California AHMCT Research Center
University of California at Davis
California Department of Transportation

AERIAL PLATFORM SYSTEM FOR BRIDGE INSPECTION
PHASE I
(DRAFT COPY)

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AHMCT Research Report
UCD-ARR-94-02-28-01

(For Review - Not For Publication)

Interim Report of Contract
RTA-32J804

February 28, 1994

* This work was supported by the California Department of Transportation (Caltrans) Advanced Highway Maintenance and Construction Technology Center at UC, Davis and by the Federal Highway Administration (FHWA).

Technical Report Documentation Page

1. Report No. FHWA/CA/92-6	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Aerial Platform System For Bridge Inspection

5. Report Date
February, 1994

6. Performing Organization Code

7. Author(s)
Wayne Grupp, Paul Moller, Jack Allison

8. Performing Organization Report No.

9. Performing Organization Name and Address
Moller International
1222 Research Park Drive
Davis, California 95616

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
RTA-32J804

12. Sponsoring Agency Name and Address
California Department of Transportation
Sacramento, California 95807

13. Type of Report and Period Covered
Interim Report 1992-1994

14. Sponsoring Agency Code

15. Supplementary Notes This development project was conducted in cooperation with the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California, Davis, California.

16. Abstract

The successful design, development and initial flight testing of the first electric-powered, twin-motor, single duct, vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV) is described. The purpose of the development effort is to provide a more effective system for inspecting the structures of bridges and other elevated highway structures. The particular UAV described is the Model ES20-10, a 40 pound (18 kg.), called an Aerobot, capable of VTOL operation carrying a video camera with tilt, pan, and zoom features, up to 200 feet (61 meters) in altitude for close inspection of the underside of highway structures. The Phase I development resulted in successful flight demonstration of the Aerobot indoors with a 100 foot (30.5 meters) cable providing electrical power and operator control inputs up to the vehicle. Fibre optic lines are provided for carrying control signals up to the vehicle and transmitting sensor images from the vehicle to the ground control station. Provisions have been included in the design to accept many enchancements to further improve the inspection capability.

17. Key Words
VTOL - Vertical takeoff and landing
UAV - unmanned aerial vehicle
Aerobot - robotic aerial vehicle
Bridge inspection

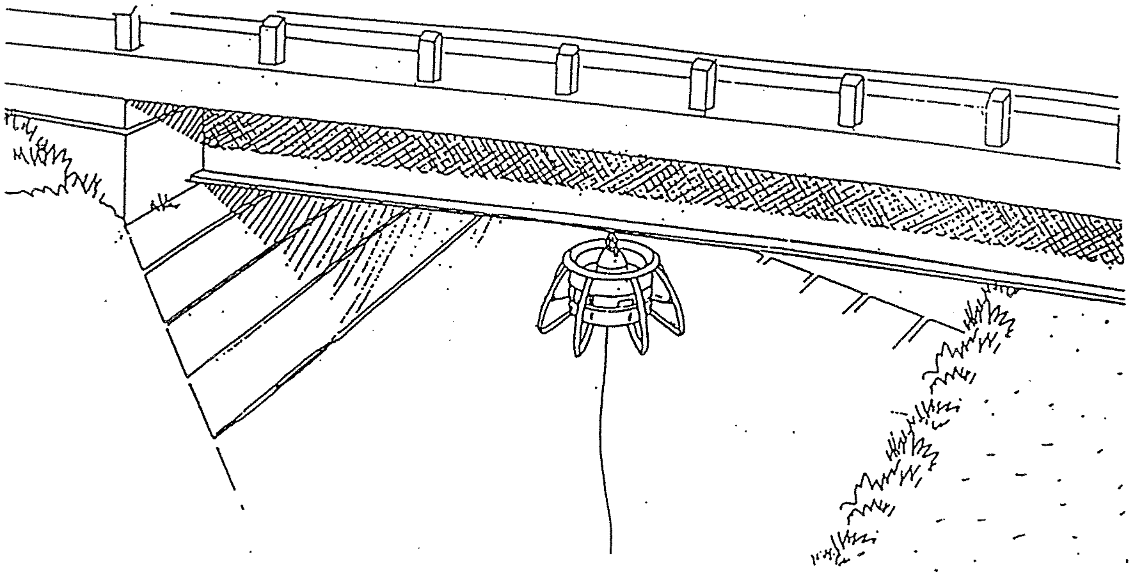
18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

REPORT NO. FHWA/CA/92-6

AERIAL PLATFORM SYSTEM FOR BRIDGE INSPECTION



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INTERIM REPORT

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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 CAL92-6. The value of the contract is $230,146. The Principal Investigator was Wayne Grupp, Aerobot Program Manager, Aerobotics Incorporated.

AEROBOTICS INC.

AERIAL PLATFORM SYSTEM
FOR BRIDGE INSPECTION

Phase I - Final Report

1. INTRODUCTION

This report describes the Phase I development of an electric-powered, twin-motor, ducted-fan unmanned aerial vehicle for the purpose of creating an improved method of inspecting the structure of bridges and other elevated highway structures. The result is a robotic aerial vehicle, named Aerobot, designed to carry a high resolution video camera in close proximity to the structure and record detailed images of each surface. The electric-powered Aerobot is illustrated in Figure 1.

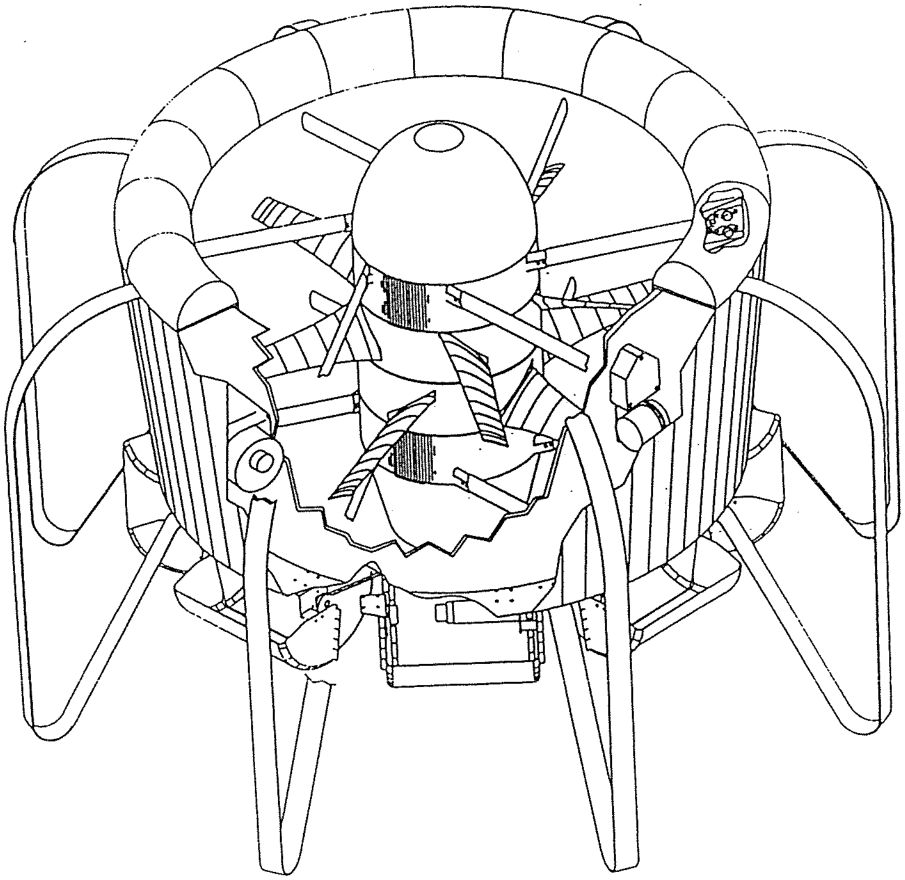


Figure 1, Aerobot Model ES20-10

The vehicle is designed as a vertical takeoff and landing (VTOL) sensor platform that can be remotely operated at distances up to 200 feet (61 meters) from the ground control station. The Aerobot is tethered to a cable which consists of fiber optic lines for transmission of control signals up the line and video or other sensor images down the line plus thin copper wires for carrying high-voltage electrical current up to power the motors, vehicle electronics, and sensors. Vehicle thrust for lift and control is produced by twin 6 HP (4476 W) brushless DC motors which directly drive counter-rotating fans facing one another in the center of the duct. The electric Aerobot is capable of remote operation at any combination of distance and height up to 200 feet (61 meters). The on-board sensors and control system automatically stabilize the vehicle and the pilot controls operate in a very simple and logical manner so it will be feasible to train operators in a relatively brief period of time.

2. EQUIPMENT DEVELOPMENT

2.1 Requirements

The contract called for development of a device for use by bridge inspectors to efficiently inspect California's 1,000 fracture-critical bridges. The conventional method involves using a snooper truck with hydraulic telescoping arms to extend an inspector underneath the structure for visual inspection. This project utilizes a free flying robotic platform as the mobile base for bridge structural inspection. The flying platform must be capable of vertical takeoff and landing and is to be equipped with a high resolution video camera for inspection purposes. It must utilize a unique electrically driven ducted fan technology (no exposed moving parts for safety purposes) that will enable the camera to be positioned within 24" (61 cm) of the structure to be inspected. This will eliminate the need for workers to physically scale these structures.

2.2 Design Goals

The first phase focused on development of the Aerobot and the basic ground control station needed to test and demonstrate its flying capabilities. The design was intended to incorporate two electric motors, each driving an independent fan in the center of the duct, so that the loss of one motor would still allow an emergency landing to be conducted safely. Normal thrust from the two fans was to be sufficient to lift the vehicle and the payload with adequate reserves to handle normal wind gusts. The initial payload goal was 10 pounds (4.5 kg), which was considered sufficient to carry the inspection video camera with ample reserve for future addition of a high intensity light, a paint gun to mark particular sections of the bridge for later re-examination, and additional video cameras for use by the pilot to enable him to fly the Aerobot effectively out of visual range. The pilot controls were intended to be very simple and logical so that learning to operate the Aerobot would be feasible for the "average" Caltrans employee. The electronics were to be compatible with use of either readily-available commercial power or a "standard" diesel generator.

2.3 Design Specifications

The design specifications which were planned to be incorporated in the first phase of this project are as follows:

1. A single duct electric vehicle employing two counter-rotating fans.
2. Vehicle weight of 35 pounds (15.9 kg), including the cable.
3. Payload capability of 10 pounds (4.5 kg).
4. Gross thrust of 50 pounds (222.25 N), leaving 5 pound (22.22 N) reserve for countering wind and gusts.
5. Two motors and fans, providing an emergency landing capability on one motor.
6. Payload mounting above the duct, computer controls around the exterior.
7. Two electric motors at 4 HP (2,982.8 W) each = 8 HP (5,965.6 W) total.
8. An on-board stabilization computer with gust resistance.
9. Motor power controller to produce 200 Volts DC.
10. 200 foot (61 meters) cable for power and signal transmission to/from the Aerobot.
11. Multi-axis joy stick for pilot control - deflect to translate, rotate to turn the Aerobot.
12. Single lever for controlling power of both motors to change altitude.
13. No exposed moving parts on the Aerobot.
14. No exposed hot surfaces on the Aerobot nor the ground station.
15. All control signals transmitted by wire for a secure communications link.

2.4 Sensors

The vehicle sensors consist of a vertical gyro and three quartz angular rate sensors. These sensors were chosen for their light weight, small package size, and high reliability. Each sensor unit is commercially available, relatively inexpensive, and has been extensively tested both by the manufacturers and through previous applications. The vertical gyro monitors roll and pitch attitude, and the rate sensors monitor rate of change of pitch, roll and yaw angle. Information from the sensors is sent to the on-board flight control computer (flight controller), described below.

2.5 Flight Controller

The mission and nature of the Aerobot determines the requirements of its control system. Since the vehicle is essentially a remotely operated flying camera platform, the operator must have the ability to control vertical and horizontal vectors, velocities and rotation rates. Therefore, the operator-commanded parameters are net thrust, pitch and roll angles, and yaw rate. The vehicle thrust is controlled by varying the torque applied to the fans, thus controlling climb, descent and hover. The thrust lever gives an average torque command to the motor drives, which may be modified by the flight computer if the yaw rate sensor detects a torque imbalance. (see below) When the pilot commands a net roll or pitch angle of the aircraft, a horizontal component of thrust is created, moving the vehicle laterally as commanded.

Yaw control is achieved by varying the relative torque of the two motors to produce the desired net torque. For steady hover, the net torque is automatically maintained at zero by the yaw rate sensor, the flight computer, and the motor drives. Upon command from the joystick, a positive net torque gives rise to a yaw rate to rotate the vehicle to the intended heading.

The control system is based around a high performance 16-bit microcontroller. This microcontroller 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 microcontroller receives vehicle roll and pitch attitude information and three axis rate information from the sensors mounted on the vehicle. Because of the low sampling rate of the microcontroller, it is possible for high-frequency noise to alias, providing a false signal which is within the bandwidth of the control system. In order to counteract this phenomenon, there is a low-pass filter for all control signals which processes the data before it enters the flight computer.

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

The microcontroller reconciles information about vehicle position and rate, and the commands of the pilot, and generates commands for the eight control servos. These servos rotate a set of eight thrust deflectors which stabilize the vehicle in hover and create the commanded thrust vectors.

2.6 Pilot Controls

The operator controls the vehicle via a "roving cockpit" which is illustrated in Figure 2. The roving cockpit contains the pilot controls. Data from the controls is transmitted to the ground-based central processing unit (CPU).

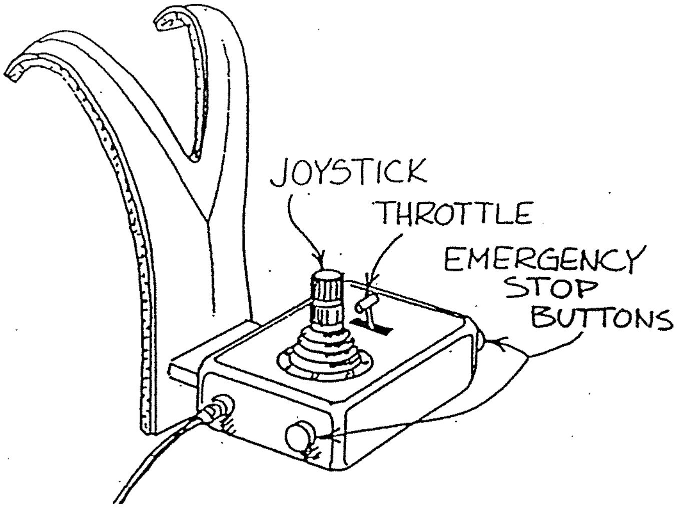


Figure 2 - Roving Cockpit

The operator commands the vehicle's roll and pitch angles and yaw rate with a three axis joystick. Vehicle thrust is controlled using the thrust lever. The roving cockpit is suspended from the operator's shoulders by a fiberglass harness. This allows the pilot to have both hands free to manipulate the controls as he walks about to maintain the best vantage point to view the Aerobot. There is a single "enable" button located on the roving cockpit which is activated immediately before flight. This button closes the power circuit to the flight motors. As a result, all personnel should be clear of the aircraft before the operator presses this button. There is also a provision on the roving cockpit for eliminating power to the flight motors in the event that it should become necessary to do so. If the pilot depresses both of the red buttons on the sides of the roving cockpit at the same time, all power to the flight motors will be eliminated immediately.

2.7 Central Processing Unit (CPU)

The CPU is the communications interface between the pilot, vehicle, and flight motor drives. It contains an LCD video screen which displays the status of the vehicle whenever power is applied to the ground station. The center of the screen displays information about commanded pitch and roll angles, and pitch and roll angles which are fed back from the vertical gyro. This gyro information is valuable during the warm-up period of the aircraft. The box at the center of the screen will be observed to revolve around the centered position as a result of the precession of the gyro. As the gyro reaches its operating speed, this precession is eliminated. During the warm-up period, the Aerobot is ready to fly when the box on the CPU screen stops precessing. On the sides of the display, the position of the thrust lever is displayed, along with the position of the yaw command on the joystick. The CPU contains a PC-based computer which controls all communication and a 3.5 in. (8.9 cm) floppy disk drive which can be used to store data acquired during flight.

2.8 Flight Motors

The electric motor design goal, re-calculated to achieve operational effectiveness with a ten pound (4.5 kg.) payload in moderate winds, was 5.2HP (3,877.6 W) at 5000 RPM from each of the two motors installed. The motors were tested on a water-brake dynamometer to characterize power delivery, heat generation and dissipation, and reliability. The motors achieved a power output exceeding 6HP (4,474 W) at 5000 RPM and proved capable of instantaneous torque of more than twice the nominal operating torque. This is an important element of the yaw stabilization system because the counter-rotating fans can provide large controlling torques for short durations in the event of drastic gusts or contact with rigid structures. The thermal characteristics of the motors were analyzed using thermocouples embedded in the windings of the motors and mounted to various locations on the aluminum housing. It was verified that the housings were capable of rejecting the heat generated by the motors through convection to an outside airstream, without any air entering the motor housings. This is critical because it allows the sensitive motor components to remain sealed, avoiding possible damage from dust and debris. Under normal operating conditions, the copper windings operate at 220°F (104 C) and the outside surface of the motor housing is 160°F (71 C). This is substantially lower than the 300°F (148.9 C) maximum temperature rating of the windings.

2.9 Scoop Servos

One of the most important design elements for the Aerobot is the response time of the moveable deflector (scoop) servos used to stabilize the vehicle in roll and pitch. Based on experience gained from previous vehicles, a servo design goal of a 90 degree slew angle in 50 msec was set. In order to meet that goal, carbon fiber composite was used to fabricate the scoops. This material provides an excellent weight-to-strength ratio, which keeps the inertia of the scoops to a minimum. A miniature brushed DC motor with a planetary gear head and integral magnetic encoder was chosen as the servo motor. It provides a rugged, sealed servo which functions well with the digital servo controller chosen for the design. Calculations, followed by bench testing, showed the servos to be capable of slewing 90° in less then 40 msec which exceeds the design goal by a comfortable margin. Prior to procurement, the servos were tested for 100 hours of constant, full-torque use with no external cooling, and then checked for any signs of wear or damage. The servos are cooled by the air traveling through the scoops during flight. Vehicle testing has proven them to be sufficiently fast and reliable.

2.10 Vehicle Power Supply

The requirement of keeping the umbilical as light as possible led to the use of high voltage DC to provide power for the flight motors and onboard electronics. High voltage allows the current, and thus the wire size, to be as small as possible. A voltage of 300 V was chosen because it is high enough to keep the current down and still low enough to use readily available off-the-shelf components. The voltage is then locally regulated on the vehicle using high efficiency switching power supply modules to provide the necessary ±5 and ±15 volts for the onboard electronics.

2.11 Ground Power Supply

The system is designed for field operation using power from a 3-phase 208VAC source. This AC power can be drawn from commercial power or a standard generator and is input directly into the drive enclosure. The power is converted to 300VDC in the drive enclosure for vehicle power as well as power for the ground-based motor drives and CPU.

2.12 Umbilical

The umbilical is a hybrid copper and fiber optic cable which provides power for the vehicle as well as communications between the ground computer and the vehicle. Power for the flight motors and onboard electronics is carried through copper wires to the Aerobot. The fiber optic lines carry pilot commands to the Aerobot, feed motor commutation information to the motor drives, and carry sensor images down to the ground-based imaging hardware. The fiber optic bundle is very rugged, but the copper conductors use a thin insulation in order to minimize weight. The umbilical should not be stepped on nor driven over.

2.13 Flight Controller Software

The flight controller software performs the tasks of controlling and stabilizing the vehicle and communicating with the pilot. The majority of the computer code is written in "C" with specialized modules written in assembly language. It was designed with future expandability in mind, allowing easy addition of software modules to meet future needs.

2.14 Control Panel Software

The control panel software performs the functions of managing communications between the vehicle and pilot and controlling the flight motor drives. The majority of the code is written in "C" with specialized modules written in assembly language. It also was designed with future expandability in mind to meet future needs.

2.15 Fans

Each fan assembly consists of multiple blades and a central hub, all milled from aluminum. The initial blade design was carried out using a purchased computer program. This program was able to compute blade geometry only for a single ducted fan, so the extrapolation to a twin counter-rotating system was carried out separately. The blade geometry was generated using 3D CAD/CAM software. The blades were then cut from standard aluminum plate on CNC mills. They are attached to the high-strength aluminum hub using two 8-32 socket-head cap screws per blade. The mounting allows for adjustment of the blade root angle over a range of 6 degrees. The fan hub has a taper in the center which matches the taper of the motor crankshaft, and the hub is clamped to the shaft using a single nut.

Testing of the fans showed that the initial five-bladed design had too much solidity (percentage of duct vertical view filled by the fans), causing the fan to operate well below the 5,000 rpm design goal. The fans produced 58 lb. of gross thrust which was judged to be sufficient to carry a modest payload while maintaining a thrust margin to overcome wind gusts.

Since the time of the initial blade design, an expert consultant has been located who has a more complete computer application for the design of twin, counter-rotating, ducted fans. His design analysis suggested that greater thrust could be achieved by using three of the original blades, spinning at a greater speed than the original five-bladed design. In order to do this, it was necessary to fabricate a new fan hub. This three-bladed configuration should significantly increase the available thrust, and thus provide additional options for increased payload and/or operation in higher winds. An amendment to the Phase I contract was approved to design and fabricate new fans. Testing of the new three-bladed fan configuration showed that the available thrust was increased to 65 pounds (289 N).

2.16 Motor Housing

The motor housing was designed to be light weight, to effectively cool the motor using the airflow from the fans, and to support the motor over the entire operating range of the aircraft. The main motor housing is machined from 7075-T6 aluminum. The strut support tabs and fins on the outside of the housing were cut using wire EDM, and the precision inside features were turned on a lathe. The motor housing uses mechanical interference as the primary means of supporting the motor. At room temperature, the motor housing is .012 in. (0.31 mm) smaller than the outside of the motor. It is heated, slipped over the motor, then allowed to cool, creating a strong and uniform grip. Heat created in the copper windings of the electric motor is transferred through conduction to the aluminum surface, and then through convection from the fins to the airstream.

The outer plates (top of the top motor, bottom of the bottom motor) each carry one of the two shaft bearings and are designed to support all of the axial load created by the motor and the fan. They also support the hall-effect commutation assembly which feeds motor speed and rotational position information to the motor drives.

The inner plate (bottom of the top motor, top of the bottom motor) is designed to carry only radial loads from the crankshaft to the motor housing. It supports the other shaft bearing in the center and has ribs to carry radial loads. It has no provision for carrying axial loads.

2.17 Motor Shaft

The motor shaft is a two-piece assembly which connects the rotor of the electric motor to the fan assembly. It consists of a central steel shaft with precision-machined bearing surfaces and an aluminum web which is pressed onto the steel shaft and connects to the inside diameter of the rotor. There is a taper machined on the drive end of the steel shaft to support and drive the fan hub.

2.18 Payload Dome (Aerodynamic shroud above upper motor)

The payload dome serves several purposes and can be redesigned to fit many different applications of the Aerobot. The primary purpose of the payload dome is to serve as an aerodynamic surface to smoothly accelerate the airflow as it enters the top of the duct and approaches the cooling fins of the upper motor and the first fan. The height of the dome can be changed if necessary for the packaging of a specific payload. The payload dome is made from carbon fiber cloth and epoxy resin to provide a lightweight part which has complex curvature. If necessary for a specific application, the dome can be strengthened in order to support the weight of a camera or other payload components.

2.19 Tail Fairing (Aerodynamic shroud beneath lower motor)

The tail fairing is a carbon fiber composite part which covers the fiberoptic subframe mounted to the bottom of the lower motor. It serves both as an aerodynamic surface and a protective cover. It also helps to carry loads from the umbilical support plate to the outer plate of the lower motor. The umbilical support plate has provisions for supporting and relieving strain on the fiberoptic bundle and the copper conductors at the tail of the aircraft.

2.20 Airframe Barrel

The airframe barrel (duct) is the basic structure which supports the drive motors, the servos and scoops, all electronic components, and the landing gear. It is a composite structure of sandwich construction formed with 2-layer carbon fiber, plain weave facesheets, and a 1/4 in. (6.35 mm) thick nomex aramid core. The matrix material is room-temperature-cure epoxy resin. The layup is symmetrical in order to minimize the deformations inherent during curing of the epoxy. It was formed on a cylindrical mold which had less than .010 in. (0.254 mm) total runout. The accuracy of the mold resulted in fabrication of a uniformly accurate inner duct wall, allowing a very small clearance between the fan blades and the duct surface, an important factor in achieving duct efficiency. A white gel-coat was applied on the inside surface to protect the composite and to reflect solar heat. The airframe was post-cured to 130 F (54.4 C) on the mold and may undergo uneven deformation at temperatures above that.

The barrel has a carefully formed, leading-edge bellmouth which uniformly accelerates the airflow without inducing flow separation. There is a radial composite flange bonded to the bottom of this bellmouth, creating a closed section surrounding the top of the airframe This very rigid feature supports the upper attachment points of the landing gear system and the tether which is used during flight testing and development. The airframe also has a radial flange attached to the bottom which adds rigidity, and supports the scoops, servos, and the lower attachment points of the landing gear system.

2.21 Airframe Struts

The purpose of the struts is to support the motor and fan assemblies and to carry wires from the outer duct surface to the motor assemblies. The struts carry motor power wires, motor commutation signal wires, thermocouple wires, and any payload links necessary. Because the struts are mounted in the duct airflow, it is considered imperative that they be small and aerodynamically clean as well as strong enough to support the loads.

Each strut consists of a foam core, a stainless steel tube, and a carbon-fiber outer skin. The steel tube is the conduit which carries the wiring to and from the center assemblies, and it is exposed at the outboard end so that it can be grounded to provide EMI shielding.

There was some difficulty in the development of the process for fabricating these struts. They are formed using a process called pultrusion. The idea is to first cast the foam core around the steel tube. Next, the foam core is wrapped with carbon fibers and wet epoxy, and then pulled through a mold which is slightly smaller than the outside of the foam piece. Therefore, the foam will be slightly squeezed as it enters the mold, the extra epoxy will be squeezed out, and the part will conform very accurately to the shape and size of the mold.

The most difficult part of the process is casting the foam core. The core is a two-part, syntactic foam cast in a Teflon mold. The problem was that the syntactic foam stuck to the mold, so the part was destroyed during removal. The solution was to cast the foam with a thin fiberglass veil adjacent to the mold surface for support. The fiberglass veil added very little weight to the struts, but provided sufficient strength to allow removal from the mold.

The struts are attached at their outboard end to a carbon fiber flange. This flange is bonded to the outside of the duct using structural adhesive. The strut is bolted to the strut flange using floating nut plates which provide for radial adjustment of the motor assembly. This adjustability ensures that the motor will always be in the exact center of the duct, independent of manufacturing tolerances. This accurate centering of the motor / fan assemblies is critical in order to minimize the gap between the blade tips and the duct surface. The inboard end of the strut has a machined aluminum insert bonded to it. This aluminum insert is then bolted to flanges machined onto the outside surface of the motor housings.

Upon completion of the first strut, the design was tested using a spare duct and strut flange. The strut was able to resist loads far greater than those expected under normal flight conditions. In addition, eachstrut used on the vehicle was proof-tested under expected loading conditions to ensure the integrity of the bonded joints.

2.22 Landing Gear

The original design goal was to produce a landing gear system capable of withstanding a 9g impact. This was intended to allow the vehicle to survive a hard landing. However, problems with ground resonance, feedback through the inertial sensors from the airframe, and limited funding, resulted in a compromise in this goal.

In order to eliminate the ground resonance problem at minimum cost, the stiffness of the landing gear was greatly increased. Although that reduced the ground resonance problem, it created a very rigid undercarriage which is not capable of protecting the vehicle from high g-loads in the event of a hard landing. An experienced pilot will have little problem executing a landing which is safe for the aircraft, although it was our original intention to avoid damage even during poor landings.

Ideally, air shocks or some other means of rate dampening should be used to reduce the ground resonance problem while maintaining the impact absorption capability needed to meet the original design goal. A redesign of the landing gear is proposed for Phase II of the program.

2.23 Thrust Deflection System

Each aerodynamic deflector assembly consists of a moving deflector, called a scoop, and a stationary deflector. There are eight of these assemblies, equally spaced around the exit of the duct. The travel of the scoop ranges between the fully-deployed position where the leading edge lip cuts a substantial chord of the circular duct in the top view, and the fully retracted position, where the scoop is retracted in telescopic style into the larger deflector, and is completely removed from the duct in the top view. The function of the deflector is to continue the turning of any air caught by the scoop to an angle of 170 degrees from the original downward direction. In order to understand the way in which the scoops and deflectors control the aircraft, it is simplest to discuss one opposed pair of scoop/deflector assemblies.

During steady-state flight, each of the scoops is partially deployed into the airstream, diverting a small amount of air, while the majority exits the duct and creates thrust. This normal position of the scoops is termed the "centered" position, and is adjustable. When a gust of wind strikes the vehicle, it causes the vehicle to tilt slightly. At this point, it is necessary to reduce thrust from the side of the aircraft that is highest, and add thrust to the side of the aircraft which is lowest. To accomplish that, when the sensors detect the imbalance, the flight control computer directs the servos of the low side to retract the scoops, allowing more air to exit on that side of the vehicle, and directs the servos of the high side to deploy further, redirecting more of the air on that side of the vehicle. When the sensors detect the return of the vehicle to its upright, or commanded position, the scoops are returned to their centered position. In this coordinated way, the vehicle stability is maintained. Because of the sensitivity of the sensors involved, there is rarely any uncommanded angular motion of the vehicle, as the control system resets the vehicle to its upright position before it can diverge a noticeable amount.

The scoops are made of carbon fiber/epoxy composite for lightweight and to minimize the rotational inertia, allowing the servos to move them rapidly. The deflectors are made of carbon fiber to further minimize the weight of the vehicle and to allow easy fabrication of the required smooth, complex curves.

3. INTEGRATION AND TEST

As mentioned previously, each mechanical component was tested prior to final assembly. Scoop servos were tested to ensure adequate slew speed and to verify endurance. Flight motors were evaluated in order to characterize motor performance and thermal properties. Motor support struts were tested to verify the design goals and the final parts were proof-tested prior to installation. Duct stiffness was carefully designed and runout of the finished part was carefully checked prior to assembly. Finally, each fan assembly was carefully balanced prior to integration.

Each electronic assembly was bench-tested before integration into the system. The complete electronic system was then tested and the software was verified and revised. Each mechanical part was inspected for compliance to prints before assembly.

The first operational testing of the vehicle was performed with the vehicle restrained on a rigid structure attached to the wall of the building. This rigid support is called the thrust boom. The boom restrains the vehicle and allows measurement of thrust and control moments. Motor speeds were increased incrementally, with complete inspections after each increase in speed. All systems were thoroughly checked for mechanical failure, and electronic data was analyzed to check performance of the system. Full-current thrust measurements showed the vehicle to be capable of generating 58 pounds (258 N) of thrust, which is sufficient to meet the design goals. Following installation of the re-designed propulsion fans, tests showed an increase in net available thrust to 65 pounds (289 N). After some initial modifications to the software, it was determined that all control algorithms were correct, the sense of all sensor inputs was correct, and the yaw stability system was well tuned.

Indoor, free-flight testing of the vehicle began using a steel "bridle" attached to the top of the vehicle and to a tether line. This system allowed free flight of the vehicle while providing a means of recovering the vehicle in case of a mishap. The tether line was strung over a pulley mounted in the ceiling of the building. The free end of the tether is attached to a handlebar which is held by a technician. The idea of the tether is to provide enough slack to allow the Aerobot to fly freely, while eliminating excessive slack. If too much slack is allowed in the tether, the vehicle will accelerate too much before it is "caught", or it may hit the floor before the tether becomes taught. Indoor tethered flights allowed for the tuning of control gains for the best flight characteristics. It also allowed many hours of safe flight time to be accumulated to check for any system defects. Several flight tests and demonstrations were successfully performed without the safety tether.

4. TEST RESULTS

Flight tests have proven the capability of the Model ES20-10 Aerobot to respond accurately to all commands transmitted by the operator while performing vertical takeoffs, climb and horizontal flight (within the constraints of the umbilical cable), and vertical landings. The maximum available thrust was measured on a test stand and determined to be 65 pounds (289 N). The weight of the vehicle is 42 lbs (19.1 kg), the payload weighs 2.5 lbs (1.1 kg), and the 100 ft. (30.76 meters) umbilical cable weighs 8 lbs. (3.6 kg). The excess of thrust over all-up weight provides a comfortable margin of power for climb, maneuver, and overcoming the effects of wind and wind gusts. The air-cooled electric motors and propulsion fans have not shown any signs of ill effects from over 70 hours of operation. It is expected that the Aerobot vehicle will prove to be rugged. Maintenance should be minimal so that operational availability for use on the job should be very high.

5. CONCLUSIONS

The Model ES20-10 Aerobot has been successfully demonstrated on several occasions and has proven to be fully capable of vertical takeoff and landing and controlled flight with a video camera on-board plus the necessary electronics to transmit images through the umbilical cable to the ground control station. In gusty wind conditions the operator is quite busy manipulating the controls to hold the Aerobot in the desired position in space for inspection of an elevated structure. A considerable number of system enhancements have been identified which can improve effectiveness.

6. RECOMMENDATIONS

It is recommended that work proceed on Phase IA, which includes the following tasks:

1. Preparation of documentation, including an "Operations Manual" containing instruction and guidance on the operation and field maintenance of the Aerobot and the Ground Control Station as they will exist at the conclusion of Phase IA, plus schematics, a bill of materials for the Aerobot, and electronic circuit diagrams. This work has been completed and the documents are attached hereto.

2. Design, fabrication, and test of a pan and tilt mechanism which supports a CCD camera. This system will provide a video signal to the ground-based imaging system developed by Odetics.

3. Redesign, fabrication, installation and testing of new propulsion fans for the Aerobot, to provide an increase in thrust. The new fans have been fabricated and testing has shown an increase in thrust from 58 pounds (258 N) to 65 pounds (289 N).

4. Conduct additional test flights, including outdoor flying, to determine the effects of winds of various velocities and thereby develop recommended operational parameters.

5. Train Caltrans personnel in the operation and maintenance of the system.

It is further recommended that a Phase II enhancement program be initiated to include the development, integration, testing, and demonstration of the following additional capabilities:

1. Increasing thrust to 70 pounds by further improvement in the design of the fan blades.
2. A controllable timing advance circuit in the motors to increase the available horsepower at higher RPM's while allowing the motors to safely start in the correct rotation.
3. Height Holding. The ability onboard the Aerobot to sense absolute altitude above the terrain, to detect any excursions from the commanded altitude, and to autonomously take corrective action to return to and hold the commanded altitude. The addition of this feature with the associated feedback loop is intended to eliminate the present requirement to have the thrust deflectors (scoops) in the duct airflow stream. This will increase net available thrust directly by increasing the flow area.
4. Azimuth Holding. The ability onboard the Aerobot to sense compass direction, to detect any excursions from the commanded azimuth, and to autonomously take corrective action to return to and hold the commanded azimuth.
5. Stereoptic Vision. The installation of dual video cameras onboard the Aerobot with the cameras separated by the width of the vehicle and pointed in the same direction so that the operator receives dual images. The images will be integrated to provide stereo vision which is expected to give the operator good depth perception in guiding the Aerobot into the best positions for inspection. This feature is considered imperative in the event the vehicle is flown out of view of the operator.
6. Improved Landing Gear. A new landing gear should be installed to achieve the capability to absorb a moderate impact resulting from a hard landing or from a sideways impact with a bridge or other structure.
7. Body Shell. A protective outer shell of lightweight composite material will provide additional protection for the electronics and payload around the exterior of the duct and will improve the appearance.
8. Generator. Commercially available portable generators will be studied and the best selected, procured and integrated as a power source for operation at remote sites.
9. Battery Backup Power. A battery-powered system to assure that backup power is immediately available to recover the vehicle in the event of generator failure in the field.
10. Redundant Control System. A redundant electronic control system to assure continued vehicle operation in the event of failure of any portion of the onboard system.
11. Umbilical Cable. A 200 foot (31 meter) umbilical to provide increased range of operation.
12. Marking Device. When inspection reveals an area of interest, it will be important to be able to mark the area for later, more detailed inspection. A marking device, such as a paint gun is to be integrated on the vehicle for that purpose.
13. Duct Screen. To prevent the ingestion of foreign objects, a screen will be installed to cover the duct entry

14. Structural Attachment. A device to allow the vehicle to be flown to and temporarily attached to a steel structure for detailed inspection, then detached and flown to another portion of the structure and re-attached for inspection of that area.

15. Simulator/Trainer. A PC-based flight simulator to be developed for training purposes.

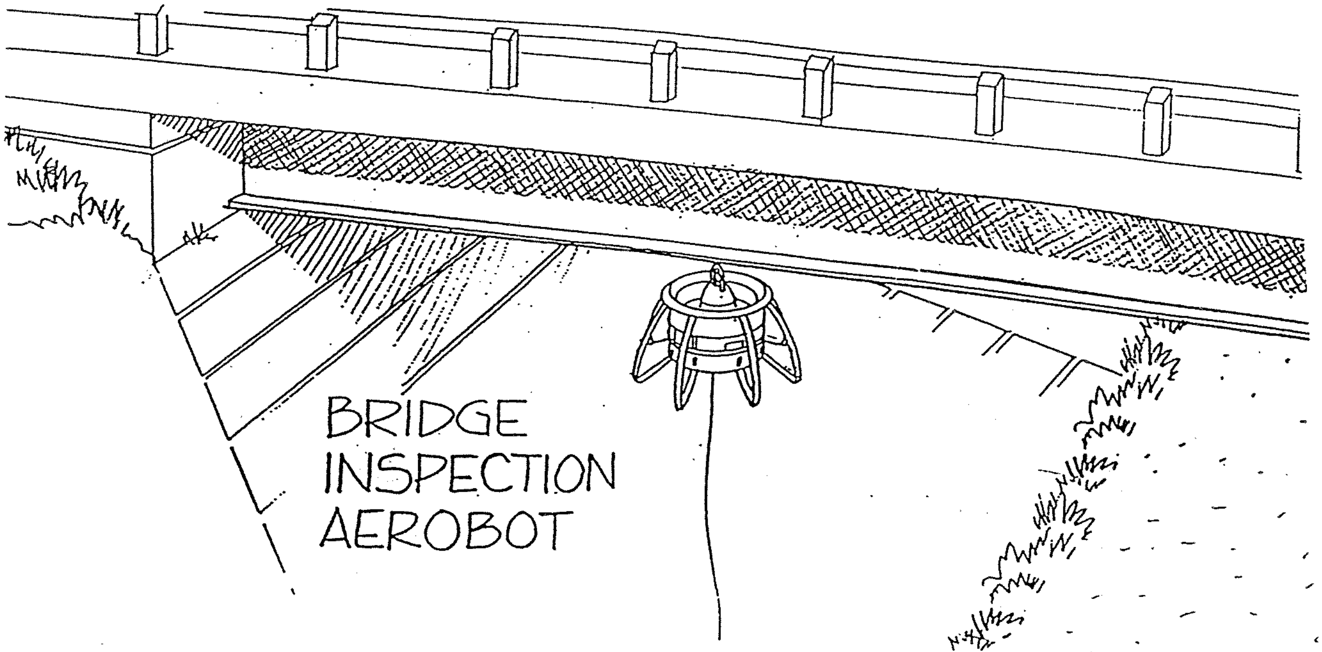
16. The Operations Manual to be revised to incorporate instructions for the operation and field maintenance of the enhancements listed above.

7. IMPLEMENTATION

The Aerobot aerial platform will provide the capability to obtain detailed structural examination of elevated highway structures while the inspection crews remain safely on the ground beneath the structure. With the Phase II enhancements installed, they will also be able to fly the Aerobot from the road surface of elevated structures and be able to control its flight beneath the structure for detailed inspections. High resolution video cameras will transmit pictures of the selected parts of the structure to the video station, which can be as much as 200 feet (61.5 meters) from the structure being inspected. The video station provides the ability to control the camera in tilt, pan, zoom, and snapshot modes. When areas of special interest are noted, they can be remotely marked for later more detailed inspection. The Phase II enhancements will enable the operator to fly the Aerobot quite precisely at a specified distance as close as two feet (.6 meter) from the structure. The Aerobot platform and its onboard camera can then be flown along the length of each structural element as the video inspection is being recorded. The Aerobot can remain in flight as long as its electrical power source continues to provide the necessary power. Under normal circumstances, the only limitation will be the quantity of fuel for the generator and that, of course, can be replenished while the operation continues. Therefore, during periods of daylight and reasonably good weather, the inspection process can continue throughout the day. Inspection capability of the Aerobot system is not limited to elevated highway structures. Due to its versatility, it may also be used to inspect such structures as the face of dams, the sides and roof of buildings, cooling towers, radio towers, wind generators, and hazardous material storage sites and spillage locations.

OPERATIONS MANUAL

ELECTRIC AEROBOT MODEL ES20-10



AEROBOTICS INCORPORATED

AEROBOTICS INCORPORATED

ELECTRIC AEROBOT MODEL ES20-10

OPERATIONS MANUAL

INTRODUCTION

This OPERATIONS MANUAL describes the operation and field maintenance of the unmanned aerial vehicle system developed by Aerobotics Inc. for inspection of bridges and other elevated structures. The system consists of a vertical takeoff and landing (VTOL) aerial platform (Aerobot) with mounting provisions for video cameras and other sensors, a ground control unit which contains pilot controls, power supplies, and electric motor drives for the propulsion motors aboard the Aerobot, and a yoke which fits over the pilot's shoulders and supports the controls, consisting of a power lever and a three-axis joystick. The yoke enables the pilot to have both hands free to manipulate the controls while affording freedom to move to the best vantage point for observing the flight of the Aerobot as it is maneuvered beneath the elevated structure being inspected.

The 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. Pilot commands, video signals, and power for the drive motors and onboard electronics are transmitted through a lightweight umbilical cable of wires and fiber optics, permitting extensive mobility for positioning the inspection camera to view elevated structures closeup 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. The Aerobot is designed to readily accept additional inspection equipment, such as stereoptic video cameras and infra-red sensors, for future enhancement of the inspection capability.

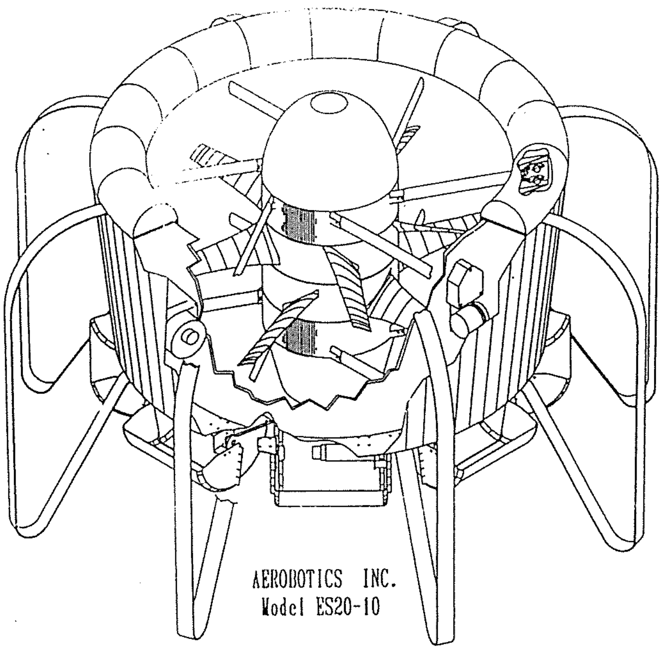


Figure 1.1 Aerobot Model ES20-10

The Aerobot developed for the Caltrans mission is designated the Model ES20-10. The model designation denotes an **E**lectric-powered, **S**ingle duct, **20** inches in interior diameter, powered by at least **10** horsepower in the two motors combined. In this case, each of the two motors is capable of producing over six horsepower. The vehicle is designed as a vertical takeoff and landing (VTOL) camera platform that can be remotely operated at any combination of height and distance up to 200 feet from the operator. Pilot commands, video images, and motor commutation signals are transmitted over a fiber optic umbilical cable. Electric power for the drive motors and vehicle electronics is transmitted over copper wires at high voltages (to reduce the size of the wire). Vehicle lift and control power is produced by twin 6 HP brushless DC motors. Each motor directly drives a multi-bladed propulsion fan. The two fans are counter-rotating so that the torque and air swirl produced by one counteracts those produced by the other, resulting in neutral torque and straight airflow out the exhaust end of the duct. The Aerobot is cylindrical and therefore has no natural nose nor tail. To assist the pilot in maintaining orientation of the vehicle, one small vertical segment of the cylinder has been chosen as the "tail" and has been distinctively marked for easy recognition.

The Aerobot is designed to be flown by any competent employee with a moderate amount of training and experience. The operator controls the vehicle via a "roving-cockpit" which is illustrated in Figure 1.2.

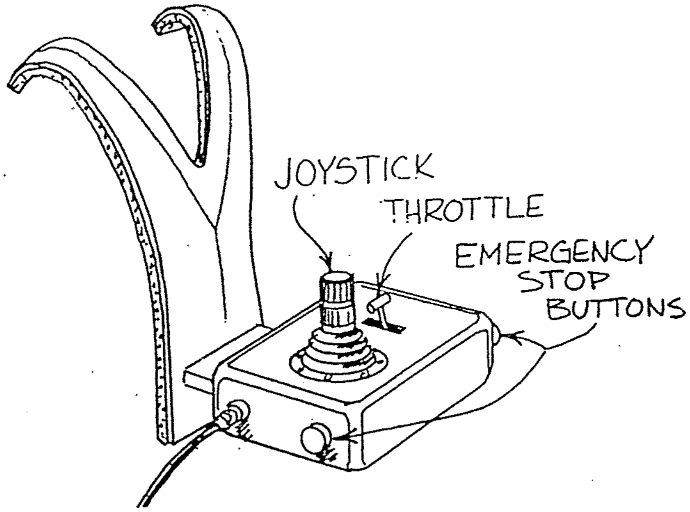


Figure 1.2 Roving-Cockpit

The "roving cockpit" consists of a control box mounted on a fiberglass yoke which 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 airstream 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.

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.

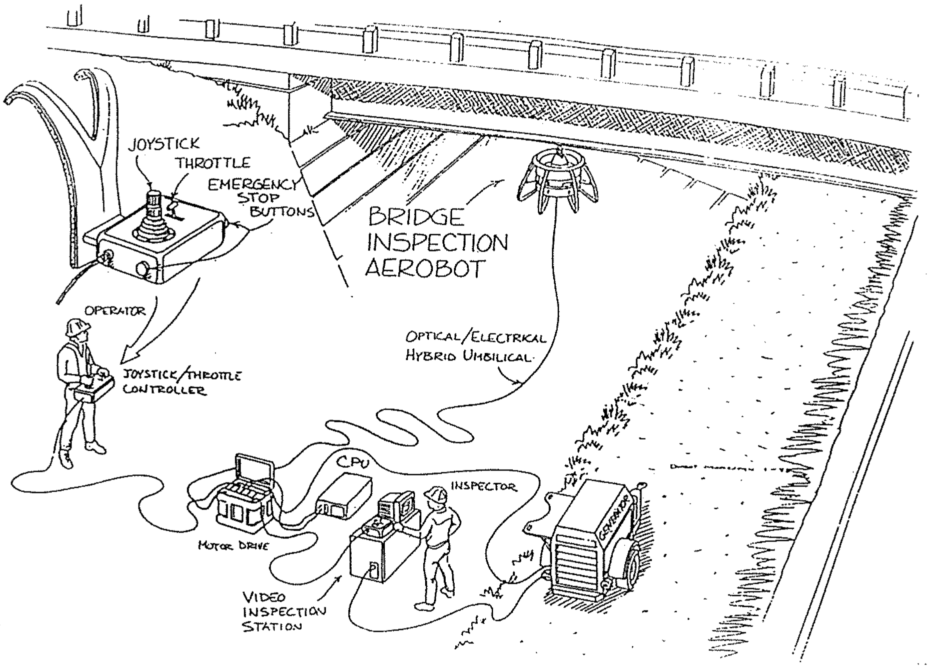


Figure 1.3 Ground Control Station

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 servo motors 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.

TRANSPORTING THE AEROBOT SYSTEM

The motor drive enclosure, central processing unit, and roving cockpit are each composed of strong electronic components which 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.

WIND AND WEATHER

The Aerobot Model ES20-10 is capable of carrying a ten pound payload and operating in moderate winds. As this is being written in April, 1994, only preliminary flight tests have been completed to determine the wind velocities and gust loads which 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 which 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, 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, 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

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.

END

Aerobotics Inc.

Model ES 20-10

Bill of Materials (ref. P/N 531710)

	Part #	Qty.	Description	Source
1.	521201	1	Payload Dome	Aerobotics, Composite
2.	521700	1	Motor Housing Assembly, Upper	Aerobotics, Assembly
3.	521008	6	Strut Insert, Upper	Aerobotics, Machined
4.	521203	12	Strut	Aerobotics, Composite
5.	521702	1	Fan Assembly, Upper	Aerobotics, Machined
6.	521703	1	Fan Assembly, Lower	Aerobotics, Machined
7.	521701	1	Motor Housing Assembly, Lower	Aerobotics, Assembly
8.	521026	6	Strut Insert, Lower	Aerobotics, Machined
9.	521209	1	Tail Cone	Aerobotics, Composite
10.	522104	1	Anti-Aliasing Filter Card	Aerobotics, Electronic
11.	522201	3	Rate Sensor	Systron Donner
12.	521029	1	Mount, Yaw Rate Sensor	Aerobotics, Machined
13.	522103	1	Flight Control Computer	Aerobotics, Electronic
14.	521028	2	Mount, Rate Sensor	Aerobotics, Machined
15.	521705	1	Airframe Assembly	Aerobotics, Assembly
16.	521208	8	Landing Leg	Aerobotics, Composite
17.	522203	1	Vertical Gyro	Humphrey
18.	521200	12	Flange, Strut	Aerobotics, Composite
19.	521707	8	Scooper System Assembly	Aerobotics, Assembly
20.	522107	1	Switching Power Supply Board	Aerobotics, Electronic
21.	522200	1	Power Supply	Vicor