

Using Fly-By-Wire Technology in Future Models of the UH-60 and other Rotary Wing Aircraft

Courtney K. Solem¹

Oregon State University, Corvallis, OR 97331

Oregon NASA Space Grant Consortium, Corvallis, OR 97331

NASA Ames Research Center, Moffett Field, CA, 94035

Abstract

Several fixed-winged airplanes have successfully used fly-by-wire (FBW) technology for the last 40 years. This technology is now beginning to be incorporated into rotary wing aircraft. By using FBW technology, manufacturers are expecting to improve upon the weight, maintenance time and costs, handling and reliability of the aircraft. Before mass production of this new system begins in new models such as the UH-60MU, testing must be conducted to insure the safety of this technology as well as to reassure others it will be worth the time and money to make such a dramatic change to a perfectly functional machine. The RASCAL JUH-60A has been modified for these purposes. This Black Hawk helicopter has already been equipped with the FBW technology and can be configured as a near perfect representation of the UH-60MU. Because both machines have very similar qualities, the data collected from the RASCAL can be used to make future decisions about the UH-60MU. The U.S. Army AFDD Flight Project Office oversees all the design modifications for every hardware system used in the RASCAL aircraft. This project deals with specific designs and analyses of unique RASCAL aircraft subsystems and their modifications to conduct flight mechanics research.

Nomenclature

<i>AFDD</i>	=	Aeroflightdynamics Directorate
<i>AIS</i>	=	Active Inceptor System
<i>CAAS</i>	=	Common Architecture Avionics System
<i>CONDUIT</i>	=	CONtrol Designers Unified InTerface
<i>DARPA</i>	=	U.S. Defense Advanced Research Projects Agency
<i>EGI</i>	=	Embedded GPS/INS
<i>EP</i>	=	Evaluation Pilot
<i>FBW</i>	=	Fly-By-Wire
<i>FCC</i>	=	Flight Control Computer
<i>FCS</i>	=	Flight Control System
<i>HQR</i>	=	Handling Quality Rating
<i>ICM</i>	=	Inceptor Control Module
<i>KIAS</i>	=	Knots Indicated Air Speed
<i>MUCLAWS</i>	=	UH-60M Upgrade Control Laws
<i>RASCAL</i>	=	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
<i>RFCS</i>	=	Research Flight Control System
<i>SP</i>	=	Safety Pilot
<i>UHPO</i>	=	Utility Helicopter Project Office
<i>VMS</i>	=	Vertical Motion Simulator
<i>VTOL</i>	=	Vertical Take Off and Landing

¹ Undergraduate Intern, Aeromechanics Branch, U.S. Army's Aeroflightdynamics Directorate Flight Projects Office, Ames Research Center, Oregon State University.

Introduction

Rotary wing aircraft technology is about 50 years behind fixed wing aircraft. Currently research is being conducted to help reduce this gap in technology. A primary focus in this research is towards incorporating a fly-by-wire (FBW) flight control system (FCS) into future models of rotary wing aircraft. This type of technology has been used for several years in fixed wing aircraft and in aircraft capable of vertical takeoff and landing (VTOL) such as the V-22 Osprey.

The most recent model of the Black Hawk Family is the UH-60MU. Before the Army buys a fleet of this Black Hawk model, more testing and research must be completed to insure not only its safety but the necessity of having such an aircraft in their fleet. In this report the history of rotorcraft and FBW will be given. Following this the UH-60M Upgrade will be discussed as well as how the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) will help researchers bring the FBW technology into the UH-60MU and to any future rotorcraft models.

I. History of Rotorcraft

In the early 1500s the first attempts of flight were made.

At the end of the 19th century the combustion engine was available to the public, launching the race for vertical flight [1]. In 1906 the Bréguet brothers began experimenting with airfoil shapes alongside their professor, Charles Richet. In 1907 the team constructed the Bréguet-Richet Gyroplane No. 1, one of the first devices capable of nearly hovering. At this stage of development, there was no way to control the machine once in the air.

Igor Sikorsky made his first attempt at rotorcraft in 1909 in Russia with the S-1. As seen below in Figure 2, this rotorcraft had a frame made out of wood and had dual coaxial rotors. Unfortunately the strongest engine available was not powerful enough to carry its own weight.

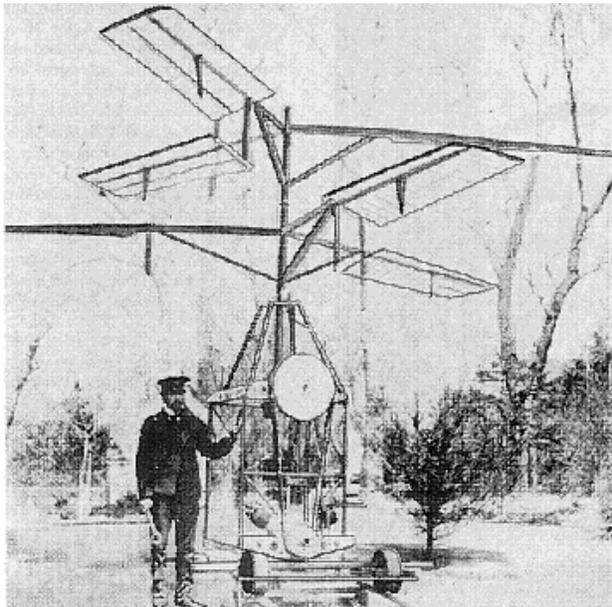


Figure 2. Igor Sikorsky with the S-1, his first rotorcraft [3].



Figure 1. Autogyro built by Pitcairn in the United States under the license of Cierva [2].

The S-2 was built the next year with an airframe which weighed 50lbs less than the previous model. Sikorsky was able to get this aircraft off the ground but it shook violently. The vibrations had proven to be too much for the weak wooden structure. With this Sikorsky took a break from rotorcraft, picking it back up in the United States in the 1930s.

As engines improved, hovering capabilities increased. However there was still the problem of controlling these machines once in the air. In 1912, Boris Yuriev built the first rotorcraft which resembled today's helicopters. Yuriev was the first inventor to use a tail rotor to stabilize the rotorcraft.

The first rotorcraft to fly was an autogyro built by Juan de la Cierva in 1920 in Spain [4]. The autogyro is very similar to a helicopter. The difference is its lack of ability to hover in place. This rotorcraft would simply float down as if it was being held by a parachute. When Cierva presented his invention in France he shut the engine off and simply floated down to Earth in front of his audience of several thousand people.

Becoming widely known, Cierva had autogyros being built under his license in France, Germany, Russia, Japan and the United States. [2]

II. Fly-By-Wire

A. History of Fly-By-Wire

The first flight test of the FBW technology was completed on May 25, 1972 at the Flight Research Center, Edwards, CA, now known as the Dryden Flight Research Center [5]. The plane used for this test was a modified Vought F-8 Crusader, now on display at Dryden and can be seen in Figure 3. This research had the support of Neil Armstrong after the Apollo 11 Mission. He told researchers his knowledge of electronic control systems was available to them if needed for the development of FBW. In fact, the first FBW system used was an “off the shelf back-up, Apollo digital flight control computer (FCC)” [6]. This system also included the inertial sensing unit. This unit is what takes the pilots input and transfers it to the actuators in the F-8 control systems.



Figure 3. The modified Vought F-8 Crusader used for NASA’s Fly-By-Wire research in 1972 through 1985 [7].

Research on the Crusader continued for 13 years and completed 210 flights. Since this research was completed, FBW has been incorporated into several fixed wing aircraft such as the Boeing 777. This technology has also been used in VTOL aircraft. VTOL aircraft were the first rotorcraft to have a FBW FCS. The

development of this machine came from the realization during a failed hostage rescue mission that the military needed an aircraft which could take off and land vertically as well as have the capability to hold several people and travel at high speeds. Bell Helicopter and Boeing Helicopter were contracted to complete such a feat after submitting a proposal of a model which greatly resembled the Bell XV-15 on April 26th, 1983. [8]



Figure 4. Bell XV-15(Top) [9]. BellBoeing MV-22 (Bottom)[10].

The U.S. Army is now making an effort to bring the FBW technology into their aircraft, starting with the UH-60M Upgrade. Only two of these Black Hawks have been made while the Army focuses its resources on other aircraft. The Army has been hesitant to buy a fleet of this Black Hawk model for a few reasons. The most important is due to testing on the RASCAL to reduce the risk of the system, which will be further explained later in the report.

B. Benefits of Fly-By-Wire

There are many benefits to incorporating the FBW technology into rotorcraft. This system lowers the work load put on the pilot. This is because the flight control computers (FCC) will be making flight decisions which will help in several situations, including hovering and maintaining stability. If a pilot makes an incorrect decision during the flight, the FCC will correct it. The system in many fixed wing aircraft has proven to save many lives just because of this one aspect. FBW systems will remove about 484 lbs of mechanical systems which translates to about 372 parts which will be replaced by wiring [11]. This means the aircraft will either be more fuel efficient or be able to carry more cargo. Also, maintenance will decrease greatly. There will be fewer parts which will need tuning up between flights or replacement due to fatigue. One of the greatest benefits of this system is its ability to integrate new systems in the future.

There is one small disadvantage to switching to a FBW system, the immediate costs. As with most things, dramatically changing the FCS can be pretty expensive. Most of the expense comes from the research and testing of the new system before it is even incorporated into the design. However, spending the money on this now could save the government money in the future in factors such as maintenance and fuel.

C. Misperceptions of Fly-By-Wire



Figure 5. UH-60M Upgrade [11].

There are many concerns about the FCC making decisions during flight. Some worry it will make a fatal decision and the pilot will not be able to correct it if needed. It has been observed that the pilot and the computer will “fight” each other. There have been instances of the pilot being more worried about pushing buttons and such to get the computer to do what they wanted rather than focus on actually flying the aircraft. This can be due to the pilot not being used to the new system. Once it has been in place for a little while pilots will become used to using the new system.

Some worry about the FCS failing during flight and those inside being completely helpless. This is why there are three FCCs on board the aircraft. If one fails, the other two will take over. During flight the FCC’s monitor each other. If one starts giving

different “answers” the other two will bypass the faulty system and allow it to reboot [12].

Many veteran pilots worry about the lack of mechanical feedback pilots receive from the aircraft itself. Due to the mechanical linkages, pilots can feel strong vibrations in the controls. This would help them gauge how the aircraft was reacting to their controls. Because the FBW FCS removes these mechanical linkages, this vibration is lost. To help make up for this, force-feedback motors have been incorporated into the Black Hawk’s controls. This will give the pilot the same feel he/she would have with the mechanical FCS. Research on this topic is currently being conducted in the Vertical Motion Simulator at Ames Research Center in Moffett Field, CA. [13]

III. UH-60M Upgrade

The UH-60MU is the latest model in development for the Black Hawk family. This is the United States Army’s first helicopter fitted with the FBW FCS with promise of being successful. The Comanche was the U.S. Army’s first rotorcraft with FBW technology but was canceled before put into production [11]. Only two UH-60MUs have been made as of



Figure 6. UH-60MU [14].

today. Sikorsky Aircraft and the U.S. Army has been working together to develop the upgrade for the UH-60M. This new flight control system (FCS) will keep the conventional controls of a UH-60 but will have 3 flight control computers (FCC) [15]. The idea behind the redundant FCC is to protect the system in case one fails during flight. If one FCC begins to compute incorrectly the other two systems will realize this and shut it down. The correct signals from the FCC’s will send signals to the main rotor servo actuator and the tail rotor actuator. These signals are what drive the actuators rather than mechanical linkages. The U.S. Army is currently putting their resources towards other aircrafts while research on the UH-60MU continues on the RASCAL. The purpose of this research is to reduce risk in the new system as well as to reassure the U.S. Army of the worth of the addition of this new UH-60 to their fleet.

IV. RASCAL



Figure 7. Rotorcraft Aircrew Systems Concepts Airborne Laboratory. [3]

The Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) is a JUH-60A, meaning it is one of the earlier models of the Black Hawk. This utility helicopter is very unique. RASCAL is a highly modified JUH-60A used for several research purposes. The U.S. Army Aeroflightdynamics Directorate, NASA Ames Research Center, and Boeing Helicopter at all involved in the

development of RASCAL [15]. This specific aircraft is great for this research due to its ability of rapid prototyping as well as its fail-safe testing environment. RASCAL has two completely isolated FCSs on board, a FBW FCS call the Research Flight Control System (RFCS) and the original mechanical FCS. The original FCS has been kept on board for safety reasons.

RASCAL must have two pilots at all times, one for each FCS on board. There is the evaluation pilot (EP) and the safety pilot (SP). The EP flies RASCAL using the RFCS. The SP is there to take over the controls with the mechanical FCS in case some of the experimental equipment begins to fail during flight. The switch between FCS's can be done manually by either of the pilots. This switch may also occur automatically buy the FCC. Throughout the flight the FCC is monitoring the FCS. If anything happens to go wrong with the FCS, the monitors will send signals to the FCC which will switch controls to the SP.

V. RASCAL's Contribution to the Development of UH-60M Upgrade

A. Reasons for Selecting RASCAL

Before the U.S. Army commits to purchasing a fleet of UH-60MUs research must be done to reduce the risk of the new FBW FCS as well to prove the superiority and advantages to using this Black Hawk compared to older, more familiar models of the UH-60 [15]. RASCAL was selected and used to conduct some of this research. The focus of the research was on risk reduction. Along with the safety reasons stated previously, RASCAL was chosen for its similarities between itself and the UH-60M, its capabilities of rapid prototyping, and ability to receive near instant feedback. Feedback comes from the pilot comments and handling quality ratings (HQR). The ability to receive feedback so quickly has proven to be a great advantage to have. This allows researchers to make adjustments quickly into the system design.

B. Modifications Made to RASCAL

Although the two machines are very similar in design, RASCAL was modified to incorporate a few elements from the UH-60MU. These elements include the Active Inceptor System (AIS), Honeywell H-764G Embedded GPS\INS (EGI), Common Architecture Avionics Systems (CAAS) primary flight displays, and the UH-60MU Control Laws (MUCLAWS) [15]. Changes were also made to the flight test course at Moffett Field, CA. These changes included the construction of a hover tower.

C. Test Phases

There were three phases to this research. Starting with Phase 0, the system integration was completed and verified through about 10 hours of flight testing in hover and low speeds. Phase 1 consisted of about 40 hours of forward flight at speeds of 40-100 KIAS (Knots Indicated Air Speed). The research was wrapped up with evaluations of handling qualities in Phase 2. In Phase 2, the Cooper-Harper Handling Quality Rating system [16] is used by the researchers to gain an understanding of the handling quality of RASCAL once all the modifications have

been completed. This handling quality rating system, known as HQR, was developed shortly after World War II at Ames Aeronautical Laboratory at Moffett Federal Airfield, CA which was run by the National Advisory Committee for Aeronautics (NACA) [17]. George Cooper conducted flights with Bob Innis and Fred Drinkwater [17]. During his time at Ames, Cooper created a standardized system for rating an aircraft’s flight qualities. This system was named The Cooper Pilot Opinion Rating Scale and was published in 1957. Nine years later Cooper received the Admiral Luis de Florez Flight Safety Award for his contributions to flight safety and was also awarded the Richard Hansford Burroughs, Jr. Test Pilot Award in 1971. In 1969 it was known as the Cooper-Harper Flying Qualities Rating Scale after Robert Harper, who worked at the Cornell Aeronautical Laboratory, improved upon Cooper’s system. Both retired, Cooper and Harper were asked to reiterate the Cooper-Harper Scale in 1984 by the American Institute of Aeronautics and Astronautics at the Wright Brothers Lectureship in Aeronautics.

1. Phase 0 – System Integration and Verification

To insure all runs smoothly, each new system was added one at a time. This way a flight test could be completed between each installation and the research team would be able to pin point any initial problems with the system. Added first was the AIS. Because this system was added early one only the basic functionality of the system was tested. Some fine tuning of the stick force-feel characteristics were competed at this stage as well. Following the AIS, the EGI and MUCLAWS were added. To wrap up this phase a final flight test was conducted to verify all systems were working as expected.

2. Phase 1-Flight Test Based Optimization

In this stage of testing the control laws were further developed. During this process AFDD provided the support to bring in the MUCLAWS into the Control Designers Unified Interface (CONDUIT) for Sikorsky Helicopter, who had technical lead of the development of MUCLAWS. CONDUIT is a program which “performs linear analysis and optimization of the MUCLAWS to determine control law gains that satisfy the performance criteria set for the system” [15].

3. Phase 2-Limited Handling Qualities Evaluation

Predicted handling qualities parameters and assigned handling qualities ratings (HQR) were studied in this final stage [15]. The Predicted handling qualities involved quantitative engineering maneuvers including frequency sweeps and attitude quickness. The assigned HQR studies involved Mission Task Elements (MTE). There were two parts to the assigned HQR tests. First the flight tests are flown in good visual conditions (GVE) and next are flown in simulated degraded visual conditions (DVE). Six MTEs were flown in this set of flight testing. These were precision hover, hovering turn, lateral reposition, departure/abort, and vertical maneuver. Each MTE was flown in GVE and DVE as well as in both RASCAL and the AFDD’s EH-60L. The EH-60L was used to gather a set of control data to compare to.

In total there were 5 pilots involved in flight testing, two from Sikorsky and three from the U.S. Army. Each pilot flew the following six flights:

- RASCAL/MUSCLAWS familiarization flight
- MTE familiarization and practice with MUSCLAWS in RASCAL in GVE and simulated DVE
- Give MTE evaluation with MUSCLAWS in RASCAL
- DVE MTE evaluation with MUSCLAWS in RASCAL

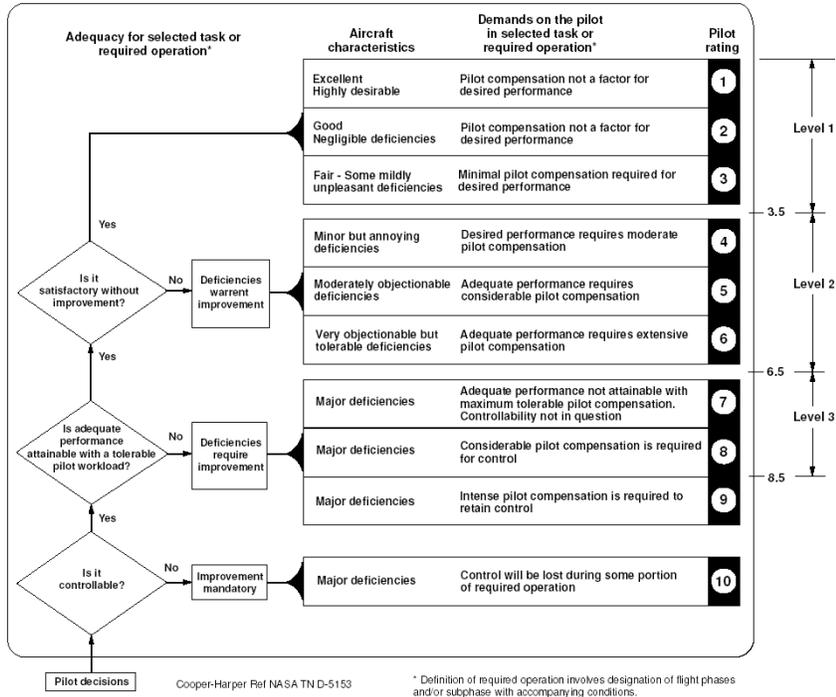


Figure 8. Cooper-Harper Handling Quality Rating (HQR) [17].

- GVE MTE evaluation in EH-60L
- DVE MTE evaluation in EH-60L

During practice flights, the pilots were given feedback from the flight test engineers on their performance against the ADS-33 criteria only if they performed poorly. This helps the pilots “calibrate” to the course.

VI. Recent Projects Involving RASCAL and FBW Technology

A. Sandblaster

Occasionally, when a helicopter is hovering near the ground or coming in to land, dust, snow, etc. get blown around making it very difficult for the pilot to see where the aircraft is with respect to its surroundings. This situation is called brownout. Sandblaster is a system which will help pilots navigate in a brownout situation and help land the aircraft safely. The U.S. Defense Advanced Research Projects Agency (DARPA) helped sponsor Sandblaster during its second phase in research and testing [19]. In this phase, RASCAL was used for flight testing. The DARPA Strategic Technology Office chose a team from Sikorsky in 2006 to build the Sandblaster system which will be compatible with existing aircraft. Because of its capability of being molded into an aircraft similar to the UH-60M Upgrade, RASCAL was an obvious choice for this research.



Figure 9. A UH-60 experiencing brownout [18].

Four separate technologies were integrated into RASCAL, a millimeter wave radar, digital terrain knowledge grid, low speed cockpit symbology, and FBW Flight Control with point-in-space approach capabilities. This last technology is one of the main reasons RASCAL was selected for the research. Due to previous research conducted for FBW technology in RASCAL, incorporating the capability of point-in-space approach was simple. The FBW control laws from the UH-60M Upgrade were used in this research as well. The flight control logic used for Sandblaster as developed and studied in a Sikorsky simulator in Connecticut. Once the simulation was completed flight testing began in RASCAL.

This system was designed to find obstacles from 1000 feet off the ground. These obstacles could be anything that the aircraft would need to avoid but not able to be seen during a brownout landing. The flight testing was completed and Moffett Field, CA. In the test site the AFDD created a variety of obstacles. The height of these obstacles ranged from 1 foot to 4 feet, all of which the system could detect. A wire detection test was also conducted here, proving this system could also spot power lines during a brownout. The Sandblaster system



Figure 10. Here is a snapshot of the view from a camera on board RASCAL and the Sandblaster display during one of the test flights [19].

exceeded all expectations and the pilots almost enjoyed using such a system. One of the test pilots described the experience as playing a video game.

B. Active Inceptor Handling Qualities Study

Currently research is being conducted at Ames Research Center to investigate the force-feel influences pilots rely on when flying a helicopter. As previously stated, the FBW FCS removes mechanical linkages between the pilot's controls and the actuators. Because these mechanical linkages have been removed, the forces in the controls have also been removed. There are concerns that absence of these physical cues will adversely affect the ability of the pilot to maneuver the aircraft. Researchers are looking into Force-Feel systems which will induce vibrations within the controls to simulate the forces from the mechanical linkages in the older flight control system [13].

Research flight testing is being conducted to determine the impact of force-feel characteristics on the handling qualities of a rotorcraft as well as to define handling qualities FCS design guidance. Currently, little guidance is provided in ADS-33 regarding inceptor force-feel characteristics. In this research, ADS-33 is being used as the guideline for the flight testing campaign. Two maneuvers, hover and slalom, as defined in ADS-33 have been employed for investigation.

For hover testing, the pilot initiates the maneuver by flying a path diagonal from their starting position. At the end of this path the test pilot must come to a stable hover over a designated position on the ground. The pilot relies on a set of reference markers on the course that will cue him/her as to the position of the aircraft relative to the hover position. These markers consist of two white squares lined up vertically and two smaller black squares also lined up vertically. The pilot must line up in such a way that the black targets are lined up in the middle of the two white targets, effectively holding a position within ± 3 feet horizontally and ± 2 feet vertically. This position is held for 30 seconds and concludes the test. This task tends to require low amplitude yet high frequency control inputs from the pilot. This means the pilot is making small but frequent adjustments with the controls in order to keep the black targets within the white targets. The Slalom test course consists of a weaving path resembling a sine wave. The pilot begins by flying forward in a straight path. Next the pilot begins the weaving maneuver around four obstacles while keeping inside the cones which mark the path. The maneuver ends with another straight flight along the centerline of the course. This task forces the pilot into making large lateral inputs, meaning large amplitude but low frequency controls will be made by the pilot. The two different control techniques required are intended to expose potentially different deficiencies in the inceptor configurations and control system laws.

This research is still in the early stages of data collection and does not have any results currently. RASCAL would be a great tool for researchers due to its ability to be reconfigured to emulate multiple types of aircraft and CLAWS. Another key feature RASCAL has is the FBW technology from the UH-60M Upgrade flight testing. [13]

VII. Conclusion

Once all flight tests were completed, RASCAL has proven to be a great rapid prototyping tool for analysis and optimization of the FBW FCS. Also with this testing the research team has learned having accurate math models for lead-lag dynamics is essential for creating good estimates. The MUCLAWS have shown to greatly improve hover and low speed handling qualities compared to the UH-60A/L baseline. The U.S. Army is still hesitant to bring the UH-60MU into their fleet of helicopters due to unfortunate events some aircraft have experienced due to electrical interference or computers suffering from "insanity". A tragic incident involving electrical interference with the horizontal stabilizer in the tail of one of the U.S. Army's helicopters ended not only with the loss of the aircraft but of all crew members aboard [20]. Research is still continuing on with hopes to improve upon the system to make it easier on the pilots while making a safer aircraft.

Rotorcraft has been through many stages of design since the first in the early 1950s. Now rotorcraft takes a new step forward with FBW technology. With the help of the Aeroflightdynamics Directorate, NASA Ames Research Center, Sikorsky, Boeing, and all others who have worked with RASCAL, the U.S. Army may be able to add another member to the Black Hawk family.

Acknowledgments

The author thanks Dr. William Warmbrodt, Mr. Gary Fayaud, and Mr. Sam Huang for their support and guidance through this report and for the experiences with the Aeroflightdynamics Directorate Flight Projects Office of the U.S. Army and the Aeromechanics Branch of NASA Ames Research Center. The author also thanks the Oregon NASA Space Grant Consortium for sponsoring this undergraduate internship experience.

References

¹Rurerman, Judy. "Helicopter Development in the Early Twentieth Century ." *U.S. Centennial of Flight Commission*. U.S. Centennial of Flight Commission, n.d. Web. 27 July 2011. <http://www.centennialofflight.gov/essay/Rotary/early_20th_century/HE2.htm>.

²"Juan de la Cierva." *Wikipedia*. N.p., n.d. Web. 27 July 2011. <http://en.wikipedia.org/wiki/Juan_de_la_Cierva>.

Oregon NASA Space Grant Consortium – Internship Final Report

- ³Leishman, J. G. *A History of Helicopter Flight*. University of Maryland, 2000. Web. 25 July 2011. <<http://terpconnect.umd.edu/~leishman/Aero/history.html>>.
- ⁴Harris, Frank. Personal interview. 21 July 2011.
- ⁵"Past Projects - F-8 Digital Fly-By-Wire." *Dryden Flight Research Center: Research*. Ed. Marty Curry. National Aeronautics and Space Administration, 13 Aug. 2009. Web. 22 July 2011. <<http://www.nasa.gov/centers/dryden/history/pastprojects/F8/index.html>>.
- ⁶"Aeronautics - Fly-By-Wire." N.p., Apr. 2011. Web. 22 July 2011. <http://www.ahrtp.com/RSS-JSfeeds/Fly_By_Wire.htm>.
- ⁷"Fly-By-Wire." *Wikipedia*. N.p., n.d. Web. 27 July 2011. <<http://en.wikipedia.org/wiki/Fly-by-wire>>.
- ⁸"Bell-Boeing V-22 Osprey." *Wikipedia*. N.p., n.d. Web. 25 July 2011. <http://en.wikipedia.org/wiki/Bell-Boeing_V-22_Osprey>.
- ⁹Harding, S. *Bell 301 / XV-15*. N.p., n.d. Web. 11 Aug. 2011. <http://www.aviastar.org/helicopters_eng/bell_xv-15.php>.
- ¹⁰*Bell Boeing V-22 Osprey*. Military-Today, n.d. Web. 11 Aug. 2011.
- ¹¹Maj. Ott, Carl. Personal interview. 12 Aug. 2011.
- ¹²Jean, Grace V. "Army Slow to Adapt Fly-By-Wire Controls for Helicopters." *National Defense Industrial Association*. National Defense Industrial Association, Apr. 2011. Web. 5 July 2011. <<http://www.nationaldefensemagazine.org/archive/2011/April/Pages/ArmySlowToAdaptFly-By-WireControlsforHelicopters.aspx?PF=1>>.
- ¹³Malpica, Carlos A. Personal interview. 8 Aug. 2011.
- ¹⁴Web. 27 July 2011. <http://sikorsky.com/StaticFiles/Sikorsky/Assets/images/products/Military/BLACK%20HAWK/mil_UH60M_ovr_a.jpg>.
- ¹⁵Fletcher, Jaya W., Jeff Lusardi, Mohammadereza H. Mansur, Ernesto Morallez III, David R. Arterburn, Ifor Cherepinsky, Channing S. Morse, and Kevin F. Kalinowski. "UH-60M Upgrade Fly-By-Wire Flight Control Risk Reduction Using the RASCAL JUH-60A In-Flight Simulator." *American Helicopter Society (2008)*: N. Pag. Web.
- ¹⁶Cooper, George E., and Robert P. Harper. *NASA Technical Note: NASA TN D-5153*. Washington, D. C.: NASA, 1969. Print.
- ¹⁷"Cooper-Harper Rating Scale." *Wikipedia*. N.p., n.d. Web. 2 Aug. 2011. <http://en.wikipedia.org/wiki/Cooper-Harper_rating_scale>.
- ¹⁸Colucci, Frank. "Digging Out From Brownout." *Vertiflite*. N.p., 2007. Web. 4 Aug. 2011. <<http://www.vtol.org/vertiflite/brownout.pdf>>.
- ¹⁹Colucci, Frank. "Making Sense of Sandblaster." N.p., 2009. Web. 4 Aug. 2011. <<http://www.vtol.org/vertiflite/sandblaster.pdf>>.
- ²⁰Warmbrodt, William G. Personal Interview. 4 Aug. 2011.