three quartz angular rate sensors and two angular accelerometers. These sensors were chosen for their lightweight and high reliability. The vertical gyro provides roll and pitch information to the flight controller in order to keep the vehicle oriented.

Umbilical

GOAL

The umbilical will be a two hundred foot shielded cable composed of fine copper wire and fiber optic cable, providing power to the vehicle for all on-board systems and communications between the CPU and the vehicle.

STATUS

The umbilical was fabricated and tested. During one test the umbilical remained coiled (rather than being laid out) and overheating occurred causing the optical fibers to melt. Cutting out the damaged portion and splicing it back together successfully repaired the umbilical. Additionally, checks were defined for the maximum current allowed, although no software/hardware modifications have been implemented to limit the allowed current.

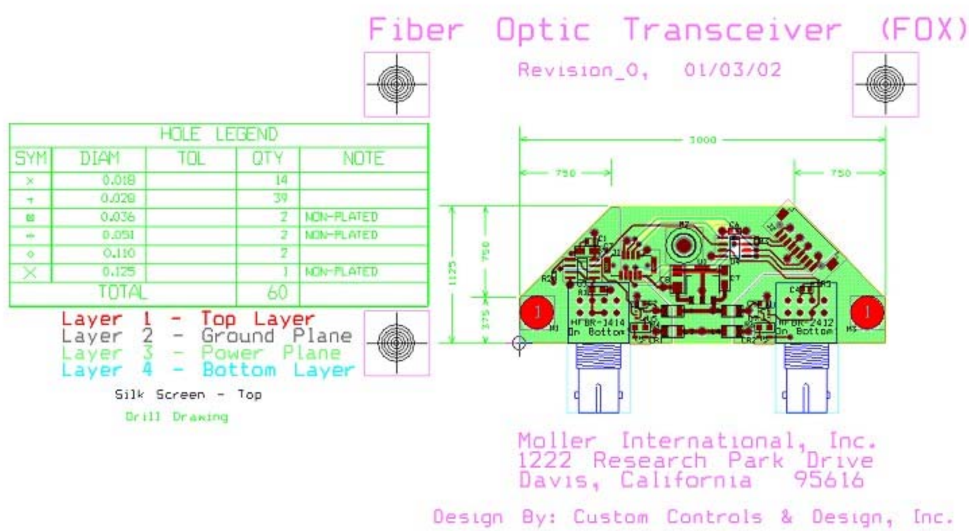
Fiber Optic Transceiver

GOAL

Provide a cost effective method of transmission for the control signals to the Aerobot.

STATUS

The Fiber Optic Transceiver (FOX) was designed, fabricated and tested.



Detailed Inspection

GOAL

The Aerobot will have a remotely operated light to enable inspections under conditions of inadequate natural light.

STATUS

This feature was designed and specified, although it was not fabricated or installed.

Impact Absorption

GOAL

The platform will include a lightweight body shell and a hood to protect the Aerobot and its on-board systems from debris and contact with the structure being inspected. In addition, the Aerobot will have a dampened landing system capable of absorbing moderate impacts from poor landing and inadvertent contact with the structure being inspected.

STATUS

The structure of the Aerobot used high-strength carbon fiber construction. In addition, it was produced for ease of assembly and disassembly.

Control and Power Systems

GOAL

The Aerobot will have a complete backup control system capable of operating the vehicle in the event of a primary system failure. Two generators, each operating a drive motor, will be provided so that in the event of a failure of either motor or generator, continued operation and control of the Aerobot will be assured. This redundancy is considered superior to a single generator with battery backup because the capability and status of the two generators will be known at all times whereas the status of backup batteries is an unknown until they are called upon to provide power.

The primary improvements over the old system:

- Use of compact commercial generators minimize space requirements
- Configurable to specific support vehicle constraints
- Ground station uses ruggedized industry standard PC and embedded control technology

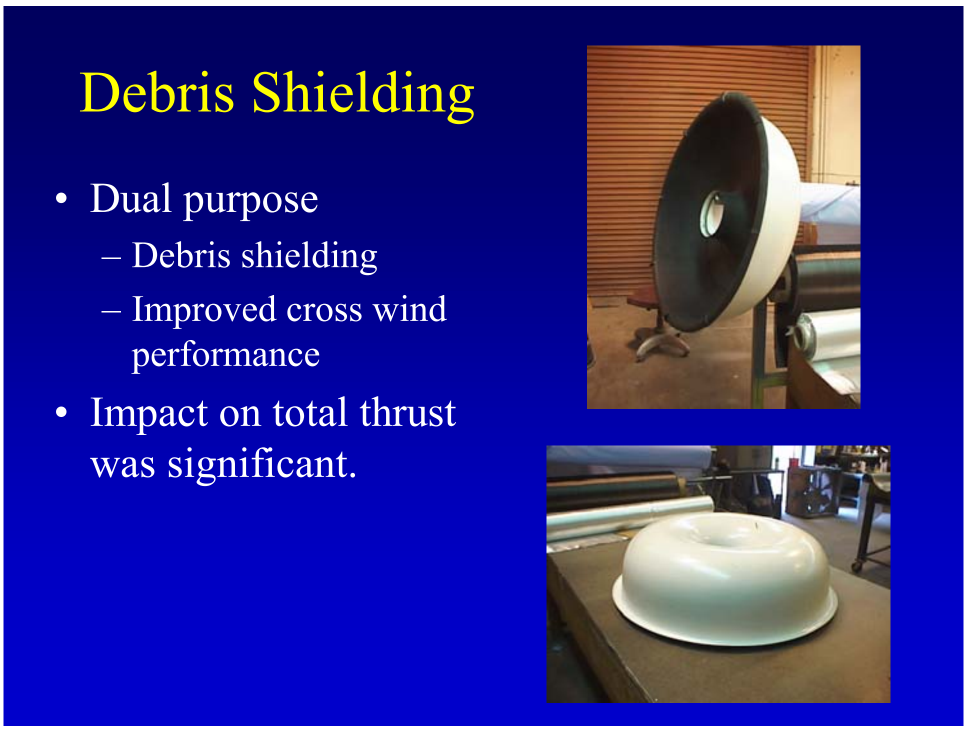
STATUS

Two commercial generators were acquired for this program and used successfully in the initial testing of the Aerobot.

Particulate Matter

GOAL

A hood will be installed above the upper surface of the duct for improved aerodynamics and to protect the Aerobot from ingesting foreign objects.



STATUS

The hood was fabricated from low-weight, high-strength carbon fiber composite materials. When tested, the hood reduced the available thrust significantly and impacted the performance of the unit to a degree that was not acceptable. This approach does not appear to be satisfactory and remains an unresolved issue.

Additionally the shield was intended to prevent the possible inadvertent suction of the Aerobot to the nearby structure, but this concern was mitigated by the use of a wire frame support above the duct and the side-mounted deflection scoops. During the limited testing performed there was no indication that the Aerobot was inclined to attach itself to the structure as configured without the hood.

Complete System Size

GOAL

All of the equipment will fit into the bed of a full-size pickup truck.

STATUS

A layout of the components in the target vehicle was performed on our CAD system. All system components were successfully arranged in the CAD model of the truck bed, but the units were not physically installed.

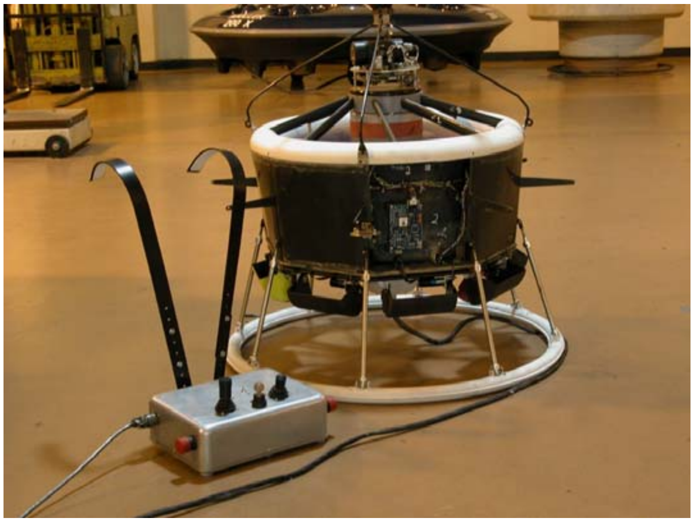
Roving Cockpit

GOAL

Provide an easy-to-use, portable interface to the controls for the Aerobot that allows the operator to remain mobile and keep the Aerobot in direct line of sight.

STATUS

The "roving cockpit" consists of a control box mounted on a fiberglass yoke that fits over the pilot's shoulders, leaving his hands free to manipulate the controls. The two primary controls are the thrust lever, which controls the torque of the motors and thus controls the amount of thrust generated by the fans, and the joystick, which controls the movement of the vehicle about the roll, pitch, and yaw axes. (Roll is movement about the horizontal (fore and aft) axis; pitch is movement about the lateral axis; yaw is movement about the vertical axis.) The vehicle responds to pitch and roll commands through the action of one or more of the moveable thrust deflection vanes located at the exhaust end of the duct. Upon command, those vanes rotate into the air stream and effectively reverse a small portion of the thrust, which results in a roll or pitch force on the vehicle. When the vehicle tilts, a horizontal component of thrust is created and the vehicle moves in the direction of the tilt. The operator commands the vehicle's vertical takeoff, climb, positioning for inspections, and return to a vertical landing, using the thrust lever and the joystick. Additional controls include a key for activating the control module, a small red activator button, and two large red buttons on the sides of the module, which are emergency "kill" switches to immediately eliminate the flow of power to the drive motors.



Aerobot with Roving-Cockpit

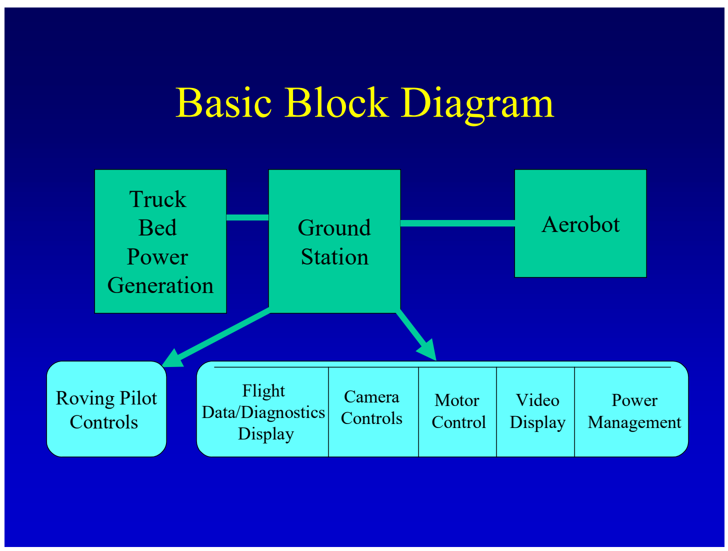
Ground Control Station

GOAL

Provide a compact man-portable, environmentally sealed enclosure for the motor drives, central processor, and interface to video inspection console.

STATUS

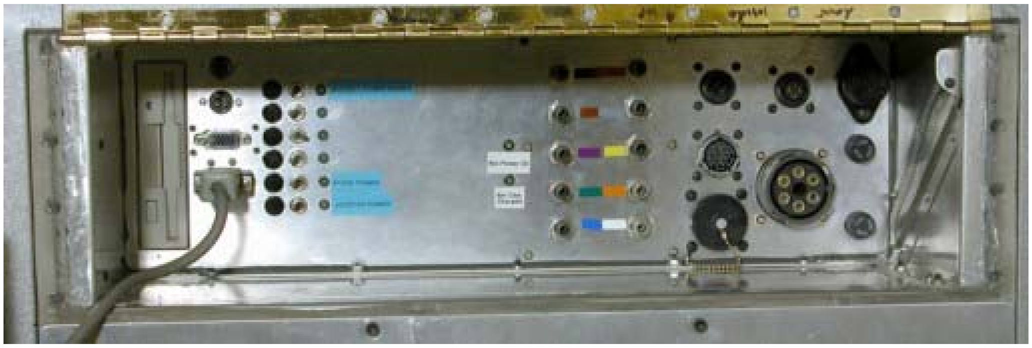
In addition to the yoke-mounted roving cockpit, the ground control station consists of a motor drive enclosure, central processing unit (CPU), video inspection station and power source as illustrated in Figure 1.3 below.



Ground Control Station Block Diagram

The drive enclosure receives power from either a commercial source or from a generator. Acceptable power is in the range of 207 to 253 volts, three-phase, alternating current. The power is converted to 300 volt DC in the drive enclosure and then transmitted through the umbilical cable to the Aerobot. The drive enclosure has only two switches, both located on the face of the unit, which must be in the "on" position for operation of the system. There are no other controls and no requirement for field adjustment of the drive enclosure. The power cable and fiber optic cable are permanently attached to the Aerobot at the airborne end of the system. The central processing unit (CPU) receives power from the drive enclosure and receives information periodically from the operator, as commands are input via the thrust lever and the joystick. The CPU processes the inputs from the pilot's controls and sends commands to the drive enclosure for changes in power and to the servomotors, which control the moveable thrust deflectors for changes in vehicle attitude and the resultant horizontal movement of the vehicle. The CPU has no external controls and no requirement for servicing in the field.

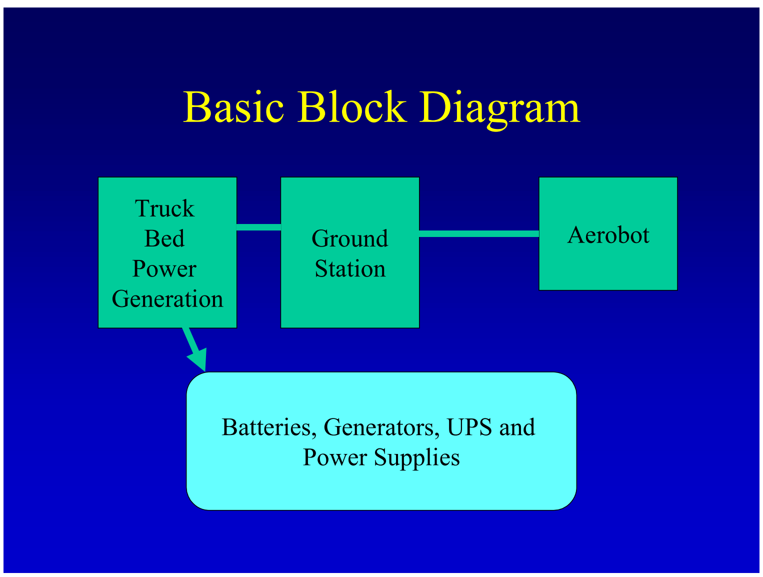
The cables connecting it to the drive enclosure are permanently attached at both ends.



Truck Bed Power Generation

GOAL

The object of this element was to achieve a readily transportable configuration of the required hardware, including the power system components, ground station controllers and Aerobot. All equipment should fit in the back of a standard-size bed pickup truck.



STATUS

Two (2) identical portable generators were acquired for the project. The generators selected were Gillette Gen-Pro Kleen-Power® 13,500 Watt, 240 Volt, 40.5 Amp generators. These generators were to be mounted in the bed of the CALTRANS provided pickup truck.

The remaining equipment was sized and 3-D CAD models were generated with

Models : GPN-90E, GPN-105E, GPN-125E, GPN-140E

several alternative arrangements that suggested that all the necessary components would fit easily into the bed of a provided vehicle. Due to the other issues, the installation was not attempted.

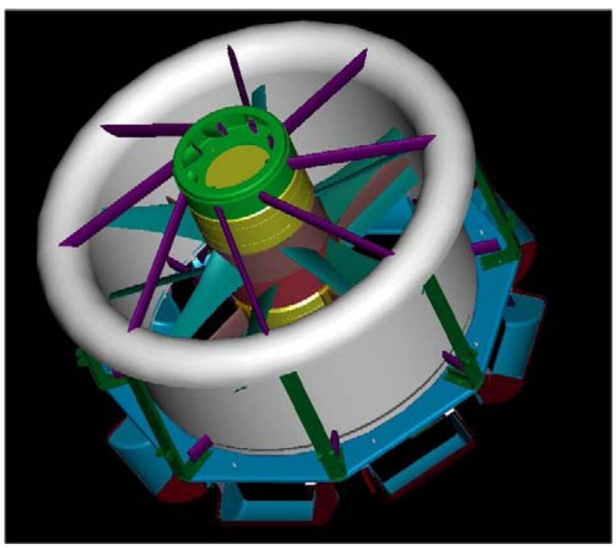
4. CONCLUSIONS AND RECOMMENDATIONS

Due to a number of implementation issues as discussed above, the device did not perform as expected within the initial or extended schedule of events and was not deployed. An initial successful test flight of the CALTRANS Aerobot in October 2003 achieved a stable flight at ~50% of maximum current, but the project has not resulted in a fully-deployable Aerial Robot meeting the specifications outlined in UCD02-02371.

Moller International regretfully suggests that the program be terminated.

The following accomplishments have been realized during this phase of the project:

1. It has been determined that the optimum vehicle design meeting all requirements of the project is a single-duct Aerobot built around a duct with a 20 inch interior diameter, a 26.6 inch exterior diameter and 12 inch height. The duct is mounted above a 36-inch diameter-landing ring with four shock-absorbing legs holding the bottom of the duct approximately 6 inches above the landing ring. This arrangement gives the duct a total height of approximately 18 inches - plus the sensor payload. The top of the sensor module will be approximately 36 inches above the duct inlet, giving an overall height of 54 inches.



Aerobot Model ES20-10 CAD Model

2. It was determined through extrapolation of test flights of a somewhat larger and heavier Aerobot that the new design would be capable of sustained hovering flight carrying a 10 to 15 pound payload above 200 feet altitude during conditions of cold to moderate temperature (under 30 degrees C), winds below 20 knots and no more than light precipitation. While we have been unable to verify all of these characteristics, most of our conclusions were correct. We anticipate that

more adverse conditions can be overcome as motor design improves, payloads become lighter and more compact and overall Aerobot and tether weight is reduced through improved materials and design.

3. A study of the feasibility of reducing the number of thrust-reversing "scoops" from eight to four was conducted in an effort to reduce weight. It was determined that the four-scoop design would require considerably larger individual scoops and larger servo motors to drive them. The inertia of the larger scoops increases their reaction time to control inputs to a significant degree. Therefore it was decided that the eight-scoop control and stabilization system would be retained. The scoops are constructed of carbon fiber and the servomotors are small, lightweight and extremely powerful.

4. Additional studies have reinforced the determination that the optimum location for sensor payloads and their control and communication modules is in a streamlined pod mounted above the centerline of the duct. Moving the sensor package as far as practical above the duct has been determined to enhance stability. Vehicle electronics and mechanical control and stabilization items are distributed evenly around the duct, within the duct wall wherever possible, to assure even weight distribution around the centerline.

5. It has been determined that the lightweight lithium polymer batteries which possess the attributes necessary to make a practical battery-operated, free-flying Aerobot are not yet available. However, it is considered practical to provide a ground-based battery pack and high-speed automatic switching which will enable the Aerobot to be landed safely on battery power in the event of a generator failure. That feature is proposed for addition to the electric Aerobot.

6. Milestones achieved during this phase of the project:

- Constructed an Aerobot with the optimum vehicle design and size to meet all requirements of the project.

- Installed the best available advanced electric motors.

- Built and installed propulsion fans that are designed to generate the required thrust as quietly as feasible.

- Designed, developed, built and installed appropriate sensors and controls to provide capabilities for height holding, azimuth holding and position holding.

- Prepared an operator’s manual that provides instruction regarding Aerobot transport, preparation for flight, launch and control operations, landing and securing the Aerobot. The manual included a description of operational capabilities and limitations in terms of altitude, temperature, precipitation, and wind, including gust levels. Also included were instructions for routine maintenance and field repair of the Aerobot and its supporting equipment.

7. Recommendations for further research & development:

-Finalize Operations Manual

-Integrate Video Camera

-Install and Integrate Lighting system

-Test and Demonstrate New Propulsion Fans

-Conduct Additional Test Flights - In Wind

-Train CALTRANS Personnel

-Test & Demonstrate Stability And Maneuver Control System

- Magnetic heading sensor
  - Test for re-occurring EMI or grounding problems
- Flight Stability Testing
  - Resolve re-occurring heading sensor problems
  - Resolve other possible stability issues (aerodynamics related)
  - Implement “altitude” hold
  - Tuning in benign environment
  - Tuning in bridge environment

-Emergency power switching test

5. CONTRACTOR’S INDEPENDENT ACTIONS

Moller International anticipates that it will continue to work on the CALTRANS Aerobot as time and resources allow. We are committed to making this system perform as stated in the original proposal.

It is the Company’s intent to continue to work on the system and identify any underlying issues that limit the reliability and utility of the vehicle.

6. APPENDIX

OPERATIONAL HANDBOOK

OPERATIONAL HANDBOOK OVERVIEW

Approach

Our approach in preparing the Operational Handbook was to have a simple, easy-to-understand set of instructions that a person with basic mechanical and technical skills could use to transport, setup and operate the Aerial Robot Inspection System.

Intended Audience

Our intended audience for this handbook was a CALTRANS engineer or technician that had been familiarized with the basic components of the Aerial Robot Inspection System. Nomenclature for the various devices was assumed.

Organization

The organization of the document was laid out in the order one would encounter the components, typically from the start of a mission through transport, setup and use.

A DRAFT OF THE HANDBOOK FOLLOWS:

<u>Transporting The Aerobot System</u>
The motor drive enclosure, central processing unit, and roving cockpit are each composed of strong electronic components that are firmly attached inside their sturdy cases. The Aerobot is also built to withstand some stresses. However, as with any complex, expensive electronic equipment, prudence dictates that the system be handled and transported with great care. In preparation for transit, the ground station components should be strapped down and the Aerobot should be placed on four to six inches of foam cushioning material and strapped down. Vehicle drivers should be cautioned to traverse rough roads and unprepared surfaces slowly and with caution. Care in loading and unloading is a requirement.

<u>Wind And Weather</u>
The Aerobot Model ES20-10 is capable of carrying a ten-pound payload and operating in moderate winds. Only modest tests have been conducted to date to determine the wind velocities and gust loads that can be handled safely. Until more extensive testing is completed, do not attempt operations in steady-state winds above 10 mph. Operation in any type of precipitation should be avoided.

PRE-FLIGHT

Equipment Positioning
Upon arrival at an inspection site, the Aerobot System components should be positioned with the following considerations in mind:

The Aerobot should be launched from a level spot that is clear of rocks, brush, trees, or debris of any kind. If the available launch area has a surface which is sandy, dusty or laden with small rocks, placing a 6' X 6' piece of indoor-outdoor carpet on the surface and pinning the corners will provide a suitable launch area.

The drive enclosure and the CPU should be positioned adjacent to the generator or other power source and close to but not directly beneath the structure to be inspected.

The tether cable should be laid out in a snake-like fashion between the Aerobot and the drive enclosure so that it can be lifted by the Aerobot without danger of becoming entangled.

Inspection
Visually inspect the Aerobot, the motor drive enclosure, the CPU, and the roving cockpit for any evidence of physical damage, loose connections, dirt or debris or any other impediment to operations. Correct any problems detected.

Power
Connect the power cable from the motor drive enclosure to the generator or other power source.

Roving Cockpit
Make certain that the thrust lever is in the zero thrust position.

Motor Drive Enclosure
Place the two switches on the face of the motor drive enclosure in the "on" position.

Aerobot
It is imperative that a three-minute warm-up period be provided for the vertical gyroscope in the flight stabilization system to "spool up" to operating speed. Observe the action of the scoops as the gyro "spools up". All eight scoops should be active during the three-minute warm-up period. After the warm-up, check the functioning of the stabilization system by grasping the top of the duct wall on opposite sides, lifting and tilting the Aerobot in fore and aft and side-to-side directions to observe the action of the scoops; i.e., those on the high side should extend into the airstream and those on the low side should retract into the stationary deflector.

Power Check

While standing beside the Aerobot, add a small amount of thrust and observe that both fans are responding to power commands. Also lift and rotate the Aerobot in both clockwise and counter-clockwise directions while observing the relative fan speeds, which should be different as the control system attempts to overcome the rotational force. Move at least eight feet from the Aerobot prior to takeoff.

OPERATION

Takeoff

With the joystick in the centered position, move the power lever forward smoothly to add power until the Aerobot climbs approximately four feet, and then retard the power lever slightly to hold that altitude. Move the joystick gently fore and aft and side-to-side to assure that the control system is responding correctly, tilting the Aerobot slightly as commanded. Rotate the joystick to assure that the control system is properly activating differential thrust for yaw control, causing the Aerobot to rotate clockwise and counter-clockwise as commanded.

Climb

Add power smoothly to achieve a moderate rate of climb. A slight increase in power required occurs as more and more of the tether cable is lifted so it will be necessary to gently add power to maintain the climb. Reduce the rate of climb as the Aerobot approaches the structure until a hover is established at the desired altitude for inspection. Note the "tail" stripe on the Aerobot to maintain proper yaw orientation for camera pointing.

Inspection

With the inspection camera pointing at the structure to be inspected, move the Aerobot close enough to the structure to obtain the required detail, and then move it laterally to inspect the entire structural member. Note that whenever a horizontal movement of the Aerobot is commanded, it tends to lose a little altitude because some of the thrust is expended in the horizontal direction to create the lateral force. It is necessary to add a small amount of power in conjunction with the horizontal command in order to maintain altitude, and to reduce power again as the horizontal movement is stopped. This type of altitude control will become second nature as experience is gained. While maneuvering the Aerobot to conduct an inspection, the pilot should move to maintain a good vantage point for viewing the Aerobot and the structural member being inspected. At the same time, it is important to keep the Aerobot's "tail" stripe in view in order to maintain orientation of the camera on the structural surface. Inspect each of the surfaces within reach, moving as feasible and necessary to maintain a good view; then retard the throttle slightly to create a slow rate of descent and maneuver the Aerobot to a position about five feet above the landing spot. At that point, add enough power to slow the rate of descent to less than one foot per second. At about 18 inches above the surface, add a little more power to slow the rate of descent further for a soft landing.

POST-FLIGHT

Inspection

After each landing, the Aerobot should be visually inspected for loose electrical and mechanical connections and any other external evidence of damage. The fan blades should receive particularly careful scrutiny to detect any nicks or cracks, and the landing gear should be examined closely to detect any damage. Any evidence of damage must be carefully evaluated to determine whether additional flights may be safely accomplished before repair actions are undertaken.

Storage

The Aerobot and Ground Station can be safely stored indefinitely in a warm, dry environment out of the elements. If storage time is to exceed 30 days, it is recommended that the Aerobot and each of the three components of the ground station be encased in plastic to protect them.