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Free Flight Rotorcraft Flight Test Vehicle Technology Development

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Abstract

A rotary wing, unmanned air vehicle (UAV) is being developed as a research tool at the NASA Langley Research Center by the U.S. Army and NASA. This development program is intended to provide the rotorcraft research community an intermediate step between rotorcraft wind tunnel testing and full scale manned flight testing. The technologies under development for this vehicle are: adaptive electronic flight control systems incorporating artificial intelligence (AI) techniques, small-light weight sophisticated sensors, advanced telepresence-telerobotics systems and rotary wing UAV operational procedures. This paper briefly describes the system's requirements and the techniques used to integrate the various technologies to meet these requirements. The paper also discusses the status of the development effort. In addition to the original aeromechanics research mission, the technology development effort has generated a great deal of interest in the UAV community for related spin-off applications, as briefly described at the end of the paper. In some cases the technologies under development in the free flight program are critical to the ability to perform some applications.

Background

Several 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. Therefore, the investigation of these dynamic issues must 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.

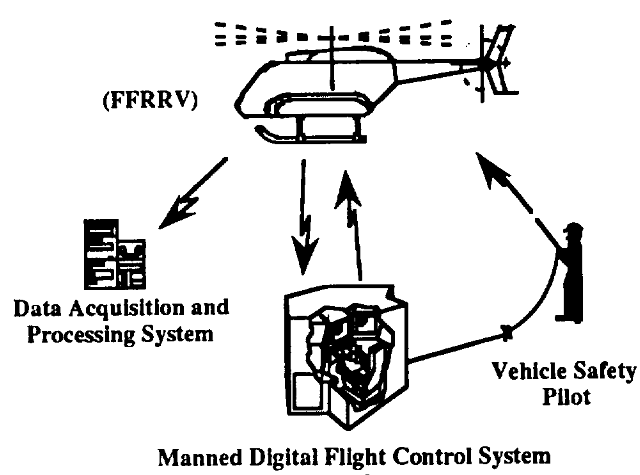

Figure 1
Free Flight Research Technique

A joint U.S. Army and NASA program is currently underway to develop the technologies necessary to operate a teleoperated, instrumented, free-flight, reduced-scale powered rotorcraft, to refine these validation techniques (Figure 1). This paper provides an overview of the approach, the current status of the free-flight program, and a brief discussion of the spin-off potential of the technology developments to other UAV applications.[1]

Free-Flight Research Technique

The free-fight research technique using a model for conducting simulation research is illustrated in Figure 1. The 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 (Figure 2). Flight data are 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 than having him fly by line of sight should ease some of the FFRRV's control system autonomy requirements. This results from the pilot's situational awareness of aircraft state being better 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. Sensory inputs to the research pilot are provided by images from three fixed miniature television cameras and two microphones mounted in the vehicle's nose (Figure 3). One of the cameras is pointed directly forward while the other two are aimed 50 degrees off centerline to each side. The video images are projected onto three fixed, 20- inch color television monitors and the audio signals are fed into a headset. The video links provide the research pilot sitting in a ground station with a stationary 150 (Horizontal)x 35 (Vertical) 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.

Figure 2
Ground Control Cockpit Station

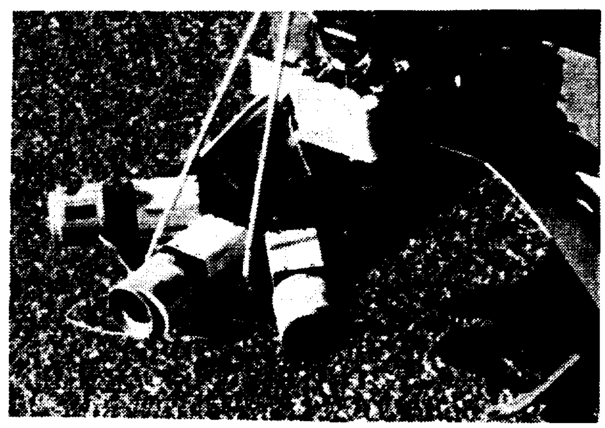

Figure 3
Fixed Three Camera Platform

Currently, new designs are being developed to upgrade this telepresence system from three fixed cameras to a stereoscopic vision system with the ability to tilt, pan and roll the image to match the head motions of the pilot wearing a Head Mounted Display (HMD) (Figure 4). There are two efforts currently underway. One is for a stereoscopic HMD with a mechanical tilt-pan-roll camera platform on the vehicle that is slaved to the pilots head motions. The other effort is looking at a solid state video and computerized image processing system that performs the tilt-pan-roll function without the on-board mechanical devices.

Figure 4
Head Mounted Display

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 can take command of the vehicle like a conventional radio controlled model helicopter.

The Flight Vehicle

The FFRRV is a 210 pound minimum 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 less 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 loading, corresponds to a model weight of 200 plus pounds. This rotor size is also scaled similarly to other wind tunnel models that the U.S. Army Aeroflightdynamics 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 component within the model to which the other essential modules are attached. This core consists of:

- A steel frame
- 40 horsepower rotary engine
- 1.5 kW alternator
- Variable speed ratio belt drive system
- Fixed ratio main rotor transmission
- High speed swashplate actuators
- Flexible shaft driving a separate tail rotor drive gearbox

The core is designed to carry all the loads generated in the system and be the mounting point to attach all of the other modules. 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. As illustrated in Figure 5, attached to this basic core are the additional modules which can be changed or modified as the testing 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 vehicle, many different test configurations can be studied quickly and at very low cost. The flexibility and utility of the vehicle also allows many different types of testing such as acoustics, aeromechanics, sensor development and electronic flight controls research. 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. However, this flexibility greatly challenges the control system design. Every time you change a component on the test vehicle, the control laws and therefore the control systems changes. To keep the program from becoming dominated by constant control systems redesign, an adaptive control system technique was developed, as discussed in the next section.

Control System Overview

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

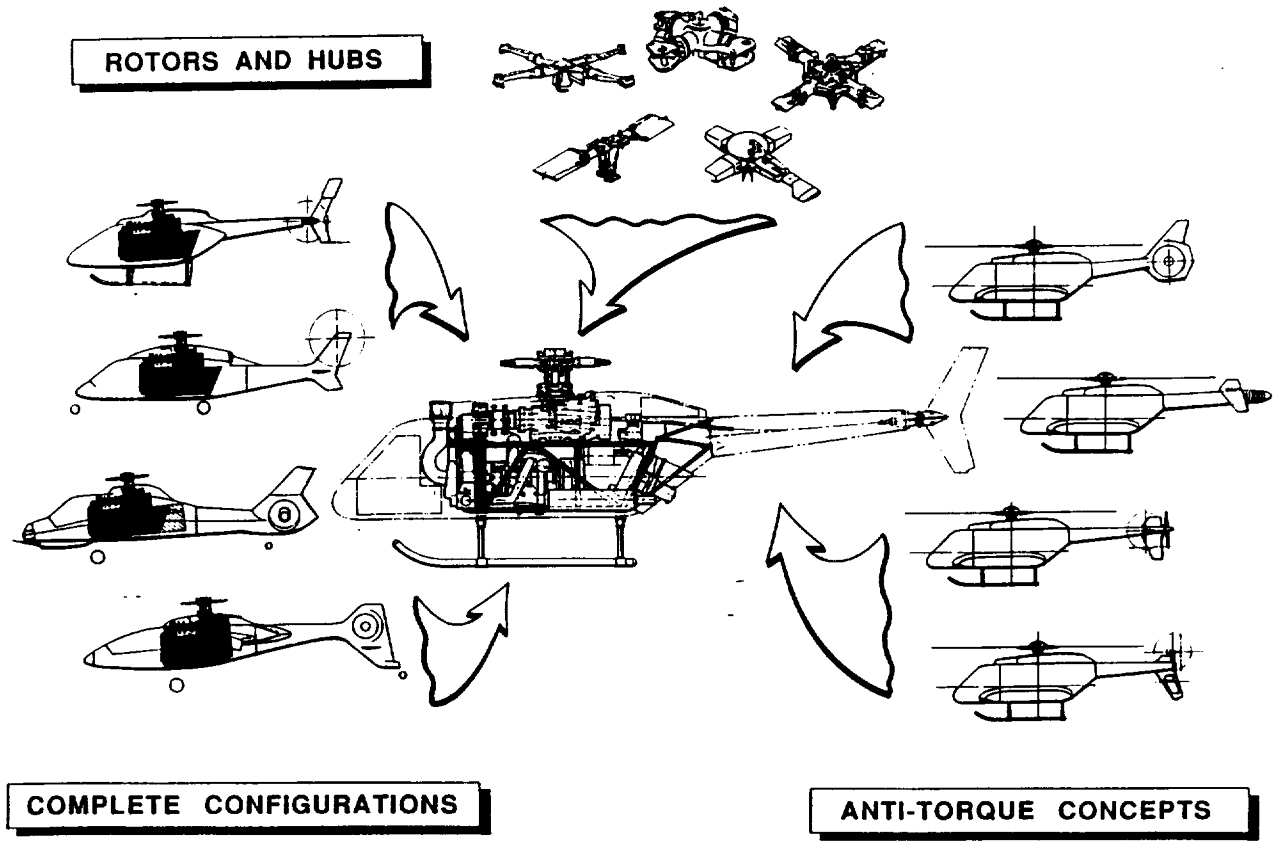

Figure 5
Free Flight Test Modules

into sub-modules facilitates rapid prototyping and testing of new modules 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 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 operator commands can be overlaid. This requirement of the controller is a greater challenge 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 makes the FFRRV respond quicker to control movements than a full sized helicopter. This "sensitive" control responsiveness requires some measure of stability augmentation for teleoperated flight.

In order to provide an easily modifiable controller essential for a research tool, and to 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 execute a self recovery on loss of communication with the ground.

A secondary but highly relevant advantage of splitting the control system between the ground and the air vehicle is the reduction in volume of 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.[2]

The Ground Station Control System: 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 Airborne Control System: 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 are: (1) Sensor data can be preprocessed before telemetering it to the high level controller on the ground. (2) It provides the model with some from of machine intelligence that can react to deteriorated communications from the ground.

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 was developed to simplify testing the logic of both the airborne and ground station controllers.

Being a research tool, where all future uses are not known, it is logical to provide control processing capability on the air vehicle beyond that required in the initial development. This additional capability and speed can be used to provide room for growth with new research missions. It will also allow rapid testing of unoptimized algorithms without computational speed becoming a limiting factor.

Application of Artificial Intelligence Techniques To Control System: Because of the constantly changing nature of the different test configurations, it was necessary to develop a technique to adapt the control system to various test conditions. The solution being pursued is to apply existing artificial intelligence techniques such as neural networks, fuzzy set theory, genetic algorithms and expert systems in a hybrid fashion for adapting a non-linear control system. Much of this basic research was developed in non-aerodynamic control disciplines. Neural networks are being used in many model identification problems and the Japanese have extensively applied fuzzy control to complex non-linear control problems, including model helicopter flight. The controller under development combines a hierarchical fuzzy logic scheme originally developed at Tokyo Institute of Technology (TIT) with an in-house-developed tuning system based on neural networks and genetic algorithms.[3] The resulting controller will couple a continuous time base low level controller with a discrete event-driven high level controller.

Status and Plans

The program follows 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.

As discussed in the next two sections, the first two phases of this plan are being actively worked at this time.

Proof of Concept Tests and Prototyping Efforts

To lower cost, speed development and reduce the risk of damaging the research vehicle, commercial radio controlled model helicopters are used to resolve issues about systems integration. These smaller proof of concept (POC) helicopters are equipped with video cameras, inertial instruments and the associated telemetry (Figure 6). The POC helicopters are out-of-scale when you look at their aerodynamic surfaces and power systems. However, these models are very useful because most of the integrated systems can be debugged on these vehicles and ported unchanged into the FFRRV.

Presently, models are flying at a 200 percent gross weight increase from their original design with a 100% increase in rotor system solidity and 50% increase in power. Normally the models would have a flying weight of 9.5 pounds. However, the addition of proof of concept equipment and rotor modifications brings the gross weight up to 28 lbs.

The first use of this heavy out-of-scale vehicle is to fly missions to develop the control system. Initially this effort involves building a mathematical model of the aircraft and collecting flight data to validate the model. 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 be added to existing modules that have already gone through this checkout phase. This will incrementally increase the capability of 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.

An operations study has been initiated to see what the minimum equipment and training needs are to reliably fly the small

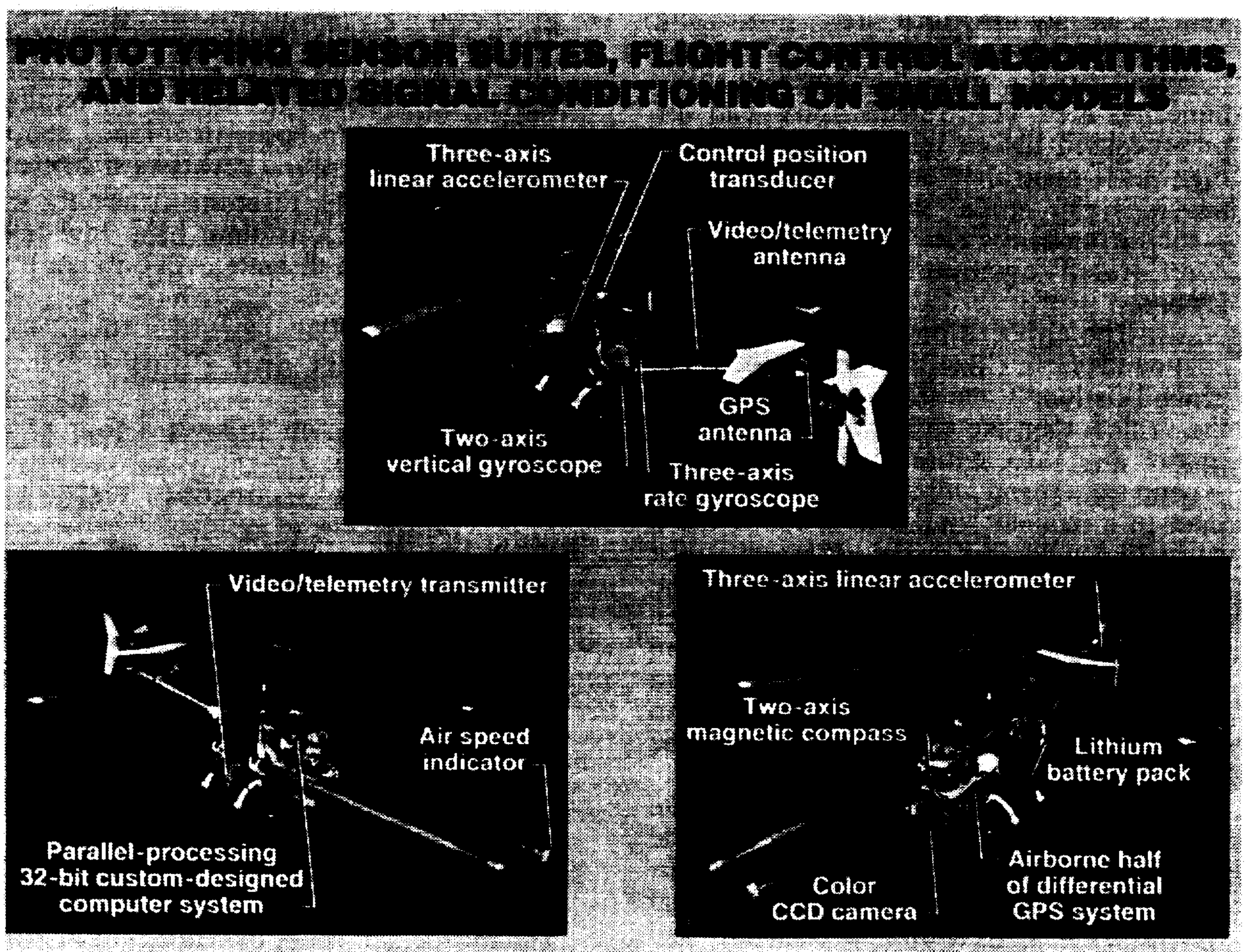

Figure 6
Proof Of Concept Development Helicopter

POC helicopters at various levels of flight control stability augmentation. Initial development flights for this study, from the ground station, have been taking place since January 94 with three axis rotational rate dampening. More advanced stability augmentation systems have been developed and will be progressively flight tested.

Design and Fabrication of a Research Model

The initial wind tunnel test of the FFRRV has been completed. 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 for the required stability.
3. Study the effects that forward flight has on the radiator used for engine cooling and ensure there is enough heat being dissipated by the radiator.

The results of this tunnel entry dictated small 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 power plant. A new, larger radiator has been installed and follow-on tests have indicated a solution is available.

Currently the drive train has been integrated and tuned. A dynamometer test verified engine power, carburetor settings, belt drive system and ignition settings. The main rotor and tail rotor drive train was broken in and tested by an electric motor. Integration of the rotary engine has been completed and initial testing done. Powered hover testing will be conducted this year. The vehicle will also enter NASA Langley's electronic 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.

Control System Implementation: The distinct tasks that this control system must perform have been logically broken down into separate modules, each with a specific objective (Figure 7). The resources necessary to achieve each distinct objective are assigned to the respective module. With this breakdown, parallel development of the separate systems is occurring and will culminate with the final integration and complete system testing.

The first helicopter to use the free flight controller, with AI techniques, is an unmanned UH-1H target drone for the U.S. Army. The Fuzzy Logic Adaptive Control - Helicopter (FLAC-H) exploits fuzzy logic in its flight control system to provide a robust solution to the control of the helicopter's dynamic, non-linear systems. Straight forward, common sense fuzzy rules governing helicopter flight are processed instead of complex mathematical models.[4]

An adaptive algorithm allows the FLAC-H to "learn" how to fly the helicopter, enabling the control system to adjust to varying helicopter configurations. The adaptive algorithm alters the fuzzy rules and their related sets to allow control of the new configuration, reducing the development costs associated with redoing the control system.

The FLAC-H hardware is designed around low-cost, off-the-shelf computers and sensors. The software is modular and exploits object-oriented techniques in an effort to reduce maintenance costs. This hardware and software design allows efficient reliable enhancements to be made. FLAC-H is comprised of three subsystems. Each subsystem has the responsibility of interfacing with one of the external systems. The subsystems are the Translator, the Sensor Processing Unit (SPU), and the Flight Control System (FCS). The FLAC-H system diagram, shown in Figure 7, shows the subsystems and their interface connections.

The Translator is on the ground and interfaces the FLAC-H with the ground pilot's station commands and processes digital sensor data from the SPU. The SPU interfaces with the sensor system and provides the FCS and Translator with reliable aircraft state information. The FCS interfaces with the actuator system by calculating and transmitting the proper signals to the actuators that control the flight of the aircraft. The FCS also has a self recovery mode in the event that communication with the ground control system is disrupted.

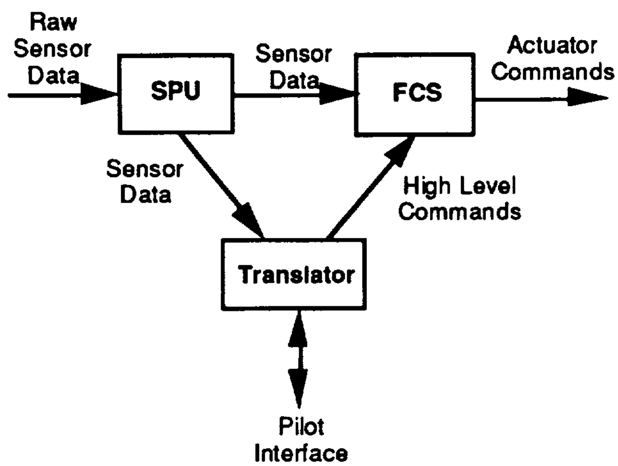

Figure 7
FLAC-H System Diagram

Spin Off Applications of FFRRV Development

Technology Applications: The ability of a helicopter to maneuver, hover, and go wherever it can fit into, makes it a very valuable tool for many uses. However, the ability to completely and accurately control the helicopter is crucial to the achievement of that capability. Many attempts have been made to use helicopter UAVs for surveillance, patrol, photography and payload delivery, without much success. Almost all of the failures can be attributed to the inability to properly command and control the vehicle. The greatest benefit the FFRRV program will have on the UAV community is to help solve these command and control challenges for helicopter UAVs. In addition to the control system research, the FFRRV program has development efforts in telepresence-telerobotic control, small light sensors, stabilized controls and helicopter UAV operations.[5]

Civil Mission Applications: The civil users that have indicated the most interest in the FFRRV program are disaster-law enforcement agencies. The requirements are for a completely stabilized platform that can survey an emergency situation, such as a leaking chemical tank car with video (Figure 8). Law enforcement could use the helicopter to safely survey situations like hijackings with hostages. Search and rescue operations could benefit from a vehicle that could quickly search remote difficult terrain. Part of the desired capability would be the ability to drop something like a first aid kit or cellular phone to someone in a remote location. Pollution enforcement agencies could use a helicopter with an air sampling instrument to make unannounced inspections of smoke stack plumes to check compliance with air quality regulations. In Japan, a few manufacturers are already producing robotic helicopters in the 100 to 150 pound gross weight range for crop spraying. A small helicopter would be easier and safer to operate around crop fields that are surrounded by power lines or trees.

Because it is not practical for operations personnel to expend large amounts of resources on training to fly these vehicles, they have to be very easy to operate. It is important that the stabilization and control systems be properly implemented for the practical application of robotic helicopters to the above missions.

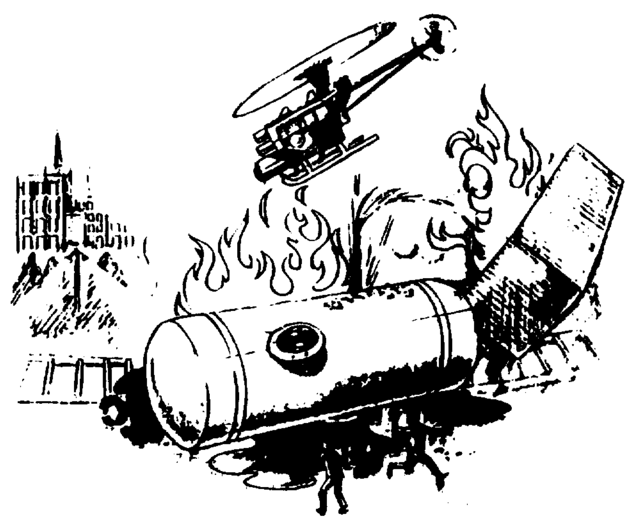

Figure 8
Survey Of Emergency Situation

Concluding Remarks

Relatively inexpensive rotor aerodynamic studies will be possible with hardware that can be taken out of the wind tunnel and placed on FFRRV for flight testing. This capability allows direct correlation between wind tunnel data and flight test data. While the program's primary goal is to develop a research tool, there are numerous spin off applications of the technologies that could be developed. The free flight program is strongly challenging the state of the art in most of the areas of robotic aircraft operations. Therefore, a high degree of multidiciplinary development is taking place to insure success.

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