Manned – Unmanned Teaming of UH-1 and Armed Vigilante VTOL UAV

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Abstract

The US Army's Applied Aviation Technology Directorate (AATD) has been experimenting with a VTOL UAV Testbed based on the Vigilante autonomous helicopter since July of 2001. The UAV system is used to explore manned-unmanned teaming between helicopters, weaponization concepts, and the integration of unmanned helicopters into the aviation infrastructure. The status of a recently completed test program is discussed herein. Significant achievements include regular operation of a tactical-sized VTOL UAV at an active Army airfield, complete (TCS Level 5) control of the UAV and payload from an airborne control station, and firing of Hydra 70 rockets from a VTOL UAV while under control of a UH-1 mothership.

A description of the UAV / UH-1 testbed system and payloads is provided. The scope and results of testing are discussed including; performance, reliability, and maintainability assessments of the UAV and Mission Equipment Package, airborne control of the UAV, weapons launching, and integration of the UAV into the aviation infrastructure at Felker Army Airfield (KFAF).

Table of Symbols

AFCS .... Automatic Flight Control System
AGL .... Above Ground Level
Alt .... Altitude
APKWS ...... Advanced Precision Kill Weapon System
ATC .... Air Traffic Control
AVO .... Air Vehicle Operator
C2 .... Command and Control
Demo'd .... Demonstrated
DoD .... Department of Defense
EO/IR .... Electro-optic / Infra-red
EP .... External Pilot
FAA .... Federal Aviation Administration
Ft/min .... feet per minute
FTS .... Flight Termination System
G .... Acceleration of Gravity
GPS .... Global Positioning System
Km .... Kilometer
Kt or Kts .... Knot or Knots
Lb or lbs .... pound or pounds
MCC .... Mission Control Computer
MEP .... Mission Equipment Package
MHz .... Mega-Hertz
Mm .... millimeters
MPO .... Mission Payload Operator
NOTAM .... Notice to Airmen
OGE .... Out of Ground Effect
Rx .... Receiver
Sec .... Second
TCS .... Tactical Control System
Tx .... Transmitter
UAV .... Unmanned Aerial Vehicle
VDC .... Volts Direct Current
VHF .... Very High Frequency
VTOL .... Vertical Takeoff and Landing

Introduction

The US Army Applied Aviation Technology Directorate (AATD) is exploring teaming of manned and unmanned aircraft to enhance war fighting capabilities. Controlling an armed UAV from a manned aircraft allows the human crew to remain at stand-off ranges from threats while reconnoitering, threatening, and / or attacking such threats.

This paper summarizes a series of flight tests that were done to extend the experience base for manned / unmanned teaming. AATD contracted Advanced Technologies Inc. (ATI) to equip a Vigilante VTOL UAV with a Wescam 12DS-200 EO/IR sensor and a HURL-II four shot 2.75-inch rocket launcher, develope the ability to control it from an airborne UH-1 utility helicopter, and demonstrate the ability to control the UAV flight profile and weapons system in a representative armed scout mission.

These tests lay the foundation for subsequent demonstrations incorporating recently developed Advanced Precision Kill Weapon System (APKWS) laser-guided 2.75-inch rockets and an EO/IR/designator sensor, thereby enabling the Army to use lightweight UAVs to effectively destroy soft targets such as personnel, unarmored vehicles, and buildings. Testing also validated the UH-1 / Vigilante system as a flexible asset for further exploration of teaming concepts.

Description of Experimental System

Test Facilities

Flight testing took place at two locations; Felker Army Airfield (KFAF) at Ft. Eustis, VA and Yuma Proving Grounds, AZ. Vigilante was the first UAV to fly at KFAF, so many operating procedures had to be developed in parallel with the test hardware. All flights were done in accordance with a Certificate of Authorization from the FAA and the Flight Release from the US Army Applied Aviation Technology Directorate (AATD) Flight Safety Review Board. Operational times and envelopes were restricted to ensure safety, the UAV flight area being closed to other aircraft by FAA NOTAM and by the Air Traffic Control (ATC) tower. The operator stations and antenna suite were housed in a trailer located near the flight field during ground controlled tests, and were mounted in the UH-1 for airborne controlled tests. Figure 1 shows the range limits used for flights at KFAF.

Flights at YPG were done on a 15 x 11 km flight range with similar restrictions imposed. No FAA involvement was required due to YPG control of the restricted airspace. A ground-based Mission Monitoring Station and Flight Termination Transmitter was employed, allowing engineers and range safety personnel to watch a copy of the Air Vehicle Operator and Mission Payload Operator Station displays. An elevated 'Hover Stand' was also employed for initial firing tests with the UAV tied down for safety.

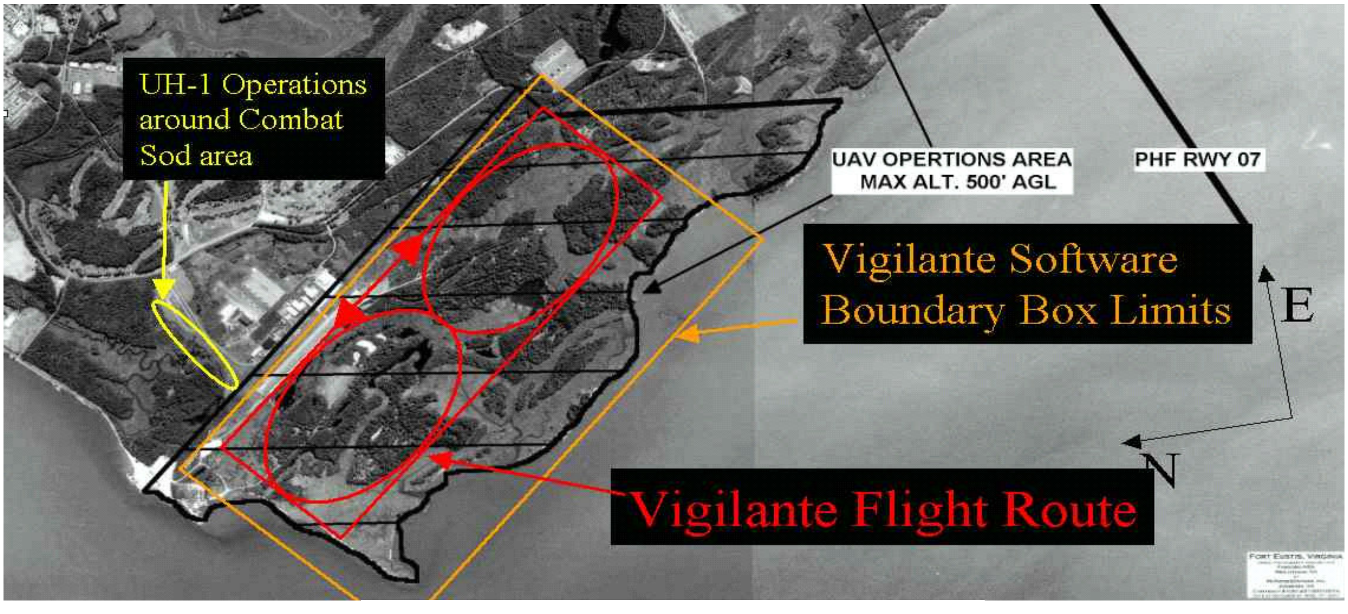

Figure 1: Flight Area at Fort Eustis, VA

Vigilante / UH-1 Testbed System

History of the Vigilante UAV: The Vigilante™ UAV was initially developed by Advanced Technologies Inc. (ATI) and Science Applications International Corp. (SAIC) in 1999 for sale to US and international customers. ATI provides the air vehicle platform, which is derived from the commercially available UltraSport 496[1] helicopter kit. SAIC provides the autonomous flight control system and air vehicle control station which are derived from the UH-1 HOVAC and the Global Hawk UAV programs respectively. Several military customers have since refined the system to meet their requirements, and the system used in these tests represents the most advanced configuration.

Vigilante Air Vehicle: Vigilante is a 1100 lb maximum gross weight, autonomous helicopter of typical penny-farthing main / tail rotor configuration. A turbo-charged, four-stroke, gasoline fueled engine provides power to the rotors through an engaging/disengaging multi-V belt drive and a two-stage reduction gearbox. The 23 foot diameter teetering main rotor has two blades which fold aft to reduce spotting space. The tail boom and main rotor blades can be easily removed, providing a small package for shipping. A composite fuselage houses the fuel cell, automatic flight control system, and any mission equipment. Hard points on the belly of the fuselage retain external payloads. Tall skid-type alighting gear provide ground clearance for external loads, and incorporate removable ground handling wheels. Duplex datalinks receive command and control messages from the Air Vehicle Operator Station, and downlinks system health and status messages. The Autonomous Flight Control System (AFCS) stabilizes all flight control axes and handles C2 message traffic to and from the datalinks. Flight control modes include GPS waypoint navigation, flight vector control, auto takeoff / landing, loss-of-link return home, and auto-rotation. Power for the AFCS and payloads is provided by a 100 Amp, 28VDC electrical system.

Mission Equipment Package: The Mission Equipment Package (MEP) is shown in Figures 2 and 3. It consists of four main elements;

- L3-Comm Wescam 12DS-200[2] Electro-optical / Infrared (EO/IR) sensor
- Hydra Universal Rocket Launcher-Intelligent Integration (HURL-II[3]) 4-shot launcher
- Advanced Precision Kill Weapons System (APKWS) 70mm laser guided rockets. Limited numbers of pre-production APKWS rockets were available during these tests, so unguided rockets were substituted.
- Vigilante Mission Control Computer (MCC) which is custom built and uses MIL-STD-1553, Ethernet, or serial commands directs the other payload elements.

Figure 2: MEP External Stores

Figure 3: MEP Rack with MCC

Air Vehicle Operator Station: The Air Vehicle Operator Station is used for primary command and control of the UAV. It records telemetry and provides a visual display of operator commands, aircraft health and status, and navigational data. It is also used to generate mission flight plans and for operator training using the embedded Vigilante Flight Simulator. Air vehicle and payload commands are sent to the UAV via the Command and Control (C2) datalinks. AVO Station hardware consists of a rugged container, Uninteruptable Power Supply, processor / display / keyboard / trackball, Duplexed C2 digital datalinks operating at 380 and 2400 MHz, an analog video receiver, a joystick console, a weather station display, and software.

The AVO Station is configured in unique fashions for ground-based control and airborne control (fig 4) missions due to crashworthiness requirements of the UH-1. For the airborne application the MPO and AVO displays are swapped, allowing the loose peripherals such as the joystick console and weather station display to be rack mounted for security. It is positioned adjacent to the cargo door of the UH-1 to provide the AVO maximum visibility.

Mission Payload Operator station: The Mission Payload Operator (MPO) Station is used for control of the rocket launcher and EO/IR sensor, and consists of the EO/IR display screen and hand controller. A graphic user interface allows initialization and control of the computerized HURL launcher. Payload commands are sent through the AVO Station and up the C2 datalinks to the UAV. A Video Receiver mounted in the AVO Station provides signal for the EO/IR display. The hand controller plugs into the AVO Station for power and signals. The HURL user interface is displayed in a window on the AVO Station display, and the menu picks are done via the trackball on the AVO Station.

The MPO Station also has unique configurations for ground-based control and airborne control missions due to crashworthiness requirements of the UH-1. For the airborne application the MPO and AVO displays are swapped, allowing the loose peripherals to be rack mounted for security and positioned adjacent to the cargo door of the UH-1. The MPO will monitor video imagery on the display mounted in the AVO station transport case.

Command and Control Datalinks: Command and control (C2) of the UAV and MEP is accomplished via redundant spread-spectrum frequency-agile digital datalinks. A pre-programmed lost-link routine is loaded into the UAV autopilot system prior to each flight, and will automatically fly the UAV through a re-acquisition profile and automatic landing if both C2 links are lost for a programmed period of time. Control of the UAV can be reinitiated if the C2 link is reestablished, but only by express command. Flight termination C2 and video telemetry are carried on other distinct Radio Frequency (RF) links.

Figure 4: AVO Station Configurations- Ground Based left, Airborne right

Control station antennas are configured differently for the ground-based and airborne control tests. See Fig. 5. Ground-based control uses an extendable mast with the angle reflector antennas oriented toward the area of flight operations. For airborne operations the large whip antenna of the 380 MHz link is replaced with an aerodynamic blade antenna. Directionality of the angle reflector antennas forced the UH-1 to keep the UAV between the 12:00 and 3:00 positions when flying in formation.

Ground Based Control

Airborne Control

Figure 5: C2 Antenna Configurations

Airborne Control Mothership

The testbed UH-1 helicopter[4] was fleet representative with the exception of the Vigilante UAV control station and antenna suite being installed. The Vigilante Control Station installation includes the Vigilante AVO and MPO Stations, and an antenna suite installed on a standard UH-1 external stores station mounted to the starboard M60 machine gun mounts. See figure 6. UAV and UH-1 crew voice communications onboard the UH-1 was via intercomm. Communications with the ground crew and ATC were via VHF radio. An External Pilot could plug into the AVO Station to assist with takeoffs and landings if required and when the UH-1 was on the ground.

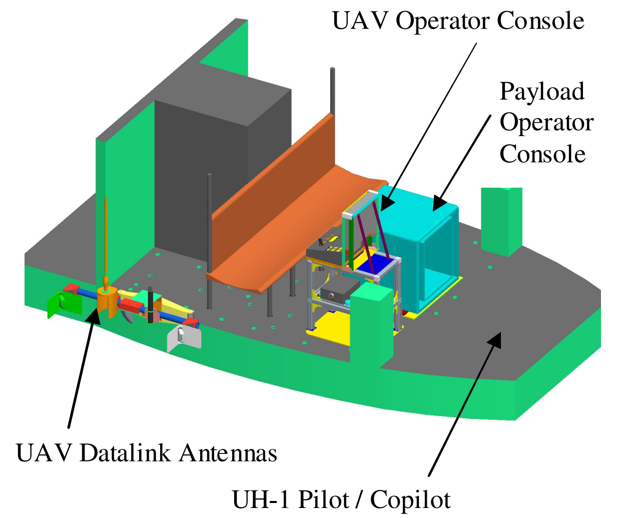

Fig. 6: Control Station Arrangement in UH-1

Mission Monitoring Station

A ground-based Mission Monitor Station allowed test and range safety personnel to view live streaming flight data and video from the Vigilante. Telemetry was relayed from the AVO Station aboard the UH-1 via wireless modem to a laptop computer running the AVO Station software. A large screen monitor displayed the data. A separate receiver picked up the video signal directly from the UAV, and the imagery was displayed on a monitor and recorded.

Flight Termination system

The UAV was not a certified aircraft whose safety had been ensured though an FAA or DOD qualification process. Therefore, a highly reliable Flight Termination System (FTS) was developed to prevent uncontrolled flight out of bounds. The FTS consists of a Transmitter, a frequency agile transceiver, and a UAV-mounted receiver. A Range Safety Officer observed each flight on the Mission Monitoring Station and could activate the FTS, sending a coded digital message to the receiver which then grounds the engine ignitions, killing the engine and causing the UAV to enter autorotation to the ground. Safety features of the system include battery backup on both Rx and Tx, link monitoring status displayed on the Air Vehicle Operator Display, shielded activation switch, and auto-terminate capability. The auto-terminate functionality activates if both the UAV C2 datalinks and the FTS datalink lose communications for a preset period of time (~3 seconds). This is done to ensure positive control over the UAVs flight path at all times.

Crew

A listing and functions of the critical test crew are summarized in Table 1 below.

Table 1: Crew Listing and Functionality

Position	Function	Onboard UH-1?
Air Vehicle Operator	Control UAV launch, flight path, recovery. Monitor and respond to UAV health. Create waypoint navigation and emergency recovery plans.	During airborne control only
Mission Payload Operator	Control operation of EO/IR sensor and Weapons, callout UAV operational checklists	During airborne control only
UH-1 Pilot	Fly UH-1 'mother ship' per test profile	Yes
UH-1 Copilot	Assist UH-1 pilot, watch UAV	Yes
External Pilot	Launch and recover UAV if auto takeoff / land not possible	No
Air Vehicle Technician	Spot, secure, fuel, inspect, start, shutdown UAV	No
Weapons Handler	Load, unload rockets	No

Description of Testing

Scope of Tests

Basic stability and control testing of the Vigilante without external stores had been completed prior to the subject weaponization program. Subsequent testing encompassed 10.7 flight hours over 21 flights and occurred in the following phases:

- **Blast Effects Testing** – Nine inert-warhead rockets were fired from a ground-based mockup representative of the Vigilante fuselage and external stores arrangement. Results validated loads and blast effects of a launch. Test were done at Yuma Proving Grounds, AZ (YPG) in late August 2003
- **Tie-down Testing** – Operation of the UAV, MEP, and Control Stations with the UAV tied down on a hover pad. Testing verified functionality, calibration, structural response, and operating procedures of the integrated system. Testing took place at ATI's Newport News, VA facility during May 2004.
- **Vigilante Baseline Flight Testing (VBFT)** – Ground-based control of the Vigilante UAV demonstrating upgrades to the Vigilante, correct operation of MEP, and safe and correct UAV operating procedures. Initial flights were done without the MEP installed, then with mass models of the MEP, then with functional MEP onboard. 4.7 hours during 12 UAV flights. Flight tests took place at Felker Army Airfield, Ft. Eustis, VA in June 2004.
- **Vigilante Under Airborne Control (VUAC)** – Demonstrated capability to safely operate the Vigilante and perform its intended missions from a UH-1 helicopter in flight. The Vigilante and its payload were controlled from takeoff to landing from two operator stations mounted in the cabin of the UH-1. 1.6 hours during 3 UAV flights. Flight tests took place at Felker Army Airfield, Ft. Eustis, VA in late August 2004.
- **Hover Tower Rocket Launches-** Evaluated blast and exhaust ingestion effects during four rocket launches under simulated hover conditions. UAV was tied down on a tall tower with rotor thrust at 1G levels to simulate out-of-ground-effect (OGE) hovering flight. Controlled from AVO station on the ground. Tests took place at Yuma Proving Grounds, AZ (YPG) in early December 2004.
- **Vigilante Under Airborne Control with Rocket Launches (VUACRL)** – Repeat VUAC tests with live rocket firings. Three simulated and four live shots were taken in flight while the UAV was being controlled from the UH-1. 4 1/2 flight hours during six UAV flights. Tests took place at Yuma Proving Grounds, AZ (YPG) in early December 2004.

Test Results

Integration into Airfield Operations

The airfield could be closed for UAV operations twice daily for 90 minutes periods. Test flights were scheduled 24 hours in advance to allow time to post FAA NOTAMs announcing UAV Operations. Pre-flight activities were accomplished prior to the beginning of the flight windows to minimize time the airfield was closed. UAV Operators maintained communication with the control tower in typical aviation fashion on normal control frequencies. Operations were flexible enough to accommodate occasional priority air traffic during test flights, the UAV landing while traffic used the field. Requests for the UAV to remain in the traffic pattern during such interruptions were denied by the Flight Safety Board due to a perceived difficulty in tracking and avoiding the small UAV during emergencies situations.

Performance of UAV

The performance of the UAV was not measured other than to confirm ability to support MEP demonstration. Flight performance was adequate to complete the test program. However, marginal hover performance was noted due to the additional weight and electrical power draw from the MEP. The envelope protection logic in the AFCS minimized the degradation of handling qualities by 'milking the collective'. Transitions to and from hover were flown in the fashion typical of heavily loaded helicopters. A summary of the flight envelope is provided in Table 2. All available control modes where demonstrated except for the Autorotation logic which was tested in simulation but deemed too risky for flight demonstrations, and the Lost Link Recovery mode which has been validated in previous flight testing. The EO/IR sensor was used to help align the UAV on approaches, a task which was otherwise difficult due to the large scale of the navigation map. Table 3 summarizes the control modes demonstrated. Figure 7 illustrates the good performance of the waypoint navigation.

Table 2: Flight Envelope of Tests

Parameter	Current Tests	Best Ever
Airspeed	50 kts	70 kts
Altitude	500 ft AGL airspace limited	500 ft AGL airspace limited
Rate of Climb	500 ft/min	500 ft/min
Takeoff Weight	952 lbs	1050 lbs
Payload Weight	215 lbs	215 lbs
Range	72* n. mi. w/ MEP + 1 rocket	100 n.mi. w/ 210 lb payload
Endurance	1.7* hrs w/ MEP + 1 rocket	2.5 hrs w/ 210 lb payload
Mission Availability	20 of 24 scheduled flights = 83%	135 flights to date
Flight Time	10.7 hours	60 hours

* = Extrapolated from demonstrated fuel consumption and available capacity

Table 3: Control Modes and Features

Control Mode or Function	External Pilot	Internal Pilot	Automatic	Comment
Tiedown Runs		X		Special Mode
Attitude Control	X			For loss of Autoland or GPS
Flight Vector Control		X		
Takeoff / Landing	X	X	X	Auto is default, 15kt winds max
Hover	X	X	X	Auto locks on GPS coordinate, 20 kt fwd, 15 kt sideward, 5 kt aft
Cruise	X	X	X	50 kts max, climb / descent, coordinated turns, ground track following
Waypoint Navigation			X	Multiple plans per flight
Lost Link Recovery			X	Previously Demo'd
Autorotation				Simulator Only
Envelope Protection	X	X	X	Limits AFCS responses prevent control saturation
Rocket Firing		X	X	Limits AFCS responses prevent control saturation
EO/IR Sensor Control		X	X	Limits AFCS responses prevent control saturation

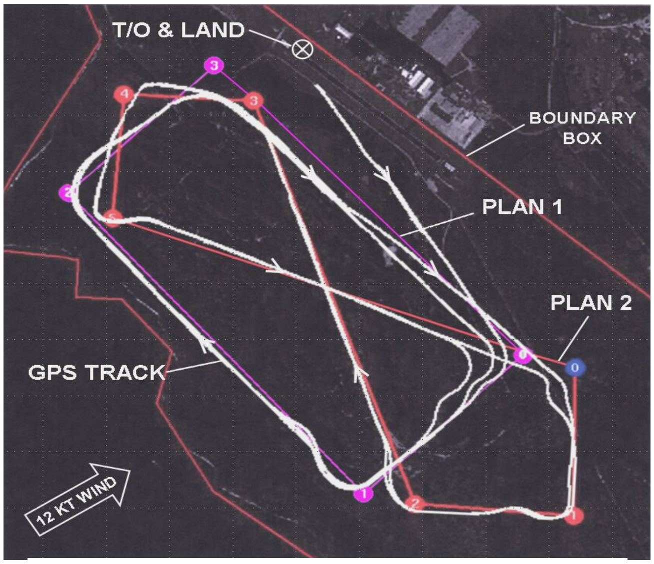

Fig. 7: Waypoint Navigation Performance

Performance of MEP

The performance of the MEP was not quantified other than to insure safe rocket firings. Identifying target areas and ensuring proper response of the rocket launcher were paramount. Video and IR imagery were stable and clear, particularly in the airborne control mode since both receiver and transmitter antennas were well out of ground effects.

Two significant areas for improvement were identified. The EO/IR sensor was not equipped with an optionally available auto-tracker which would greatly simplify tracking and targeting. The HURL interface software included a 'launch constraint checker' safety feature to verify vehicle location, heading, and attitude were within predefined limits prior to missile launch. This feature worked well, but constraints could not be updated in flight, reducing flexibility if retargeting was desired.

Airborne Control

Control of the UAV and MEP from the UH-1 mother ship was carefully planned and proved to be trouble free for these initial flights, believed to be the first of their kind. UAV takeoffs and landings were done with the UH-1 idling on the ground. This allowed the External Pilot to plug into the Control Station in case he was needed, it provided the most stable platform and frame of reference for the AVO, and it allowed the use of simple ground-wind sensor. These features could be modified such that the mother ship can launch and recover the UAV while airborne or on the ground.

A typical flight profile would start with the UH-1 idling at a safe stand-off distance from and oriented toward where the UAV had been spotted for takeoff. The External Pilot would plug into the Control Station while the UAV startup checklist was done. Once started, the Air Vehicle technician would leave the UAV and the rotor was engaged via remote command. The AVO would command an auto-takeoff, begin a climbout using vector control, then transition into a waypoint holding plan around the traffic pattern. The EP would then disconnect from the UH-1 and depart, the UH-1 was brought up to flight speed and climbed to form up with the UAV. The AVO called out all maneuvers and upcoming waypoints so the UH-1 could maintain formation 500ft above and 1500ft behind the UAV. This distance was later reduced to 500ft behind so the UH-1 could better see the UAV rotor disk and anticipate maneuvers, just as is done in other helicopter multi-ship formations. The AVO would then command another waypoint plan or use vector control to exit the loiter and depart for the test mission.

Landing procedure was the reverse of takeoff. The UAV was put into a waypoint loiter pattern, the UH-1 landed in the same spot and orientation as during takeoff, and the EP would approach and hook up to the Control Station. The AVO would change to vector control on the downwind leg and shoot an approach to hover over the end of the runway. The MPO would point the EO/IR sensor to help the AVO line up on the runway centerline and also taxi over the touchdown point. The AVO would hover taxi to the touchdown point and execute an auto-landing. The UAV would be shutdown remotely using the Flight Termination System to confirm its functionality.

Flying the UH-1 in loose formation with the UAV (ref Fig. 8) was not difficult. No UAV control problems due to the vibrations in the mothership were noted, since all command inputs are executed by the stabilized autopilot system rather than direct manipulation of the control surfaces. Several desirable modifications to the man-machine interface were identified however, including the need for an 'own ship' icon showing the location of the mothership and the ability to toggle the MPO and AVO displays between the two stations. The former enhancement would allow the crew to have better situational awareness once the UAV was out of visual contact. The latter would allow cross checking between AVO and MPO displays while the operators are constrained by shoulder harnesses.

Fig. 8: Formation Flight with UAV under Control of the UH-1

A Remote Monitoring Station was developed to allow ground-based observers to track the mission. Telemetry from the UAV was retransmitted by the AVO station onboard the UH-1 to a laptop computer running the AVO station software, allowing the observers to see a real-time copy of the airborne AVO display. An additional video receiver was used to capture the imagery broadcast from the UAV. The imagery was displayed on a dedicated monitor screen and was also recorded.

Rocket Shots

A series of rockets were fired according to the Table 4. Firing from a 35 foot tall stand (see Fig. 9) with the UAV in out-of-ground-effect hover conditions confirmed the functionality of the weapons system and showed no ill effects to the rotors or engine. Data from earlier Blast Effects testing were used in the Vigilante flight simulator to investigate the dynamic response of the UAV and necessity of modifying the AFCS. Simulation results were favorable enough that no changes to the AFCS were made.

Firing constraints were entered by the MPO prior to each shot to ensure firing could only occur in specified areas under specified conditions. Constraints included UAV position, attitude, speed, and altitude. If constraints were not met at the time of the launch command, the MCC would prevent the command from being passed to the launcher and the shot was aborted. In-flight shots were taken both while in waypoint flight and under vector command. See Figure 10. The accuracy of the shots was not measured since these tests were intended to validate safe separation of rockets. Highly accurate laser guided APKWS rockets would be used in any operational sense.

Table 4: Shot Record

Shot #	Airspeed	Altitude	Comment
1	O*	35 ft *	Rotor Stationary
2	O*	35 ft *	0.7 G Lift
3	O*	35 ft *	1.0 G Lift
4	O*	35 ft *	1.1 G Lift
5	40 kts	400 ft AGL	1st in-flight shot from Vigilante under airborne control
6	35 kts	400 ft AGL	
7	30 kts	400 ft AGL	
8	25 kts	400 ft AGL	Under flight vector control

* = UAV tied down on stand

Fig. 9: Hover Firing Test Stand

Figure 10: Vigilante Firing Hydra-70 Rocket

Vehicle response to launches was mild, with most stability and control parameters returning to pre-launch trim values within one cycle. Roll response was the most dramatic as the UAV reacted to the instantaneous loss of the 24 lb rocket. 10º of left roll would damp out in three cycles over 25 seconds. Coupling with roll would also induce 5º of nose down pitch. Heading changes of 7º were seen in response to blast pressures on the face of the launcher. Trim was reacquired after 15 seconds of non-periodic yawing. All controls had significant margin throughout the firing events. The pitot-static system experienced momentary pressure pulses which were filtered and caused no reaction by the AFCS. See figure 11.

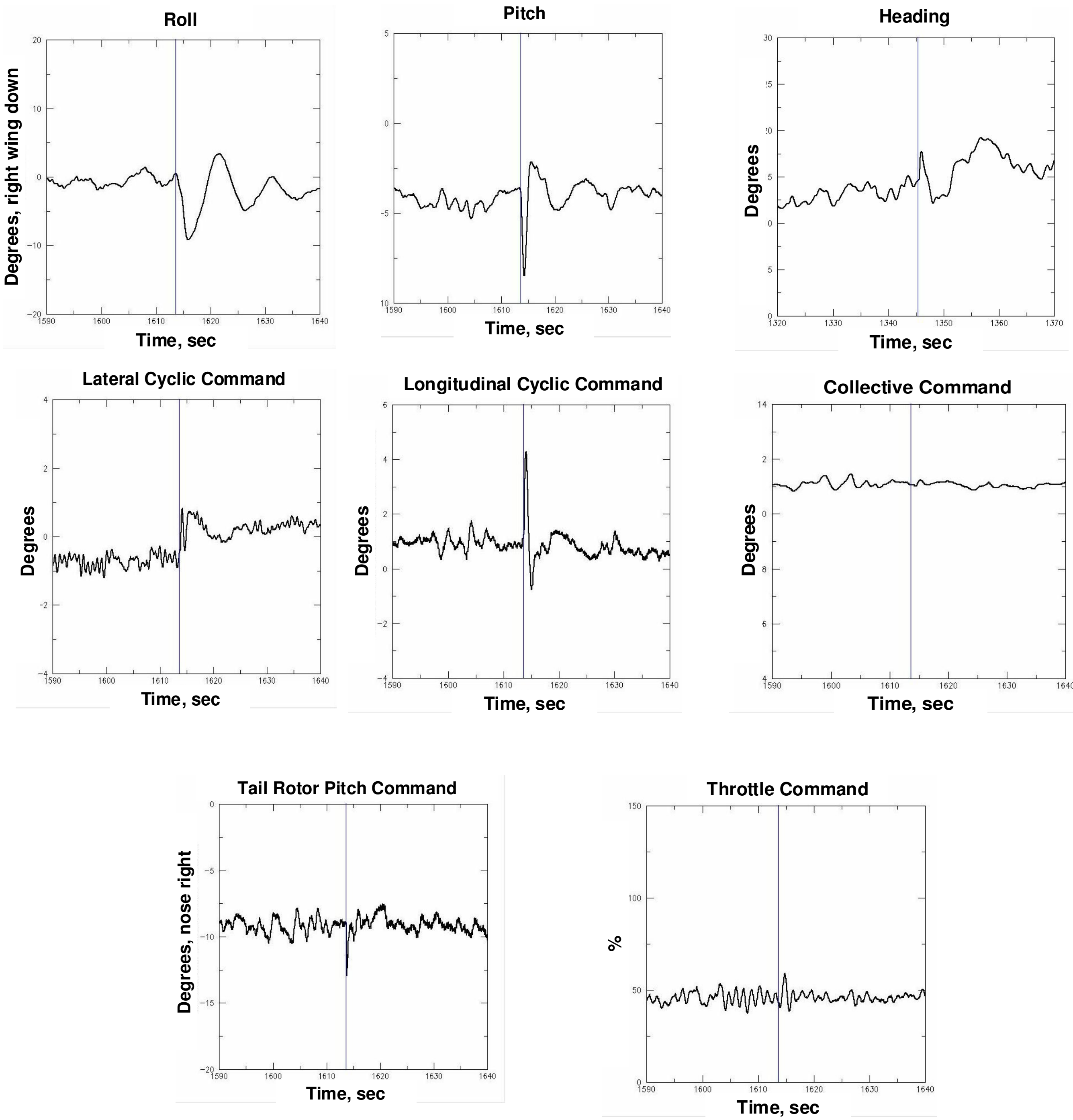

Figure 11: UAV and Control Responses to Rocket Launch

Conclusions

Recently completed flight tests have demonstrated that a two person team can exercise TCS Level 5 control of an armed Vigilante VTOL UAV and it's Mission Equipment Payload from takeoff to landing from an airborne UH-1 utility helicopter. The progress of the mission and health of the UAV can be remotely monitored using a laptop computer running a copy of the Control Station software fed by telemetry relayed from the airborne controller. Sensor imagery from the UAV can also be monitored in real time to provide complete situational awareness to an observer. The successful integration of the Wescam 12DS-200 EO/IR sensor and the firing of unguided Hydra 70 rockets from the Vigilante has paved the way for integrating APKWS laser-guided rockets and Wescam MX-12 unit having a laser range finder / designator. The Army will then have a VTOL UAV that can locate, target, attack, and destroy unarmored 'soft' targets while working under the control of an airborne master operating outside of harms way.

The Vigilante / UH-1 helicopter team developed by the Army AATD has been shown to be a flexible and low cost asset for exploring new concepts of manned / unmanned operations which will enhance war fighting capabilities and reduce risk to Army flight crews.

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