A TELEOPERATED UNMANNED ROTORCRAFT FLIGHT TEST TECHNIQUE

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Abstract

NASA and the U.S. Army are jointly developing a teleoperated unmanned rotorcraft research platform at the National Aeronautics and Space Administration (NASA) Langley Research Center. This effort is intended to provide the rotorcraft research community an intermediate step between wind tunnel rotorcraft studies and full scale flight testing. The research vehicle is scaled such that it can be operated in the NASA Langley 14- by 22-Foot Subsonic Tunnel or be flown freely at an outside test range. This paper briefly describes the system's requirements and the techniques used to marry the various technologies present in the system to meet these requirements. The paper also discusses the status of the development effort.

Background and Introduction

Several recent analyses and simulated aerial combat flight tests have demonstrated that agility is a very powerful element of rotorcraft combat survivability. Dynamic stability, maneuverability, and agility are not presently addressed in helicopter wind tunnel testing for both economic and technical reasons, and the investigation of these dynamic issues must therefore be conducted on free-flight vehicles of some type, whether full scale or model scale. Unfortunately, the cost of conducting full-scale flight tests has become so high that it can only be considered for the most important elements of research and development where any other method of test is wholly inadequate. Considerable work is now underway to supplement flight testing with simulation to the maximum extent possible. Simulation, however, can only be exploited when there is a model of the system. Recently developed techniques to validate simulation models require some form of high fidelity flight testing for confirmation. A joint U.S. Army and NASA program is currently underway to evaluate the suitability of using a teleoperated, instrumented, free-flight , reduced-scale powered rotorcraft model equipped with Mach-scaled wind tunnel model rotor systems to refine these validation techniques. This paper provides an overview of the approach and the current status of this free-flight program with an indepth focus on the model's control system.

Free-Flight Research Technique

The free-fight research technique using a model for conducting simulation research is illustrated in figure 1. A specialized flight dynamics research model known as the Free-Flight Rotorcraft Research Vehicle (FFRRV) is flown by a research pilot located in a ground control station. Flight data is telemetered to the ground and recorded in a data acquisition station. The technique of placing the research pilot in the model by means of telepresence technologies rather

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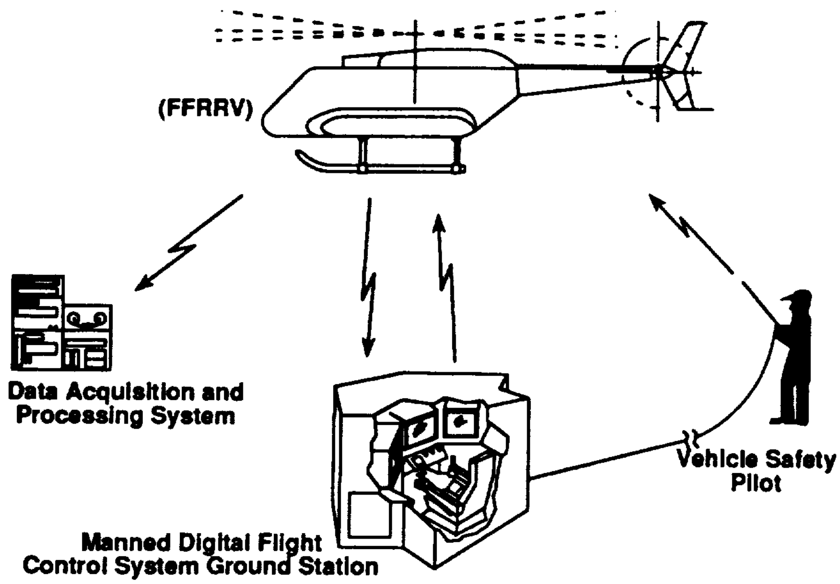

FIGURE 1:
The Proposed Free-Flight Test Technique.

than having him fly by line of sight should ease some of the FFRRV's control systems autonomy requirements because the pilot's perceptions about what is occurring will be keener and his reactions faster. Having the research pilot as an integral part of the aircraft should also allow the pilot to fly more aggressive maneuvers often encountered in nap-of-the-earth (NOE) flight than would be possible with an external pilot. The research pilot's sensory inputs are provided by images from three miniature television cameras and two microphones mounted in the vehicle's nose. The video images are projected onto three, color 26- inch television monitors, and the audio signals are fed into a headset. The video link provides the research pilot sitting in a ground station with a 150 x 35 degree field of view (figure 2). The research pilot's control commands are interrogated by a computer in the ground station and broadcast to the flight vehicle. In addition to the research pilot radio links with the aircraft, there is an external safety pilot who has overall authority over the model in an emergency situation and flies the craft by line of sight like a conventional radio controlled model helicopter.

The Flight Vehicle

The FFRRV is a minimum 225 pound gross weight, aerodynamically scaled model that was designed specifically for conducting flight dynamics research. Almost all of the primary parameters that one would desire to study in rotorcraft research are easily varied. For example, the control system could command excursions in the main rotor RPM to study the resulting variation in dynamics without having to conduct major system redesign and validation as is the case with full scale flight vehicles being flown at an off-design point.

In-house studies indicate that it becomes unfeasible to achieve aeroelastic scaling of a rotorcraft flying in air when the rotor gets any smaller than about 2 meters in diameter. A 2 meter diameter rotor when loaded like a full scale rotorcraft, with 3 to 7 pounds per square foot of disk load, corresponds to a model weight of 200 plus pounds. This rotor size is also scaled similarly to

FIGURE 2:
Ground Control Station Cockpit.

other wind tunnel models that the U.S. Army Aerostructures Directorate operates in the NASA Langley 14- by 22-Foot Subsonic Tunnel.

To maintain the desired flexibility of the test platform there is a core vehicle within the model to which the other essential modules are attached. This core vehicle consists of:

- A steel frame
- 40-horsepower rotary engine and its accessories
- 1.6 KW alternator
- Variable speed ratio belt drive system
- Fixed ratio main rotor transmission
- High speed (greater than 10 inches per second) swashplate actuators
- Flexible shaft and tail rotor drive gearbox

The core vehicle is designed to carry all the loads generated in the system. Tests involving different rotor speeds can be conducted by sizing different diameter pulleys in the belt drive system. Modifying the design rotor speed at this point in the power train greatly reduces costs and the time to modify the system when compared to modifying the rotor speed by using different gear ratios in the transmission. Since the tail rotor is driven off the main drive gearbox with a flexible shaft its location can be moved without requiring a drive system redesign. Attached to this basic core are the additional modules which can be added or modified as the mission requires. The aeroshell itself is one of these additional modules and therefore must only carry the aerodynamic loads that are imposed directly on it. With such an easily modifiable shape some basic phenomena related to detectability or the effects of fuselage shape on agility can be studied quickly and at a very low cost. Some typical configuration studies such as research to obtain a better understanding of unconventional anti-torque systems, like those depicted in figures 3 through 6 could also be conducted on the FFRRV. The overall effect of this approach is to provide a unique capability to explore new ideas in rotorcraft design in a timely and cost effective way.

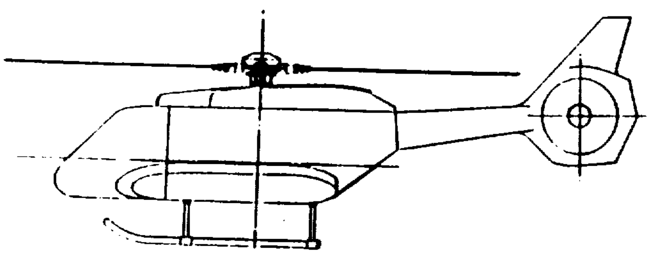

FIGURE 3:
Generic Fenestron Unconventional Anti-Torque System

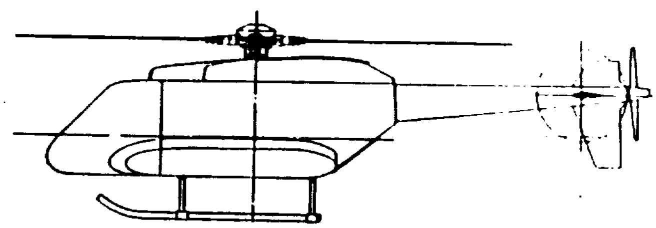

FIGURE 5:
SIKORSKY Swing-Tail Rotor Vectored Anti-Torque System

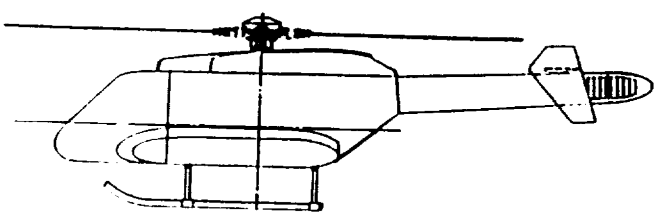

FIGURE 4:
Generic Notar Unconventional Anti-Torque System

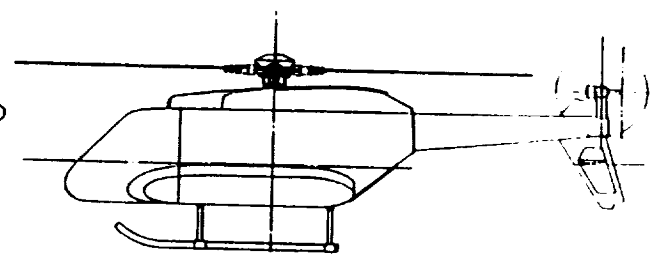

FIGURE 6:
LOCKHEED Pusher Propeller Vectored Anti-Torque System

The Control System

Modularity and flexibility are emphasized in the design of the control system architecture as with all other pieces of the complete system. Subsystem component sets as well as discrete capabilities of the integrated system are broken into separate objects. The objective of breaking the system into submodules facilitates rapid prototyping and testing of new modules and capabilities with minimal impact on existing modules.

The overall goal of the control system is to allow maximum utility to the FFRRV as a research tool by not hampering a test schedule or limiting the scope of a test because of a deficient or inadequate controller for the task. For example, if the researcher requires a certain aggressive flight trajectory to be flown at a certain location over the test range, the desired trajectory could be loaded into the flight computer to fly the vehicle much the same as a human pilot could if he were able to monitor all the parameters of interest quickly enough to maintain them within their test limits. Another desired feature of the control system is to provide a highly stable platform upon which pilot commands can be overlaid. This requirement of the controller is a greater issue with a vehicle of this small scale than it is with a full sized helicopter because the scale factors are different for aerodynamics than for mass and inertia. This difference in scale factors allows the FFRRV to naturally respond quicker to control movements than a full sized helicopter. This "overly sensitive" control responsiveness requires some measure of stability augmentation for piloted flight.

The present control system architecture allows the research pilot to vary the stability and control augmentation system (SCAS) to the specific piloting requirements during flight. The SCAS will operate in various modes in order to achieve this variability. The basic mode is where the control inputs are coupled and an input on one axis has responses on other axes. Another mode is where the controls are uncoupled to a tunable degree where the pilot can vary how much of an input on one axis affects the off-axes aircraft responses. The most augmented mode is where the vehicle is fully autonomous and the maneuver flown is preplanned. In order to (1) meet these specifications, (2) provide an easily modifiable controller essential for a research tool, and (3) enable some form of vehicle recovery in case of a loss of communication, portions of the control system are located both in the manned ground control station and on the air vehicle. The control systems data analysis and response processing cannot occur entirely on the ground if there is to be any way for the vehicle to sense a loss of communication with the ground station and/or the safety pilot and attempt self-recovery. There are various ways this self-recovery could happen since some of the vehicle's machine intelligence is located on the flight platform and is not entirely on the ground.

A secondary but highly relevant advantage of splitting the control system between the ground and the airvehicle is the potential for reducing the speed and volume of the telemetered data. One computer talking to another in a predefined language can perform at a given level with a lower communication rate than having to encode and decode raw sensor and actuator data at each end of the communication link[1].

<u>The Ground Station Control System</u>: Within the ground station, pilot and researcher commands are processed and broadcast to the flight vehicle for execution. Autonomous flight modes, where the vehicle flies a preprogrammed course on its own, will utilize the ground control station as a source from which to execute the commands. The only autonomous flight planning mode located on the air vehicle is the mode where the vehicle senses a loss of communication and performs a self recovery.

The problem of providing the tunable multilevel controller described above is addressed from both ends of the control authority spectrum. At one extreme the human pilot is in full control without any computer augmentation, and on the other extreme lies an autonomous autopilot capable of flying preprogrammed maneuvers. The middle set of flight modes, where the human augments the autonomous system, is achieved by a blending of the two extremes. In all three modes the resulting commands from the ground station broadcast to the flight vehicle remain the same. Keeping this continuity simplifies design of the airborne controller and places the burden of developing such capabilities on ground based computers where size is not of primary concern. Having this higher level problem solving on the ground eliminates the burden of packing such a capable control system into a volume that will fit into the small airframe of FFRRV.

<u>The Airborne Control System</u>: While looking at the various scenarios which the FFRRV must perform, it quickly becomes apparent that some means of embedding machine intelligence into the flight vehicle would be advantageous. Putting a digital controller on the flight vehicle allows for much faster processing throughput than if all data processing occurred on the ground. Some specific benefits of having a digital controller on the flight vehicle are: (1) Servo control loops require only telemetry to drive a set point. (2) Sensor data can be preprocessed before telemetering it to the high level controller on the ground. (3) It provides the model with some from of machine intelligence that can react to deteriorated communications from the ground.

Being a research tool, where all future uses are not known, it is logical to provide control processing capability on the airvehicle beyond that required in the initial development. This additional capability and speed can be used in two ways:

1. Providing room for growth with new research missions.
2. Allowing rapid testing of unoptimized algorithms without having computational speed become a major limiting factor.

The airborne controller will receive commands from either the safety pilot or the ground station. If the safety pilot commands the vehicle then the airborne controller will ignore any information coming from the ground station and will respond to the safety pilot in a manner similar to a hobby radio controlled helicopter model. If however, the safety pilot has relinquished control to the ground station, as in normal operation, then the airborne controller executes orders from the ground station following a predefined format. This format will be developed to simplify testing the logic of both the airborne and ground station controllers.

The airborne controller will also preprocess the analog signals from the sensor suite and broadcast to the ground control station the following processed sensory information:

- Conditioned sensor data from each sensor.
- A mathematical estimate of the vehicle attitude based on combining the various sensors.

This sensor fusion occurring in the airborne controller relieves the telemetry system from accommodating sensitive analog signals and only requires it to transmit pre-conditioned digital data. This fusion also provides the self recovery capability resident entirely in the airborne controller with accurate knowledge about the vehicle state.

Research Data Recording

The aerodynamic and rotor performance data of interest are collected and transmitted to the ground as a separate entity with minimal interference with other systems on the vehicle. The scope and accuracy of the parameters measured by the data acquisition system mimic that of a wind tunnel Mach scaled rotorcraft model.

The recording of research data occurs independently of the flight data required for the control system. There are two reasons for this:

First, the data of research interest will vary widely depending on the tests being conducted. If the control system data is not a subset of the research data being taken then the additional burden placed on the research data system to acquire the control data will hamper its flexibility. The control systems requirements for data will generally not change whereas the research data collected will vary widely. By separating the two data systems the necessary changes are restricted to one module only.

Second, the control system must be tested and validated irrespectively of the research data or research specific sensors. This allows the vehicle to be developed and flown without any research data collection facility in place. Having this capability facilitates development and makes the system more portable, so it could perform research on various flight test ranges, not just the one it is being developed on.

When a measured parameter necessary for research is the same as one required for the control system, only one instrument which satisfies the more stringent of the two requirements is used to save space. There will, if possible, be two independent pickoff's for the single sensor and all other efforts will be made to isolate any disturbances on one system caused from interrogating the sensor with the other.

If however, the subject of research is related to flight controls, like blade state feedback control, then the control system will require access to the research data recorder. This loop closure, occurring only when necessary, will be on the ground between the Research Data

Acquisition System and the Digital Flight Control System Ground Station to simplify processing and avoid potential contamination of the Airborne Control System.

Status and Plans

We are following a four phase development plan:

1. Proof of concept tests and prototyping of systems.
2. Design and fabrication of a research model.
3. Validation of systems in wind tunnel.
4. Research flight tests.

Currently we are deeply involved in the first two phases of this plan. We are conducting proof of concept flights and control system development with smaller commercial "hobby" helicopters equipped with video cameras, inertial sensors and the associated telemetry (figures 7 and 8). The actual research vehicle is approximately 80 percent complete and has already entered the NASA Langley 14- by 22-Foot Subsonic Tunnel in an unpowered configuration (figure 9). A powerful custom flight computer capable of providing the machine intelligence required on the air vehicle has been designed, built, and is being tested. FFRRV's first flights are scheduled late in the fall of 1992. Prior to these flights the vehicle will again enter the wind tunnel, but this time powered to verify an accurate implementation of the control system. The vehicle will also enter NASA Langley's anechoic chamber for tests to ensure that the assorted telemetry systems supporting the project do not have any transmission dropouts due to antenna blind spots.

The following two sections discuss our current status on the first two phases.

FIGURE 7:
Proof Of Concept Flight Testing Of A Large Commercial Model.

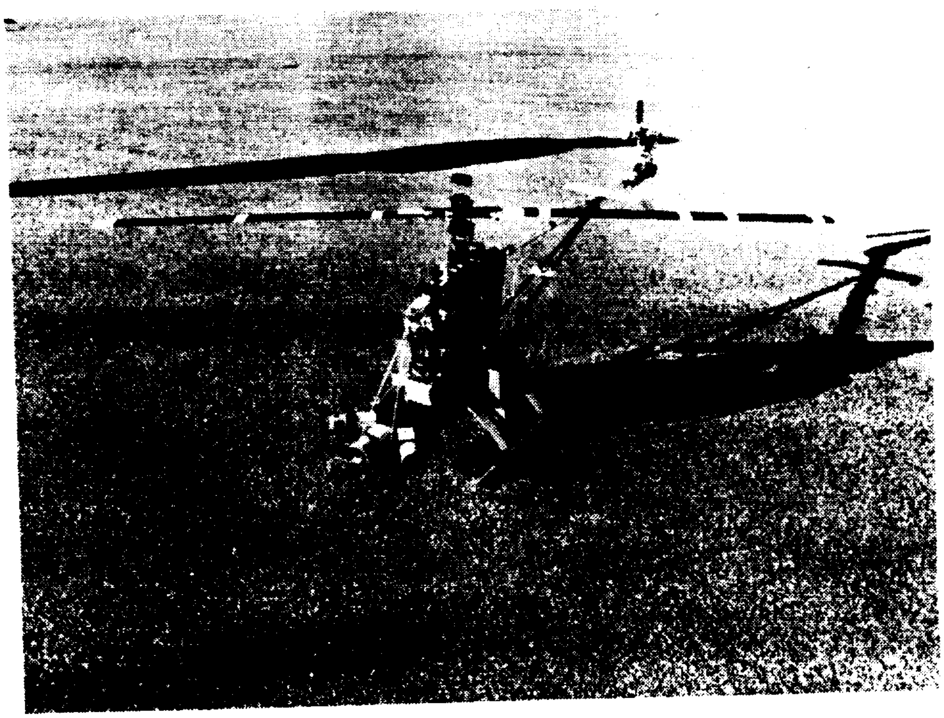

FIGURE 8:
The Large Commercial Model Equipped With Three Video Cameras.

Proof of Concept Tests and Prototyping Efforts

To speed development and reduce the risk of prematurely damaging the research vehicle, we are using commercial hobby-type radio controlled helicopters to resolve issues about systems integration. These RC helicopters are out-of-scale when you look at their aerodynamic surfaces and power systems. However, these models are very useful because we can port much of the integrated systems, debugged on these vehicles, unchanged onto the FFRRV.

Presently we have one model flying at a 200 percent gross weight increase from its original design. Normally the model would have a flying weight of 9.5 pounds, however, the addition of proof of concept equipment, brings the gross weight up to 30 lbs. The benefits of using this model are:

1. The availability of an inexpensive prototype testbed that can fly a large portion of our subsystems for development work.
2. The training of safety pilots on how to recover heavier models. Heavy models respond at different rates than the stock lighter models.

The first use of this heavy out-of-scale vehicle is to clean up the video transmission and receiving system. This work has been going on through the fall of 1991 and is nearing completion.

Following video development, the next task these vehicles will undertake is to fly missions to develop the control system. Initially this effort involves building a mathematical model of the aircraft by performing a system identification of the models and collecting flight data to validate this simulation model. This will be conducted by telemetering sensor data from the aircraft to the ground. This simulation model of the aircraft will be used to initially tune the control system prior to flight. Once modules of the control system are verified against this simulation model they will be flown and will build upon existing modules that have already gone through this checkout phase, adding incrementally more capability to the model control system. To reduce risk to the research vehicle the control system will only be flown on FFRRV after testing it as much as reasonable on the smaller models.

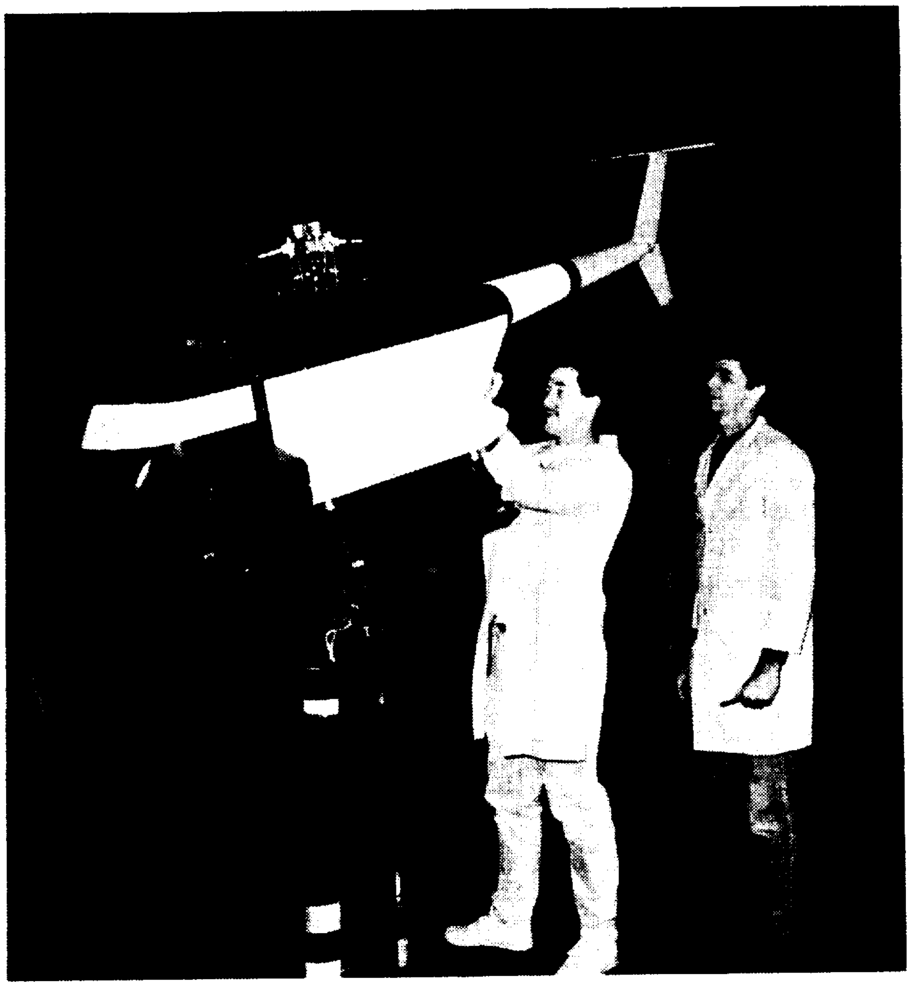

FIGURE 9:
The Scaled Research Vehicle (FFRRV)
In The NASA 14- by 22-Foot Tunnel.

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Design and Fabrication of a Research Model

The Research Flight Vehicle: The initial wind tunnel test of the FFRRV was completed on November 14, 1991. The goals of this test were:

1. Obtain aerodynamic data for baseline studies of the initial fuselage shape.
2. Ensure the tail is adequately sized and placed so it will provide the stability required.
3. Study the effects that forward flight has on the radiator used for engine cooling and ensure there is enough energy being dissipated by the radiator.

The results of this tunnel entry drove slight changes to the initial tail configuration which increased longitudinal and directional stability and provided a capability for in-flight adjustment of pitching moment due to the tail. These changes which involved the addition of vertical tip fins to the ends of the horizontal tail and the incorporation of a short-chord elevator into the horizontal tail surface were verified during the wind tunnel test. The wind tunnel test also identified the need for approximately 30 percent more heat exchange capability to cool the powerplant.

Currently the drive train is being integrated and tuned. We will initially tune the drive train with an electric motor and then later introduce the internal combustion rotary engine. Separating the integration of the drive train and the engine simplifies the tuning required.

A model support system for the wind tunnel has been designed and built which will allow the FFRRV model a limited amount of travel about all three rotational axes and along the vertical axis. This new support system provides a methodological approach to testing the control system in a controlled environment, one motion at a time, prior to flight, and will make possible a new focus in powered rotor testing where body dynamics are the major factor of interest.

The Control System: The distinct tasks that this control system must perform have been logically broken down into separate modules, each with a specific objective (figure 10). The resources necessary to achieve each distinct objective are assigned to the respective module. With this breakdown, parallel development of the separate systems are occurring and will culminate with the final integration and complete system testing.

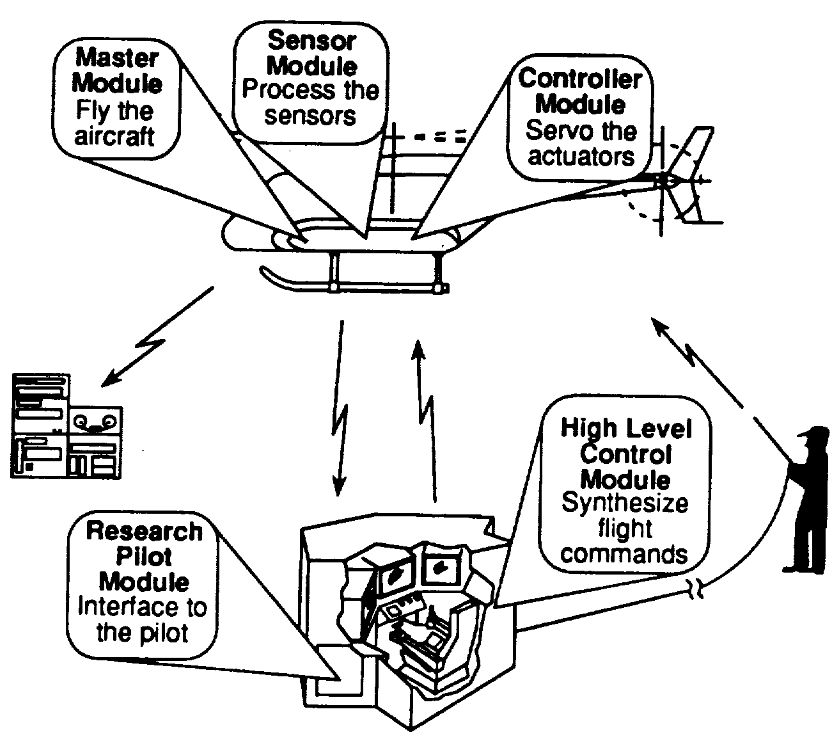

FIGURE 10:
Control System Breakdown.

Two methodologies are presently being compared to determine how best to achieve the three distinct modes of control already discussed: (1) the basic mode, where unfiltered inputs are directly applied to the aircraft (2) the filtered mode, where there is a tunable control augmentation system (3) the autonomous mode, where the aircraft flies a preplanned course. The first methodology under evaluation is based on an accurate model of the aircraft where a nonlinear exact model-following control system, using a model inversion technique, is applied[2]. The second methodology is based on a hybrid of a fuzzy logic controller and a neural network model identifier[3]. At this stage it appears that integrating the human pilot back into the control system will be easier to accomplish using the second approach. Two basic questions presently require resolution: (1) Given the limited information possessed about the model, can a hybrid fuzzy neural controller provide the same precision that an exact model-following controller can? (2) Can an exact model-following controller actually be built with the limited knowledge we have about the model?

The following sections describe the current status of the ground control station and the hardware designed for flight vehicle control system.

Ground Control Station: A working ground station capable of interrogating the research pilot, displaying transmitted video images, and relinquishing control when necessary to the safety pilot is complete (figure 2). Currently a highly modified FUTABA model 1024 9-channel PCM transmitter is operated from the research pilot's seat. In the future, when the ground station is operational with a tunable control system, the FUTABA radio will be replaced with a single high speed telemetry link from a ground computer to an airborne computer. The connection between the safety pilot's radio and the ground station is complete and allows the safety pilot to override control of the model. The video images are each transmitted on their own frequency. The three video receivers are integrated into the ground station enclosure such that the research pilot can tune the video prior to takeoff. Sensory data for the control system is also sent down on a video transmitter.

Initial flights of the heavy weight model helicopter from the ground station are awaiting installation of a stability augmentation system for the aircraft. The RC model, even in its heavy condition, requires stability augmentation prior to flying with cockpit cues without excessive training since it responds so much quicker than full scale rotorcraft.

Airborne Control System: We decided to assign computers with an identical architecture to each submodule in the airborne control system since all the flying modules have identical reliability, weight, and volume restrictions. This decision provides a single development environment and will greatly simplify the final stages of system integration. A market survey of small, powerful computers designed for embedded control application capable of accommodating these specifications was conducted in December 1990. This survey showed that several new 32-bit processors designed for embedded control had just been released. Two microprocessor families of specific interest, the Motorola 683XX and the Intel 80960, had not yet been made into an integrated system small enough to fit into the FFRRV's limited space.

We decided the flight computer must be designed specifically for the mission at hand to maximize its usefulness as a research tool and capitalize on recent microelectronics advances. As a result a control computer based on the Motorola 68332 was developed. The decision to use the 68332 was based on the available software to support it, its advanced internal time processing unit, and because board design is simplified when working with its integrated architecture [4]. The resulting airborne computer system is based on a loosely coupled network of 68332's enhanced with a user selectable amount of:

-Analog input and output for sensor processing
-Additional digital input and output for sensor processing
-Linear Variable Differential Transformer (LVDT) readers for actuator controls
-Flash memory for non-volatile program storage without having to extract the computer from its embedded location in the flight vehicle.
-Large static RAM banks to ease program development, execution, and data collection.

The computer hardware package is very compact measuring 1.5 inches by 4 inches and varies in height from 1 to 5 inches. The height depends on the amount of additional features that a particular module in the multiprocessor control system requires in addition to the basic system.

A multi-tasking real time operating system has been successfully ported to this custom control computer. Low level driver routines, interprocessor communication, and some of the basic I/O functions required in the flight control system have been programmed and tested.

An initial sensor suite was specified and is presently being integrated into the model. The sensor suite is best characterized by its small size and the individual measurements of attitude positions, rates, and accelerations along all 6 axes. Table 1 lists the states being measured and the particular sensor used for observing them [5].

Concluding Remarks

• This is a small scale program which requires a high degree of multi-disciplinary research for its success.

• The program's main goal is to develop a research tool. As the program matures it has a promising future for providing low cost research flight testing where parametric studies can be rapidly executed.

• Successful development of this novel control system will provide a test bed capable of bridging basic artificial intelligence research with systems integration.

• Relatively inexpensive rotor aerodynamic studies will be able to be conducted on hardware in both the wind tunnel and flight completely independent of scale factor corrections.

MEASURED STATES FOR DYNAMIC CONTROL

Quantity	Symbol	Sensor
Range Location	X	Differential GPS
Range Location	Y	"" "" ""
Altitude	Z	"" "" ""
Altitude	Z	15psia Transducer
Near Ground Altitude	Z	Polaroid Transducer
Pitch	Θ	Vertical Gyroscope
Roll	Φ	"" "" ""
Heading	Ψ	Magnetometer
Vertical Rate	w	Variometer
Pitch Rate	q	Reed Rate Sensor
Roll Rate	p	"" "" ""
Yaw Rate	r	"" "" ""
Fwd Acceleration	u'	3 Axis Accelerometer
Side Acceleration	v'	"" "" ""
Vertical Acceleration	w'	"" "" ""
Pitch Acceleration	q'	3 Axis Accelerometer
Roll Acceleration	p'	"" "" ""
Yaw Acceleration	r'	"" "" ""
Air Speed	V	$\alpha\beta$ Bird
Velocity Fwd Angle	α	"" "" ""
Velocity Side Angle	β	"" "" ""
Main Rotor Speed	Ω	Rotary Encoder
Ground Contact Switches	G_c	(4) Micro Switches
Flapping Angle	β	1 Blade Potentiometer

MEASURED STATES FOR ACTUATOR SERVO CONTROL

Quantity	Symbol	Sensor
Main Rotor Collective	Q_c	LVDT and Encoder
Longitudinal Cyclic	A_1	"" "" ""
Lateral Cyclic	B_1	"" "" ""
Tail Rotor Collective	Q_{tr}	Rotary Potentiometer
Throttle Position	S	Rotary Potentiometer

MEASURED STATES FOR MODEL MONITORING

Quantity	Symbol	Sensor
Engine Speed	N_E	Rotary Encoder
Engine Temperature	T_E	Thermocouple
Ambient Temperature	T_{Amb}	"" "" ""
Transmission Temp 1	T_{T1}	"" "" ""
Transmission Temp 2	T_{T2}	"" "" ""
Exhaust Temperature	T_{Ex}	"" "" ""
Clutch Temperature	T_{Cl}	"" "" ""
Water Pressure	P_{Water}	30 psig Transducer
Clutch Actuator Switches	C_{Act}	(2) Micro Switches
Fuel Quantity	F	Float Potentiometer
Lubricant Oil Quantity	L	Float Potentiometer
Alternator Current	I	Ammeter
Alternator Voltage	V	Voltmeter

TABLE 1:
Measured States For Control And Associated Sensors

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