Design, Development, and Testing of a Conformal Power Control Interface for Thrust Vectoring Aircraft

David Rozovski

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For the degree of Doctor of Philosophy

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DESIGN, DEVELOPMENT, AND TESTING OF A CONFORMAL POWER CONTROL INTERFACE FOR THRUST VECTORING AIRCRAFT

A Dissertation

Submitted to the Faculty

of

Purdue University

by

David Rozovski

In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2013

Purdue University

West Lafayette, Indiana
This work is dedicated to my Aunt Vicki. She always believed in me and I wish she were here today. Love you Avee.
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“I’m doing this because I want to do it better... You can design the most amazing thing in the world, but it takes people to make the dream a reality.”– Adapted from Walt Disney

This document represents over five years of my life and work. And while it is by far my greatest academic achievement to date, none of it would have been possible without some very special and unique people.

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ABSTRACT


Over the last five years, a new power control inceptor for tiltrotor aircraft, known as the Rotational Throttle Interface (RTI) was designed and built. Prior to the RTI, no tiltrotor inceptor had been able to simultaneously indicate both the direction and magnitude of thrust conformally. The purpose of the RTI is to provide an interface that maps to the intended vehicle response throughout ALL ranges of operation. Doing so is expected to reduce confusion that may have contributed to several tiltrotor accidents.

Two tests were conducted with the RTI, one at the NASA Vertical Motion Simulator, and one at Canada’s National Research Council’s Flight Research Lab. Overall, the tests explored two new control modes against the current tiltrotor control design. Results from the test demonstrated the feasibility of the device and indicated that there was some potential benefit in utilizing an adaptable throttle interface.

In addition to designing and building the RTI, a new evaluation theory has been proposed known as the Design Principle Hierarchy (DPH). The DPH provides a method for evaluating power control inceptors and similar interfaces.
CHAPTER 1 INTRODUCTION

1.1 Introduction

In 2005, two research gaps were identified within tiltrotor flight control design. Until this body of work it had not been possible to build a fully conformal power control interface for tiltrotor aircraft. This non-conformity has caused accidents, resulting in hull loss and even death and continues to be a problem with control strategy and potential control reversals.

This inability to create a conformal control system was due to a lack of requirement understanding in addition to and technology gap. Until this work, there was no guiding principle from a human-systems or mechanical engineering requirement standpoint on what was needed in order to create a conformal tiltrotor power interface. The problem with tiltrotor power inceptors is that, in order for them to be fully conformal, they need to possess 3 degrees of freedom (DoF). In addition, prior to this work, it was not possible to mechanically create a 3 DoF control system in which the pilot controlled the intermediate DoF.
To address both gaps, a new tiltrotor inceptor was designed using a newly proposed design structure both of which are proposed in this work. RTI construction took approximately two years. The major technological hurdle in the design was the creation and implementation of a low weight and robust Concentric Power Transfer Axis (CPTA). CPTA enables electro-mechanical drive components to be placed downstream and away from the pilot’s direct interface. This feature reduces the amount of mass the pilot has to interact with, which in turn improves fine and gross motor accuracy. It is through the CPTA system that, for the first time, a third degree of freedom could be implemented, leading to a fully conformal and congruent tiltrotor power control interface.

To address the design approach principle gap and guide the building of the RTI, the Design Principle Hierarchy (DPH) was developed. The DPH is intended as a high-level ordinal and value based system design guide to identify and validate comparative optimal configurations on both current and future conformal inceptor systems.

Historically controls have been designed to follow cognitive or stimulus-response mapping (for a detailed discussion of stimulus-response mapping, refer to Proctor & Vu (2006)). Since all aircraft control systems until the advent of the RTI only possessed 1 or 2 DoFs, this type of purely cognitive or stimulus-response compatibility mapping worked well as the control movements did not violate ergonomic or other principles. A 3rd DoF presents itself in tiltrotor power control interfaces, which results in new challenges not witnessed prior. As inceptor movement complexity increases, the issue of ergonomics, cognitive mapping, and control strategy, discussed as proprioceptive consistency below,
become critical. These issues had not previously been addressed, so the creation of a conformal tiltrotor power control interface was simply not possible. It was only through the building and testing of the RTI that these additional requirements have been addressed.

Initial validation of the RTI and DPH was conducted over the course of two experiments:

1. NASA Vertical Motion Simulator (VMS)

Both the VMS and FRL studies were conducted using either trained military test or research pilots. As the RTI was designed to map to both the direction and magnitude of thrust, this new drive mode was tested in experimental trials against the current tiltrotor inceptor baseline. Results from the VMS and FRL studies were conflicting. VMS findings suggested that the RTI did not prove beneficial to the pilot’s vehicle control. FRL findings, which occurred after addressing some of the RTI’s mechanical issues, suggest that the RTI could provide some benefit over the current baseline inceptor.

While additional studies, are needed to conclusively validate both the RTI and DPH, this work is groundbreaking in that, prior to it, there was no tiltrotor power control interface that was both conformal and congruently mapped, nor was there a framework that could guide or evaluate its design.
1.2 Contribution

The dissertation will make several contributions:

1. Identification of a set of principles for the design of control inceptors;
2. Preliminary evaluations of those principles;
3. The construction of an inceptor for tiltrotor aircraft that conforms to those principles; which includes the creation and implementation of the CPTA.

The first contribution is expected to have theoretical impact by identifying the cognitive-ergonomic principles for the design of a tiltrotor power control interface and similar systems. These principles, if validated, can guide the design of new air vehicle power inceptors, and may be adopted for use in other vehicles and devices. In addition, these principles may be used to guide the certification of inceptors in air vehicles.

The inceptor construction and flight simulation testing should have significant practical implications. It is expected that the new inceptor will be strongly considered as a possible standard design for tiltrotor vehicles, although additional testing is expected to be needed in order to confirm its performance benefits. There is clear interest in the inceptor, as indicated by the support being provided for its design and testing.

In addition, the inceptor design is expected to solve a number of mechanical design problems that have previously prevented its construction, and is expected to represent a substantial weight savings over current inceptor designs.

The RTI is a fully functional prototype and can be configured to fit into any existing tiltrotor. In addition to the RTI’s adherence to previously known and newly identified
human factors principles, the prototype solves several mechanical problems that had previously defied tiltrotor inceptor designers, all while providing a weight savings of approximately 10%. (It is expected that the production model would provide an estimated 50% reduction in weight over existing inceptors.)

There are two contributions of this dissertation, both with respect to practical impact and with respect to the design of controllers for vehicles. This work’s practical impact is indicated by the interest of members of both the U.S. and Canadian governments, who have sponsored testing of the device, often at great expense. In addition, the work will provide better guidance to regulating agencies for the certification of such devices. On a theoretical level, the proposed research identifies two new critical design principles for power inceptors, which likely extends to a more general class of controllers.
CHAPTER 2 BACKGROUND

2.1 Aviation

The design of the control interface is arguably one of the most critical areas of focus in system design. Without it, or a poor implementation of it, can leave an otherwise ideal system unmanageable. The first airplane, the Wright Flyer, was the first heavier than air, powered machine that was able to climb, sustain, and land under its own means. It was early on that the Wrights recognized the need for proper control.

Even with this recognition, it was not until 1910 that fixed wing flight controls took on the standardized form that we know today; center stick and rudder pedals/bar. The creation of what I have coined the Direction and Magnitude Framework (DMF) by Bleriot in 1910, resulted in the effective and congruent mapping of the flight control movement to both the vehicle’s intended action and rate at which this intended action will occur.

With the introduction of the Bell 47 helicopter, 1946 marked the first time the DMF control configuration was implemented in a different category of aircraft. Since then the DMF can be found in every Western-certified primary flight control system for both rotary and fixed wing aircraft.
Slightly after and parallel to the helicopter’s development, work was initiated by the same company, Bell, to address the shortcomings of the helicopter’s low forward speed by combining the positive traits of both the helicopter with its fixed wing counterpart. This work gave rise to the tiltrotor and after numerous iterations, in 1997, the Bell/Boeing V-22 Osprey became operational, marking the first mass-produced and certified “tiltrotor” aircraft.

The Osprey has been plagued with a tumultuous testing history. One of the major issues faced with the V-22 and prior tiltrotors was how to properly design the power control interface; should it be a helicopter style collective or a fixed wing style throttle? There have been numerous iterations, and the current state of the art provides a helicopter style collective for the civilian Agusta-Westland 609 and an airplane style throttle for the V-22 Osprey.

The final in the case of the V-22 power control interface iteration occurred after three separate attempts, moving from a collective to a Harrier-like throttle known as the Blotle, and finally to a six-inch linear throttle similar to those found in fixed wing aircraft. The evolution of the V-22s power control interface is described in detail later on, but it is important to highlight that at least one of these transitions was the result of a crash during flight test is due at least in part to a design flaw in the control system design (Dugan, 1998). Tiltrotor control systems are unique in that they are one of the few vehicle systems in the world that have a multi Degree-of-Freedom (DoF) control system.
Aircraft are extremely unforgiving by nature. In addition to their complexity, it is one of the only environments in the world where, when things go awry, operators cannot stop the system to deal with the malfunction. This quality only further compounds the necessity for proper system and control design.

One can identify many “control levels” of aviation systems beginning with primary basic control of attitude and power all the way to advanced envelope protection and automated system management and navigation. While the intermediate levels are expansive, without a proper foundation in control design, the aircraft, no matter how advanced and automated it is, can still be rendered ineffective if its system design foundation is weak.

An example of this effect is the control design lag that was found in the initial F-22 Raptor prototype. The control system suffered a relatively small delay from input to output, on the order of a couple of hundred milliseconds. This, however, was enough for the pilot’s control bandwidth to exceed the vehicle’s response bandwidth leading to a Pilot Induced Oscillation (PIO). The PIO event occurred proximal to the ground and nearly destroyed the aircraft and pilot. The F-22 is one of the most advanced and modern fighter in the world today, yet a simple delay in the control system nearly left this 5th generation fighter uncontrollable. This is one example that illustrates the fundamental importance of proper control design from the ground up.

Today’s aviation control design standards are incredibly well defined with a few exceptions. One would be hard pressed to find freedoms within the current design
regulations and guidelines. This has led to a very predictable set of design practices that can be seen in every modern aircraft since the late ‘40s. While these design practices are relatively long lived within the existence of aviation, there was a period of time where flight control design standards where vastly different.

2.2 Flight Control History

The first flight of a powered, heavier than air vehicle occurred at Kitty Hawk on December 1903 by Orville Wright in the Wright Flyer I. This aircraft used a sliding hip holster and forward/aft moving controls in order to control roll through wing warping, and pitch through a canard stabilator. Over the next 7 years, a variety of configurations were attempted but it was not until 1910, when Bleriot began designing his aircraft, that the current standard of a center stick and rudder pedal/bar configuration was adopted.

The move to this control design configuration began what today is considered the standard in aircraft control configuration. By using a center stick and rudder pedal configuration (Figure 1), the controls directly indicate two very important pieces of information to the pilot, the direction and magnitude of intended control response. Another way to state this is that the controls themselves indicate both the direction and the magnitude (rate) at which the vehicle should respond. This contribution adheres to what will be referred to in the dissertation as the Direction and Magnitude Framework (DMF). Another implementation of the center stick is the control yoke configuration that serves the same purpose with respect to vehicle control and also indicates the same information to the pilot.
While airplanes have been present the longest of all the heavier than air powered vehicles, The DMF design implementation has affected every other type of powered heavier than air vehicle since the transition to a standard set of controls. Even helicopters, which fall under an entirely different category of aircraft, have been influenced by the DMF and adhere to this standard.

The DMF became so prevalent that the FAA made specific note of it in Aeronautical Design Standard parts 23.779, 25.779, 27.779, and 29.779 for normal category fixed
wing, transport category fixed wing, normal category helicopters, and transport category helicopters respectively.

This implementation and standardization of control design that indicates both the intended vector and magnitude of the aircraft provides a variety of benefits. Positive transfer of training is promoted due to both the stimulus and response elements being similar across platforms allowing pilots to transition from one type or category to another without learning entirely new control schemas (Wickens & Hollands, 2000). Because the control movements themselves map congruently to the aircraft’s intended response, there are fewer mental transformations required by the pilot to execute the intended action, thus allowing for an indirect reduction in workload.

In accordance with the above schema, power control systems also have had FAA design mandates placed upon them. In fixed wing aircraft, under FAA parts 23 and 25, specific mention is given to the direction of the throttle (power lever) that it must move forward (with respect to the aircraft’s firewall) in order to increase power and backwards in order to decrease. In helicopters, FAA parts 27 and 29 referred to above, require the collective (power lever) to move up (with respect to the helicopter’s horizontal plane) to add power and down to reduce it.
2.3 Tiltrotor History

As stated before, after the advent of the helicopter, designers began to look for ways to combine the positive high forward speeds of fixed wing aircraft with the hovering capability of helicopters, with this, the Bell XV-3 (figure 2) and tiltrotor were born in 1953.

Figure 2. Bell XV-3 (Bell XV-3, 2011)

Tiltrotors essentially utilize two or more rotating engine nacelles on the wing to allow them to take off and land like a helicopter yet achieve the same high-forward airspeed of that of an airplane, effectively combining the most desirable aspects of each vehicle into one.

This ability is possible due to the rotation of the thrust vector eliminating issues such as retreating blade stall and rotor head instabilities. While the rotation of the nacelles is effective from a mechanical engineering standpoint, it has caused a number of conflicting designs for the power inceptor interface configuration from a human factors perspective.
The conflict has been driven by the additional degree of freedom thrust the tiltrotor power vector possess. Until tiltrotor aircraft, all power control systems operated on a single degree of freedom since the thrust vector direction remained constant. The difference in these designs existed between fixed-wing and rotary-wing aircraft. The conflict arose with tiltrotors power control design in whether they followed the convention of an airplane, whose thrust axis is “forward-aft” from the perspective of the pilot, or a helicopter, whose thrust axis is primarily “up-down”, (See Figure 3). As both airplane and helicopter power control interfaces are fixed, they both present incongruences during different phases of tiltrotor operation. Concrete examples include an airplane style throttle when the tiltrotor is in helicopter mode (i.e. nacelles pointed up) or a helicopter style collective when in airplane mode (i.e. nacelles pointed forward).

![Image of airplane throttle and helicopter collective](image-url)

**Figure 3. Airplane Throttle (left) and Helicopter Collective (right) (Rozovski, 2008a)**

Because of the tiltrotors unique ability to morph (i.e. rotate its thrust vector), there have been many attempts to determine the most appropriate inceptor/interface type for tiltrotor aircraft. The XV-3, discussed above and shown in figure 2, was the first functioning tiltrotor and utilized a helicopter collective style inceptor interface to control the engines.
Because the XV-3’s blades were taken from a conventional helicopter, they did not have the required chord twist (pitch) in the blades in order to make them suitable for both forward and vertical flight. Because of this limitation, the XV-3 pilot had a switch on the collective that allowed the pilot to control pitch range of the blades essentially remapping the collective to both helicopter and airplane mode. Even with this added control, the XV-3 presented incongruencies in airplane mode as the collective could not rotate in order to match the nacelle angle. The system, while aerodynamically effective, proved to be cumbersome for the pilot and was further compounded by the aircraft’s marginal handling qualities, which were further compounded by its lack of power. In one flight test report, the complication of the control system was one of four primary critiques of the vehicle due to its cumbersome complexity (Deckert & Ferry, 1960).

With both the success and shortcomings of the XV-3, other companies saw the potential for a tiltrotor or tiltwing concept. In early 1960’s Ling-Temco-Vought (LTV) began experimental flight testing on the LTV XC-142. While a tiltwing as opposed to a tiltrotor, the idea was similar in that it was designed to combine the positive traits of both a helicopter and airplane into a single vehicle.

Even in the early 1960s when the aircraft was being built, there was still uncertainty as to the most appropriate design for a power control inceptor interface for tilt-rotor/wing aircraft. In the case of the XC-142, designers decided that both throttles and collectives should be present. As viewed in the figure 4 the right seat pilot had both a collective and set of throttles while the left seat pilot only had throttles. From personal communication
with D. Dugan, it appears that only the right seat could control takeoff and landing, much like a captain can only use the single tiller to taxi in larger transport aircraft. Once in forward flight either pilot could control the aircraft. In the XC-142 both throttles were linked to each other and the collective; moving the throttles forward caused the collective to rise, while lowering the collective caused the throttles to retard, and vice versa. During takeoff the right seat copilot would “guard” the throttles. This guarding was necessary due to the requirement of the flying pilot to remove their hand to move it from one control to the other during a transition flight phase (vertical to forward and vice versa) which is considered unacceptable among aviators.

![XC-142 Flight Deck](image)

Figure 4. LTV XC-142 flight deck (J. Fisher, 2009)

Using the lessons learned from the XV-3, Bell set forth and developed what many consider to be the first viable tiltrotor, the XV-15 (Figure 5). The XV-15, like the XV-3, also utilized a helicopter collective style inceptor, similar to that of the CH-47 Chinook
helicopter. Test pilots had few negative comments regarding the control system, though this may have been influenced by the direct involvement of the evaluation pilots in designing the inceptor.

![Bell XV-15](image)

Figure 5. Bell XV-15 (XV-15 tilt rotor takeoff – first NASA Dryden flight, 2002).

The XV-15 enjoyed a fruitful test life with two separate vehicles being shared by the US Army and NASA. However, the test program did not result in a production vehicle possibly compounded by the loss of one aircraft during a routine flight. After the end of the XV-15 program, Bell developed the XV-22 which would later become known as the Bell/Boeing V-22 Osprey. The V-22 is show in figure 6. The Osprey has an interesting and rich history in that it underwent three different inceptors during development: first a
CH-47 style collective, second the “Blotle”, and finally the current system, the Thrust Control Lever (TCL).

![V-22 Osprey](image)

Figure 6. V-22 Osprey (V-22 Osprey, 2011)

The original collective, similar to the CH-47 helicopter collective, came from the XV-22’s predecessor, the XV-15. However, within the program, the military had the final decision on many, if not all, design choices regarding the aircraft.

One such individual with influence over the design was Colonel Harold W. Blot USAF (now Brigadier General, Retired), a former Harrier pilot and, at the time, one of the program managers for the V-22 program. Col. Blot had the V-22 style collective inceptor
changed from a collective to a Harrier-style aircraft throttle, shown in Figure 7. The Harrier’s throttle\(^1\) consists of a 4 inch downward arc to *increase* power.

![Harrier Throttle Quadrant with Nozzle Position Selector](image)

*Figure 7. Harrier Throttle Quadrant with Nozzle Position Selector (Harrier Throttle Quadrant, 2011)*

Following a series of events in 1995, the Blotle was replaced with the current system known as the Thrust Control Lever or TCL. The TCL is a 6 inch linear actuated inceptor. Pushing forward on the TCL increases power while pulling back decreases power, much like a fixed wing throttle (Figure 8).

\(^1\) There are a few reasons that the Harrier enjoyed a successful and relatively safe service career. One of the primary reasons was the Harrier’s training protocol. Pilots tracked towards the aircraft came from a fixed-wing pipeline and the majority never had exposure to helicopters. While classified as a S/VTOL (Short / Vertical Take Off and Landing) aircraft, the Harrier rarely utilized the vertical component of its flight envelope. When it was utilized as a purely VTOL aircraft, it spent only a fraction of its flight time in that flight envelope, unlike proposed V-22 tiltrotor operations which view the aircraft as a 50%/50% split of forward and vertical flight envelope regime. The third quality that is believed to have contributed to the success of the system was the affordance of a physical nozzle (akin to the tiltrotor’s nacelle) position indicator/control. This allowed the pilot to haptically sense the nacelle position.
Parallel to the development of the Bell/Boeing V-22, Bell had also teamed up with Boeing to create the first civilian certified tiltrotor, the 609, shown in Figure 9. Since the initial partnership, the Boeing sold its share of the 609 to Agusta who since then has purchased the 609 outright turning it into the Agusta-Westland or AW 609. The AW-609 is a 7-11 seat tiltrotor designed for executive transport and possible Search and Rescue (SAR) missions.

While the V-22 and AW-609 are similar in their configuration, method of operation, and even flight controls, the AW-609 possesses a helicopter collective style power inceptor
(Figure 10), which operates orthogonally and in some cases reversed to that of the V-22’s new TCL. The reason for the BA-609 collective choice was twofold: first, it was based off the XV-15, and second, hovering the aircraft, especially close to the ground, was seen as the most critical phase of flight, control-wise, for civilian operations.

![AW-609 Collective](image)

In contrast, the military program office desired an aircraft throttle style inceptor due to the critical importance of the air-to-air refueling phase. Air-to-air refueling requires extremely fine control along the longitudinal axis as one aircraft is trying to match the exact speed as the other. Using a throttle style inceptor for this task proved more effective than a collective during this phase of operation. Moreover, military designers believed that pilots trained to fly fixed-winged aircraft, rather than helicopter pilots, would be
transitioned to fly the V-22, making a throttle a more familiar control design, in retrospect more helicopter pilots have transitioned.

2.4 Consequences

With the design progression of the XV-3 through the V-22 and AW-609, there are a multitude of consequences that have resulted from the design selections implemented within each platform (i.e. V-22, AW-609) as well as across them. While design mandates exist for current vehicle categories such as fixed and rotary wing aircraft, there is little to no documentation on what the standard should be from a certification or even human factors perspective on new categories of aircraft such as tiltrotors. By implementing either a fixed-wing or rotary-wing control interface in a tiltrotor, compromises have to be made. One system could work well in one flight mode while the other system may work equally as well in the helicopter mode. Depending on the control style selection, either these choices can violate stimulus-response (S-R) compatibility in the alternate mode of which can result in negative transfer of training, can be ergonomically incorrect, and/or can result in proprioceptive inconsistencies. (The first two principles are established in human factors literature, the latter two are discussed as part of this dissertation).

2.5 Theoretical Overview Established from Master’s Thesis

S-R compatibility dictates that the intended input should map appropriately to the intended system response (Fitts & Seeger, 1953). By following this principal, the number of mental transformations are kept to a minimum and performance should increase
accordingly relative to a system in which the principal is violated. S-R compatibility is well-established as critical to good control performance (Proctor & Reeve, 1990).

During the initial development of the DPH and RTI design framework, Stimulus Response (S-R) Compatibility was used as a guiding stepping-stone. While direct parallels do not exist between the S-R body of work and off-axis back-driven continuous control system interfaces, there are applicable take-aways that exist.

Even prior to the development of the tiltrotor itself, work had initiated on relevant issues that would have far reaching implications on not just aircraft, but all vehicle controls. Andre, Haskell, and Wickens (1991) noted the importance of compatibility in orthogonal control systems, specifically calling out aviation. Bertelson (1963) looked at the issue of orthogonality a few years after the development of the first tiltrotor, although he did not specifically address aviation; his study focused on orthogonal stimulus response across perpendicular alignments. Another study conducted by Vince and Mitchel (1946) focused on participant manipulation of a continuous control interface left to right to control a vertically aligned continuous display, and found a preference for right to up pairing.

In all, S-R compatibility has attachments to the DPH and RTI as a parallel though it was never the intent of this work to expand the S-R body of work. This said, S-R was drawn in to illustrate one of the feature sets that the RTI and DPH encompass, at a basic level, the idea or notion that items respond in congruence with the direction of their actioned
input (i.e. the Direction and Magnitude Framework (DMF)). For a more complete
discussion of Stimulus Response Compatibility, Proctor and Vu’s Stimulus-Response
Compatibility Principles (Proctor & Vu, 2006) offers an excellent foundation on S-R
Compatibility and where the science stands today.

Violations of these principles can result in “negative transfer”, where negative transfer is
defined as “one set of task skills interfering with another set of task skills within the same
environment” (Wickens & Hollands, 2000). In other words, pilots used to flying a
helicopter power inceptor (collective) would demonstrate difficulty utilizing an airplane
power inceptor (throttle) while flying and vice versa.

Negative transfer can lead to increased training costs, pilot error, and even accidents. Due
to a variety of factors, the majority of the pilots transitioning to the V-22 are coming from
a helicopter pipeline. Because of the orthogonality between the control strategies of a
helicopter collective and the V-22’s throttle, it is currently estimated that pilots are
spending 10-100 hours on average in order to relearn the new control strategy for adding
power (Cantrell, 2007). It is this same orthogonality that is thought to cause control
reversals, which can cause pilot error and accidents.

The potential for error and accident due to control reversal problems was demonstrated
by the crash of a V-22 in 1995 when Air Force V-22 vehicle #5 was lost approximately
49 seconds into flight. The controls of vehicle #5, whose inceptor (the Blotle; downward
4-inch arcing travel path) followed the fixed-wing convention, had had two of its three
roll vyros miss-wired, nearly resulting in a complete loss of control. To recover the aircraft, the pilot, who had previously flown helicopters, attempted to land the aircraft by bringing the throttles to idle, which is accomplished in a helicopter by pushing on the collective. However, for the fixed-wing-type inceptor installed in vehicle #5, this action increased the power to maximum. The aircraft, shown in Figure 11 after the accident, flipped and was destroyed; the aircrew survived.

Figure 11. USAF vehicle #5 after accident (Source Unknown)

The incident with vehicle #5 highlighted the potential consequences of human factors problems with tiltrotor inceptors. In personal communication with D. Dugan, it was indicated that the inceptor movement closely resembled that of a helicopter collective yet operated like that of a fixed-wing throttle. In addition, the roll and pitch control of the vehicle was out of phase due to a miss-wire in the roll-vyros (devices used to keep the aircraft stable) as stated above. The pilot, a former helicopter pilot, committed the control reversal when attempting to bring the vehicle to the ground after the malfunction was recognized. The ensuing control reversal may have been compounded due to the
associated workload of the faulty vyros. It was after this incident that the Blotle was removed and replaced with a 6-inch linear throw throttle.

In order to prevent such incidents in the future, it is necessary, and the goal of this work, to identify a design for tiltrotor inceptors consistent with human factors best-practice principles. More generally it is necessary to understand how to drive design evolution to address continuous control systems that possess more than 2 degrees of freedom.

2.6 Initial Design Principle Hierarchy

While design mandates in control interfaces exist (FAR regulations), they dictate the direction of movement of the control interface. While this may work for the majority if not all current aircraft flight controls, tiltrotor aircraft present a unique challenge in that their power control inceptor possesses an additional 3rd Degree of Freedom (DoF). Utilizing current fixed wing or helicopter has proven to be problematic (Dugan, 1998, Deckert & Ferry, 1960).

Initially, it was believed that only cognitive mapping, effectively the compatibility between the inceptor’s movement and the effected action, was the critical characteristic. After some analysis however, it was deemed not to be the case as there are many successful control interfaces in the world that do not adhere to cognitive mapping consistent with S-R Compatibility.
One example of such an interface is the motorcycle throttle control grip (Figure 12). A motorcycle throttle grip adds power to the system by rolling the top portion of the throttle aft towards the operator. From the standpoint of human factors, this appears to violate the principle the stimulus-response compatibility as the motorcycle is propelled in the opposite direction of the movement of the grip. Moreover motorcycle throttle designs have not varied in over 50 years and are considered a standard for such vehicles.

Figure 12. Motorcycle throttle grip

In looking at the motorcycle throttle grip further, it was noted that a grip that did meet S-R compatibility requirement (i.e., top portion rolls forward) would be extremely uncomfortable. The reason for this being that it would not be ergonomic.

In order to explain the motorcycle throttle grip, both principles were combined giving rise to the Design Principle Hierarchy or DPH. The DPH was structured as a list of requirements, as follows:

1. Ergonomics

2. Cognitive Mapping
The DPH initially was designed as an ordinal system in that each level had to be met prior to moving on to the next level. In the case of the motorcycle throttle grip, the ergonomic level was met prior to the cognitive mapping requirement, resulting in a successful control interface.
CHAPTER 3 PRIOR WORK ON TILTROTOR INCEPTORS

An interface known as the Rotational Throttle Interface or RTI was developed based on the DPH. The RTI was able to rotate and map congruently to both the magnitude of commanded engine thrust and the direction at which this thrust was vectored in tiltrotor aircraft.

For the design the cognitive-ergonomic requirements were set forth as well as the design methodology, specification, and requirements for the RTI. This information is presented in my University of Illinois Master’s Thesis titled “Control Reversal Mitigation and Situational Awareness Improvement for Tiltrotor Aircraft Pilots via Redesign of the Thrust/Power Control Interface”. In addition to the document, a plastic stereo-lithography non-functional RTI prototype was created to do ergonomic evaluations of the system’s discrete movements and position placement.

3.1 History of Mapping Power Inceptors

While indicated above that the high-level RTI design was accomplished during the Master’s thesis, it is important to gain an understanding of what has been done prior regarding map-able throttle design for tiltrotor aircraft. The concept behind a map-able throttle system is to provide the pilot both an indication of magnitude and direction of
intended aircraft action. Because tiltrotor aircraft can vary the angle of their engines an additional degree of freedom is needed in order to accurately depict the engine vector in this type of inceptor. To date there have been three map-able throttle systems, including the RTI (chronological order in parenthesis):

1. The Magnum developed by Jim Cheatham (1st)
2. Haverdings’ system out of the Netherlands (3rd)
3. The Rotational Throttle Interface or RTI (2nd)

All three of these systems have been developed independently of a field-able aircraft design but were specifically designed to address the additional DoF found in tiltrotor aircraft. This is an important characteristic, as the goal of these three projects was to standardize tiltrotor power inceptor interface design.

3.1.1 Magnum

The first independent system, known as the Magnum, was designed by Jim Cheatham. (The name “Magnum” was a tribute to Clint Eastwood, who was one of the first private investors in civil tiltrotors (D. Dugan personal communication)) Figure 13 a-c depicts the orientation of the Magnum in reference to the nacelle angles depicted by the model. (The transposition of figure 13a relative to figures 13b and 13c is unfortunate, but these are the only three known sequential photos of the Magnum through its full envelope travel range.)

The important design characteristic of the Magnum is the selected pivot point of the unit. In Figure 13a, the Magnum operates as a collective: as the nacelles rotate forward the
Magnum rotates aft. Figure 13b illustrates the transition mode of the magnum in the \( \sim 45^\circ \) position. Once the nacelles reach the 0\(^\circ\) position relative to the approximate waterline of the aircraft, the Magnum operates as a throttle as seen in Figure 13c.

The problem with this configuration is that at some point during the transition, the pilot must reposition his or her hand while the unit is moving, requiring a period in time in which the pilot does not have positive contact with the system. This was deemed unacceptable by test pilots and ultimately led to the abandonment of the Magnum similar to the issue noted in the LTV XC-142.
3.1.2 Haverdings System

Recently, a tiltrotor inceptor has been designed by Haverdings’, which is shown in Figure 14. The Haverdings’ system is still in development, but from analysis of the design documentation it utilizes a movable gate that is concentric with the travel axis of the power rotation. This allows for the movement of the power inceptor to be mapped congruently to the intended vehicle response, which would eliminate the S-R compatibility problem.

Figure 14. The Haverdings tiltrotor inceptor (Haverdings, 2009)
However, due to the co-locality of the inceptor and gate movement axis, the pilot has no way to discern the difference between their own input vs. a nacelle movement. This sharing of movement axes can cause cross coupling during nacelle transition and power adjustments, making the pilot unable to discern haptically which component of the system is moving.

Haverdings’ system presents interesting design choices in that the throttle position is measured relative to the moving gate. The moving gate is floating and provides no anchor point to the pilot in reference to throttle position. Pilots can discern neither the current flight envelope nor the nacelle position/movement without moving full aft and full forward to interpolate the plane of travel. This interpolation is not only difficult to imagine, but also nearly impossible to do due to the lack of angular sensitivity of the pilot’s hand through the forearm and upper arm.

3.1.3 Rotational Throttle Interface

Prior to public disclosure of the design of the Haverdings’ system, development of the RTI had begun, and a patent had been filed on the design (Haverding, 2009). The question that emerged for me from the crash of V-22 USAF vehicle #5 was, “why would a highly trained test pilot commit a control reversal in a vehicle with which they were apparently familiar?” This ultimately led to a question about what the most appropriate inceptor is for tiltrotor aircraft.
3.2 Genesis of the Rotational Throttle Interface

The development of the RTI was guided in part by three systems:

1. Fixed-wing power inceptors
2. Rotary-wing power inceptors
3. Jim Cheatem’s Magnum system

In order to gain a better understanding of what was required to develop a map-able throttle interface for tiltrotor aircraft, I conducted a complete task analysis of the power control strategy for both helicopters and airplanes. The logic behind this was that a tiltrotor was a combination of both vehicle types and the uniqueness of the tiltrotor system was presented in the intermediate envelope (i.e. the transition phase). That is, if the intermediate range was the unique component, then gaining a better understanding of the discrete extreme points of the envelope (i.e. fixed-wing horizontal mode and rotary-wing vertical mode) would allow for better interpolation of what was needed in-between.

As described previously, both helicopters and airplanes have power inceptors that map congruently to their intended aircraft response respectively. This congruent mapping is not a necessary function of the aircraft per se but rather a function of years of standardization across different categories of aircraft, and is consistent with SR Compatibility.

This standardization can actually be traced back to 1946 with the marking of two important events, the first commercially certified helicopter and the creation of the
direction-magnitude framework (DMF). The DMF is defined as the direction and displacement amplitude of the control inceptor being directly indicative of the vehicle’s response. This means that the direction of the control inceptor displacement is matched to the vehicle’s response, such that as displacement of the inceptor increases, the faster the vehicle will move in said direction. The DMF is believed to apply to all controls, not just the power inceptors that are the focus of this proposal.

Concrete examples of the DMF can be found in every type of fixed and rotary wing aircraft certified since 1946. Figure 1 illustrates the center stick/cyclic and rudder/tail rotor pedals found in fixed and rotary wing aircraft respectively which follow the DMF framework.

All of these primary controls follow the idea of intended action vector depiction described above. This requirement is actually indirectly mandated in part 23, 25, 27, and 29 subpart .779 certification standards of the Federal Aviation Administration:

**FAR Part §23.779: Motion and Effect of Cockpit Controls** (Airworthiness Standards: Normal, Utility, Aerobatic, and Commuter Category Airlines, 1996)

(a) (1) Primary Control:

Aileron; Right (clockwise) for right wing down.

Elevator; Rearward for nose up.

Rudder; Right pedal forward for nose right.
(b) (1) Powerplant Controls:

Power or Thrust; Forward to increase forward thrust and rearward to increase rearward thrust.

Propellers; Forward to increase rpm.

**FAR Part §25.779: Motion and Effect of Cockpit Controls** (Airworthiness Standards: Transport Category Airlines, 1990)

(a) (1) Primary Control:

Aileron; Right (clockwise) for right wing down.

Elevator; Rearward for nose up.

Rudder; Right pedal forward for nose right.

(b) (1) Powerplant Controls:

Power or Thrust; Forward to increase forward thrust and rearward to increase rearward thrust.

Propellers; Forward to increase rpm.

**FAR Part §27.779: Motion and Effect of Cockpit Controls**

(Airworthiness Standards: Normal Category Rotorcraft, 1984)

(D) (a) Flight controls, including the collective pitch control, must operate with a sense of motion which corresponds to the effect on the rotorcraft.
**FAR Part §29.779: Motion and Effect of Cockpit Controls**

(Airworthiness Standards: Transport Category Rotorcraft, 1984)

(D) (a) **Flight Controls, including the collective pitch control:**

*Must operate with a sense of motion which corresponds to the effect on the rotorcraft.*

While the primary three-axis (roll, pitch, and yaw) controls are identical in both fixed and rotary wing aircraft, the power control inceptors vary greatly, so much so that the controls are orthogonal and even reversed in many cases when compared to each other (fixed to rotary wing). However, even with this difference, each aircraft is able to indicate the intended vector of action through its control system.

Fixed wing aircraft utilize a throttle oriented along the x-axis in a body-fixed and stability control coordinate system. Helicopters utilize a collective oriented along the z-axis in a body-fixed and stability control coordinate system. While there are differences, neither a fixed wing throttle nor rotary wing collective violates the intended vector or response concept as described above as they each move in the direction of the intended aircraft response respectively.

The importance of this standardization is significant. It is this standardization of controls that allows pilots transitioning from one type of aircraft to another to complete only a “differences training” without having to relearn the fundamentals of flight. This standardization found in control design can be seen across almost every mainstream
vehicle in the western world, including automobiles, motorcycles, boats, airplanes, and helicopters.

While this standardization has been in place for over 50 years either in practice or as a request, it seemed logical that building the RTI within these confines would yield the most positive results. Therefore, emphasis was given to inceptor design techniques that would minimize the associated learning curve of the new RTI. The RTI had to be consistent with both helicopter and aircraft inceptors, and it was believed that it also had to map to the tiltrotor’s intended response throughout all flight envelopes. The system that resulted was a throttle interface in which the linear axis of throttle travel, common in both airplanes and helicopters, rotated in order to account for the added degree of freedom of the nacelle movement.

While the initial design of the RTI is fully documented in my Master’s thesis (Rozovski, 2008a), it is important to have an understanding of the high-level design requirements. Figure 15 depicts the initial RTI base prototype model. While all parts are labeled, the items of most importance are:

1. Rail Housing Rotation Axis
2. Rail Housing
3. Grip and Pinion Sled Rotation Axis
4. Grip
These four components allow the RTI to map congruently to the tiltrotor’s nacelle angle. In order to accomplish this there are 3 Degrees of Freedom (DoF) that need to be implemented:

1. Nacelle Matcher; This rotational DoF links the angle of the throttle travel to the angle of the nacelles. The Rail housing rotates around the “Rail Housing Rotation Axis” in order to accomplish this.

2. Throttle Positioner: This linear DoF is associated to the grip travel motion and allows the pilot to set the appropriate power.

3. Grip Positioner: This final rotational DoF enables the grip to counter-rotate in relation to the Nacelle Matcher in order to keep the pilot’s hand in an ergonomically correct position.
Figure 16 depicts a discretized composite graphic of the RTI rotating in relationship to the nacelle angle.

As noted in graphic 16, it is easy to see how the top of the grip rotates aft (in relationship to the aircraft) as the rail housing rotates forward.
Moving from the high-level non-functional prototype to a fully functional testable system was a significant challenge. There were multiple phases to this process. The initial RTI design requirements were as follows:

1. Meet all ergonomic requirements (necessary in order to satisfy level 1 of the DPH)
2. Allow the RTI to map congruently to the full nacelle range (Level 2 DPH)
3. Ability to interface to off-the-shelf flight simulators (X-Plane (Digital) was chosen)
4. Ability to interface to future flight simulation systems (i.e. NASA Vertical Motion Simulator (Analog))
5. Meet or fall below current tilt rotor throttle interface system weight (80 lbs.)
6. Address failure modes which had to be mitigated and completely accounted for.

In order to develop the full system, an independent electrical engineer and independent engineering draftsman where hired through an external source mechanism.
4.1 Electrical-Mechanical Design

Due to the limited funding nature of the project, it was decided early on to implement Certified-Off-The-Shelf (COTS) components as much as possible. This was done in order to reduce the development cost of custom components.

Of the six guidance requirements listed above, items 2, 3, 4, and 6 were focused on the electromechanical design phase. In satisfying item 2, allowing the RTI to map congruently to the full nacelle range, some form of actuation was needed. The two choices that were available were stepper motors and servos. In looking at the cost/benefit analysis between the two, it was deemed that the use, cost, complexity, and programming of a stepper motor was significantly less than that of a servo of equal size and capacity. In addition to this, stepper motors provided significantly higher movement and holding torque than an equivalently sized and priced servo translating to a smaller actuation system footprint.

To minimize cost further, two identical COTS industrial grade stepper motors and drive control units were selected to drive the RTI. The units themselves were highly available, they were very easy to program, a single size was available that could drive both the rail housing and grip rotation without having to have different sized motors or drive units.

In order to meet requirement 3, the ability to interface to off-the-shelf flight simulators, I implemented a USB Analog to Digital (A to D) interface. The electromechanical system could then be driven using a standard personal computer running Windows 7 interfaced
through a small C++ software module interfaced to Laminar Research’s X-Plane 9 for the flight math model.

One of the added benefits of placing an A to D interface between the system computer and the RTI itself was that the RTI could be driven in an analog direct mode in future testing such as NASA’s VMS (Req. 4).

The last requirement, item 6 was to address all failure modes. In order to mitigate any associated failures, it was decided that all control systems would be closed loop with normally closed signals. This is important because the torque and speed of the motors is so great that it could easily crush or cut a person if they were to get caught between moving RTI components. The importance of normally closed signals is that if you use a normally open system whose failure is indicated by a closed signal (i.e. current is turned on), if the safety system suffers a physical disconnect (i.e. wire gets cut), the system itself has no indication that anything is wrong because there is no change to the system state. With a normally closed system, the same physical disconnect cuts the signal which is the same action as the tripping the safety system, in turn shutting the system down. Even systems that were driven open loop due to connectivity limitations had normally closed safety switches that would close the loop at a specified spot within the actuation range.

Because of the complexity of this system from an electrical engineering standpoint, one of the concerns was the final connectivity validation. In order to mitigate this, many systems are typically bench tested in order to ensure proper working with all the
components. Figure 17 depicts the initial electromechanical drive bench test. Breadboards were utilized to rapidly prototype any needed circuitry including noise filters.

![RTI Initial Bench Test](image)

**Figure 17. RTI Initial Bench Test**

### 4.2 Mechanical System Design

As the electrical drive and circuitry system influences the majority of the mechanical design, it was not until after the electrical requirements were designed and frozen that we took on the task of designing the mechanical and structural system. There was some interplay between the two design sides but the predominant driver was the electromechanical system.
Because the RTI was designed to be installed into all existing and future tiltrotor aircraft, analysis of current physical constraints such as size and connectivity requirements were considered. The RTI is a combination of both a fixed-wing throttle and a rotary-wing collective, so the physical location of the unit is critical in order to meet the proper ergonomic placement of both power interfaces. Throttles typically sit higher and further forward with respect to the pilot than collectives, which often are found lower and further aft.

4.3 Multi Mixed-Command Degree of Freedom Control System Design

In order to counter rotate the grip (3 DoF), actuation needed to be effected upon the grip mechanism. Typically, from a mechanical engineering perspective, direct connection to the motor is what would be recommended. The problem with this is that electric motors of sufficient power density are not available in a form factor small enough to be feasible. Implementing a motor of sufficient power adjacent to the grip would mean that the grip would weigh a minimum of 10-20 lbs. Manipulating this much weight even in a neutrally buoyant system would cause detriments to fine controllability as larger, less sensitive muscles in the pilot’s arm need to be employed to make fine adjustments.

In order to still have control of the grip while not increasing its mass by orders of magnitude, a new design was reviewed that would allow the actuation systems to be implemented upstream of the system’s three DoFs. This approach was unique in that no other control system known to date has maintained control of the end point DoFs while
letting the operator control the intermediate DoF. Another way to look at this is that, within the RTI, there are three Degrees of Freedom as stated earlier:

1st DoF: Nacelle Angle

2nd DoF: Commanded Power Axis

3rd DoF: Power Grip Counter Rotation

The 1st DoF is controlled by the system itself. In order to mitigate cross-coupling, it was decided that the pilot would only be allowed to continuously manipulate one DoF; the Command Power Axis (i.e. throttle/collective). With this requirement, DoFs 1 and 2 had to be controlled continuously by the system, but directed by the pilot (by discrete switch as found on the V-22 and AW-609). It is important to note that the 3rd DoF, the power grip counter rotation is closed-loop controlled by the 1st Degree of Freedom (Rozovski, 2008a) and its rotational position in space is linearly correlated to the angle of the rail housing (i.e. each angle position on the rail housing corresponds to a specific angle on the grip).

To accomplish this, a novel mechanism needed to be created. No one has ever created a mechanical system in which the DoF end points where controlled by the system while allowing the operator to control the intermediate DoF. The problem the RTI faced was that, because of the limitations in drive system power density and the issues with increasing the mass at the grip, all the actuation for the grip had to be transferred through DoFs 1 and 2. There were multiple design iterations over the course of a year and half to
find a mechanism that reduced both mechanical complexity and weight. The system weight target for the RTI was 40 lbs. or less as the current collective system in the AW-609 is ~80 lbs. Figures 18, 19, 20, and 21 depict the mechanical system.

Figure 18. RTI Lower half of arm housing

Figure 19. Rear RTI Arm Interior View
Figure 20. Front RTI Arm Interior View

Figure 21. RTI Arm Mechanism Detail View
This mechanism, known as the Concentric Power Transfer Axis (CPTA) enables high-torque/high-energy transfers through relatively small confines. The system does so using a linear ball spline shaft or LBSS. The LBSS allows rotational energy to be transferred at a variety of speeds and loads with no effect on the linear movement element of the system. The reason for this is that the two power transfers are orthogonal to each other and neither has an effect on the other power transfer. This allows the RTI to maintain freedom of the 1\textsuperscript{st} and 3\textsuperscript{rd} DoF while allowing free movement of the 2\textsuperscript{nd} DoF. This ability is necessary for designing a fully conformal and DMF compliant tiltrotor power inceptor.

Figures 18-21 also depict the progression of the systems mechanical design. To rotate the grip within the housing, power is transferred to the cross cut helical gear (part 1) that in turn transfers rotational power to two meshing spur gears (part 2) of different diameters which transfer power to a worm on a linear ball spline shaft. The worm rotates the worm gear (part 3) (located above the worm) which rotates the grip power positioner.
The implementation of the linear ball spline (within part 3) and shaft allows the worm (part 3) to be rotated when commanded yet move freely linearly via the pilot’s inputs (Figure 20). The rotation of the worm (part 3) controls the rotational position of the grip while the linear displacement of the worm and worm gear (attached to the grip) (part 3) command the power position. It is the implementation of this mechanism that allows the RTI to keep control of the end point (1\textsuperscript{st} and 3\textsuperscript{rd}) DoFs while allowing the pilot to freely control the 2\textsuperscript{nd} DoF power grip position.

In order to deliver power to the cross cut helical gear (part 1) power is delivered via an extended shaft worm similar to part 4a. The worm transfers power to the mating cross cut helical gear (part 5) which intermeshes with part 1 of the housing. The configuration is similar except smaller than that of part 4.
The key importance to the design is transferring power concentrically through the actuation axes in order to not apply force to other areas. By passing rotational power through the center of existing rotations, that power can then be routed out downstream and used to control components of interest. In the case of the power grip (3rd DoF), a tremendous amount of actuation power was made available by placing a larger motor upstream of the grip through the described mechanism.

Another novel feature that was implemented was a pilot lockout that impeded the pilot form back-driving the system. To enable this, worm gear mechanisms are used. The benefit of a worm gear is that you get tremendous torque advantage due to the natural reduction the screw provides in addition to the inability to back-drive the system from the other side of the actuation end. As flight controls need to represent their action and movement very precisely, it would be detrimental for such a system if it moved without imparting effect on the control system. As stated before, the rail housing and power grip are controlled by the system and commanded by the pilot through a discrete switch (as per spec on the V-22 and AW-609). Since both the rail housing and power grip have such a long moment arm, it would be very easy for the pilot to move the system uncommanded by placing force on the unit. This concern is eliminated with the insertion of the worm gear as the applied force is transferred to the static structure and not the actuation system.
4.4 Overall Structural Design

With all projects, there are driving factors that influence the design. In the case of the RTI, there were the six key requirements listed above but in addition, the unit needed to fit within the aircraft, both physically and aesthetically.

To address weight, cost, esthetics, and structure, aircraft grade aluminum of different types was used in the RTI’s construction. Aluminum affords a variety of benefits for rapid prototyping:

1. It is easy to machine
2. Does not corrode readily
3. Can be anodized

Because COTS components were used, both the motors and the motor controllers were relatively large compared to the RTI as a whole. Due to this, we decided to separate the RTI electromechanical components from the electrical system and join them through an electric umbilical cord. The base housing structure was a six-sided structure that used an internal aluminum sub-frame skeleton for support (Figures 23, 24, and 25).
Figure 23. Lower RTI Frame (Rear Right)
Figure 24. Lower RTI Frame (Front Right)
Access panels, cooling fans, emergency shutoffs, system feedback indicators (i.e. lights, gauges) were all placed within the CAD package for design validation (figure 26 and ported over to final manufacturing.

Figure 25. Lower RTI Frame (Front Left)
One of the major lessons learned in building the RTI was the criticality of proper tolerancing. To assist with design aesthetics as well as long-term corrosion protection, the unit was anodized matte black. The reason for this selection is that this finish is known to reduce glare which could potentially distract the pilot, and matched current tiltrotor aircraft interior configurations. One of the advantages of anodizing over powder-coating is that there is relatively no material build up on the surface of the piece. This said, the thickness of the anodization compound is a function of how well the current used in the process is controlled. Because the RTI is a flight control system, tolerances were kept
very tight (typically -0”/+0.0005”) in order to eliminate mechanical slop or hysteresis. Machining tolerances took into account the milling and cutting, however the anodization was not accounted for, as the process, if done properly, does not leave any material build up. Unfortunately, this was not what occurred in the case of the RTI. It appears, after post analysis, that the current was not held constant and exceeded the recommended specification. This was determined by the fact that the thickness of the anodization well exceeded any current norm. To compound matters further, critical fit parts were not masked off due to time constraints allowing the anodizing material to infiltrate high precision areas.

Fitting of the unit went relatively smoothly as the CAD model was used to do virtual builds prior to final manufacturing and assembly. Figures 27, 28, 29, and 30 depict a composite assembly sequence of the RTI build progression.
Figure 27. Lower RTI Section
Figure 28. Lower RTI and Arm Mechanism Section
Figure 29. Open RTI Mechanical Section
In addition to the RTI, a control box was also designed and built in order to house the motor controller, fuses, power supplies, A/D converter, power filter, shutoff connectors,
fans, status lights, bus bars, and A/D external I/Os. While not an integral part of the design, every attempt to reduce system footprint was made. Figure 31 shows a mockup of the components prior to placement in the CAD software.

![Image of control box components](image_url)

**Figure 31. Control Box Concept Layout**

Once initial placement was decided upon, construction of the surrounding frame cage and panels were assembled. Figures 32 and 33 depict the final control box configuration.
Figure 32. RTI Control Box (Front)

Figure 33. RTI Control Box (Rear)
Construction of the fully functional RTI prototype was completed in the summer of 2010. The final prototype took approximately 18 months to manufacture and assemble and consisted of more than 350 components. The prototype unit demonstrated a 18% weight savings with an estimated 50% weight savings in final production over the current BA-609 collective system (D. King, personal communication, July 10, 2007).
CHAPTER 5 NASA AMES VERTICAL MOTION SIMULATOR EXPERIMENT

In order to study the RTI in its intended environment and validate the claims set forth in the Design Principle Hierarchy (DPH), testing was conducted on the Vertical Motion Simulator at NASA Ames. Figure 34 depicts a model of the system. The use was supported by a donation of time on the simulator by NASA. Because this work was integrated with other work being done using the simulator, tight control and rigorous experimental design was not possible. However, this lack of control was a tradeoff against being able to utilize a unique facility with high fidelity and actual military test pilots.

Figure 34. NASA VMS Model
The VMS is the largest flight simulator facility in the world. It is capable of 60 feet of vertical travel, 40 by 20 feet of lateral (x,y) movement, and sits on a 6 DoF yawable hexapod. The benefit the VMS’s large displacements provides is an unparalleled realism to what would be sensed in the actual aircraft.

5.1 Experimental objectives

Between the two groups, the NASA experiment combined three objectives:

1. RTI testing throughout its full envelope
2. Comparison testing of the RTI to the NASA Thrust Control Lever (TCL) baseline
3. Validate the claims made in the Design Principle Hierarchy (DPH)

Testing of the RTI is complex in that there are relatively few simulators in the world that provide a full envelope (with nacelle transition) tiltrotor math model. In fact, there are only 4 high-fidelity, full envelope experimental tiltrotor simulation models in the world, three are owned by Bell, Boeing, and Agusta-Westland and the remaining one is owned and operated by NASA. The ability to operate the aircraft anywhere in its designed envelope makes the NASA VMS an ideal testing facility to test the comparative baseline, the RTI through its full envelope, and be able to validate the claims made in the DPH.

DPH at the time of testing consisted of two levels:

1\textsuperscript{st} level: Ergonomics

2\textsuperscript{nd} level: SR compatibility
The idea was that in order to create an appropriate inceptor for continuous control, that the interface itself needed to be ergonomically sound (i.e. not violate any biomechanic principles) and maintain SR compatibility throughout its entire use, such that the direction of movement of the control would be consistent with the intended direction of acceleration of the vehicle. If the DPH did in fact hold true, then the RTI should provide improved controllability and system awareness to the pilot. As the test itself was designed to be subjective in nature, a baseline inceptor, the NASA Thrust Control Lever, was used as a control.

5.2 NASA Thrust Control Lever

The NASA Thrust Control Lever (TCL) (Figure 35) is a design developed by NASA to control their operational concept of a Large Civilian TiltRotor (LCTR). The unit closely mimics the collective of the Boeing-Vertol CH-47 in both design and physical movement. The TCL is a single axis linear inceptor supported by an air bearing and travels seven inches aft and up (increase power) through down and forward (reduce power) (in relationship to the pilot). The unit itself is connected to a NASA modified McFadden force feedback control loader to provide centering trim and neutral buoyancy.
5.3 RTI/VMS Compatibility

Connectivity between the RTI and VMS had to be accomplished. As stated in item four of the initial six RTI design requirements, I wanted to have the ability to interface to future and existing flight simulators. In order to do this, I decided that the RTI would be able to be driven either digitally or analog depending on our requirements. When NASA offered to provide simulation time on the Vertical Motion Simulator (VMS), the first step was to gain a better understanding of the Interface Control Document (ICD). The ICD is the defining communication protocol between the external world and the machine for which it is written. In the case of the VMS, the system, which was built in 1980, uses FORTRAN programming language to run the system and the I/Os to the system are predominantly analog.

Because having the capability to accommodate for analog or digital was deemed an initial requirement, enabling the RTI to interface to the VMS was more a matter of the physical
connection than a modification to the interior components or design of the system. To interface the VMS, the RTI had to have the following I/Os:

1. Nacelle Angle; Input  
2. Grip Rotation Angle; Input  
3. Throttle Placement; Output  
4. Discrete Nacelle Angle Command Switch; Output  
5. Continuous Nacelle Angle Command Switch; Output  
6. Arm Angle Limit Switches; Internal I/O  
7. Internal Emergency Stop; Internal I/O  
8. External Emergency Stop; Internal I/O

The nacelle angle input (item 1) provided the angle of the nacelles from the VMS tiltrotor model to the RTI. This was accomplished through a 0-5 volt analog signal. The signal itself was closed looped through a single-full-turn rotary potentiometer that provided a 0-5 volt signal back to verify its position. Calibration of the unit was accomplished through an engraved protractor on the back of the RTI unit prior to beginning the experimental trials.

The grip rotation input (item 2) was provided through a linearly interpolated formula \( m \cdot \text{ArmAngle} + b = \text{GripAngle} \). “m” is the factor modifier for the grip position and allows the grip angle to be a function of the arm angle. “b” is the offset modifier and sets the grips initial position. Using “m” or “b”, the grip can be set to any number of positions and then be driven as a function of the arm angle.
Throttle placement position was fed out through a linear 150mm potentiometer running on 0-5 volts. Calibration was done using the end-points of the throttle travel. The RTI has the ability to produce 5 volts, though, in order to minimize noise and interference, all signal current was fed in through the VMS and then back out again after being modified by the sensing potentiometer.

In order to both drive the model’s nacelle angle and have a comparative baseline to NASA’s TCL, modifications were made to the RTI’s grip (Figure 36) in-house to accommodate separate discrete and continuous nacelle control switches. The discrete switch is a spring to center bi-directional 0-5 volt switch. Movement of the discrete switch commanded a nominal rate of 2.5 degrees per second nacelle transition. The continuous switch was an Otto stadium style 4-way hat 0-5 volt switch. Even though the switch was able to move across 2-axes, only the single longitudinal axis was implemented in the RTI. Movement of the switch commanded a 0-7.5 degrees per second nacelle transition rate.
Figure 36. RTI Grip
During the integration of the RTI into the VMS, an unanticipated failure mode was noted. In driving the RTI, the VMS system computer would send a start and stop signal to control the grip angle. The stop was triggered by the position potentiometer’s feedback. However, if the computer crashed after the start signal was given then sensing of the position potentiometer would cease and no stop signal could be given. As stated before, the torque ratings associated with the motors is significantly high. If the RTI hit its mechanical stops, then it could destroy itself. In order to mitigate this potentially catastrophic failure mode, limit switches were implemented to control the rail housing’s position. The limit switches however were connected to the stepper motor position and speed controller via a normally closed signal. Two independent switches were employed, one for clockwise (CW) rotation and one for counterclockwise (CCW) rotation. By implementing the switches in this manner, it could disable driving the system in one direction to occur but allowed the system to back itself out if needed. In addition, using a normally closed signal, if the limit switches were disconnected from the system, then the unit would also shut down. This was advantageous, as in a normally open system, a disconnect would not register as there would be no system state change.

The last portion of the I/O series was the internal and external emergency stops. Again, as the motors were capable of tearing the unit apart, safety considerations for the pilot and system observer needed to be implemented. Two separate emergency shutoffs were provided. Each one was normally closed and a trip or disconnect between the system and switch would command a full power-down.
During RTI assembly, I requested an example of the connector plug that would be used for the VMS trials. This was done so that the plug could be incorporated physically into the system, reducing the amount of effort needed to connect the RTI to the VMS. In order to switch between the digital/analog system, the engineer would simply remove a plug from the Digital I/O board, bypassing all signals to a pure analog format.

5.4 VMS Bench Testing and Connectivity Verification

While provisions were made to mitigate the connectivity impact of the RTI to the VMS, calibration and testing needed to occur. As the VMS is a heavily utilized and expensive resource, projects typically do not have the luxury of validation testing on the motion beam prior to the experiment. In order to accomplish this task, testing needed to occur on a test bench. Figure 37 depicts the bench test configuration.
Bench testing consisted of the same analog system driver interface used on the VMS sans the primary simulator computer. As the command to the analog bridge is digital and standardized, only one component of the full system needed to be present in order to validate 90% of the drive routine. Figure 38 depicts the analog system driver.
The orange and blue patch panel on the right side of the unit are designed to be configured and moved with the system to the VMS to minimize configuration changes across system platforms. From the VMS system perspective, the RTI appeared just like any of the other flight controls the system utilized once coding was complete.
5.5 Experimental Design

Testing was accomplished using NASA’s CTR-4/95 tiltrotor model. NASA’s CTR-4/95 provides a commercial-class, V-22 sized, full-envelope tiltrotor while the NASA Ames visual scene provides both low and high speed operation areas within a familiar environment for the test pilots.

The NASA Ames VMS T-Cab (Transport-Cab) was utilized for the experiment. The cab was configured with a single set of controls for the right pilots seat consisting of a center stick, rudder pedals, and a power inceptor (TCL or RTI) mounted to the left of the pilot. The center stick and pedals were back-driven to set the inceptor trim positions at the start of each data run via NASA modified McFadden control loaders. The flight control system response type was Rate Command Attitude Hold (RCAH) for all testing.

Seven independent collimated visual displays consisting of a left and right $90^0$ lateral view (2), a left and right $45^0$ quartering view (2), a left and right $0^0$ view (2), and a chin window view (1) positioned on the right side of the flight deck for the flying pilot (all angles are referenced from flight deck pilot eye point) (Fig. 39).
Pilots were provided three reconfigurable displays (Fig. 7) consisting of the NASA Ames CTR PFD (Fig. 8), the NASA Ames VMS emulation of the CAAS Horizontal Hover Display Page (Fig. 9), and a standard top-down navigation plan view display. In addition, all three displays were emulated on the left side non-flying pilot’s station. A center display was also provided for ADS-33E maneuver criteria measures for in-between trial review.

Figure 40. NASA Ames VMS T-Cab (Captain’s side) with TCL

Figure 41. NASA Ames CTR PFD
Aeronautical Design Standards (ADS) -33E course sections were used in addition to ad-hoc courses to test the full conversion and speed envelopes of the tiltrotor.

The RTI was evaluated against the TCL by four test pilots on seven separate courses. The four evaluation test pilots came from a mixed background of either rotary-wing, fixed-wing, tiltrotor, VTOL or a combination of two or more. Each of the seven evaluation courses had an associated speed (low vs. high) and envelope transition usage (nacelles fixed, partial, or full) associated with it in order to test the RTI and TCL through all of their possible speed/envelope transition configurations.

Each of the seven test maneuvers were derived from existing ADS-33E tasks, previous LCTR simulations, and newly developed tasks to test the tiltrotor nacelle conversion corridor envelope with the RTI. The seven maneuvers consisted of hover, vertical
maneuver, depart/abort, Nap-Of-the-Earth (NOE), brown-out landing, aborted VFR “normal” approach, and instrument guidance approach task. The hover, vertical maneuver, depart/abort, and instrument guidance approach task had objective performance goals the pilot needed to meet. Depending on the achieved performance (Appendix 4), the task was assigned either a desired, adequate, or inadequate performance rating. For the NOE, brown-out landing, and aborted VFR “normal” approach, no objective performance metric was utilized, though pilots did respond to the experiment questionnaire (Appendix 5) as in the previous four. While the objective performance metrics were recorded for the experiment, only the HQR ratings based on this data was reported. The reason for this is that the evaluation contained distinct parts from NASA and this paper’s research. The NASA portion was not able to be reported due to the experiment being considered a flight test and no IRB provision existed for such data. The following section will describe each task maneuver.

1. Hover; Low/Fixed
   a. The hover runs were accomplished by maneuvering the vehicle from a predetermined start location offset aft, laterally to the left, and at a fixed altitude above a target area. Guidance was provided via traffic cones, targets, and target boxes outside of the cockpit in front of and to the right of the pilot. An example of these out of the window targets can be seen at the right side of Figure 39 & 40.
2. Vertical Maneuver; Low/Fixed
   a. The vertical maneuver was accomplished by executing a vertical climb, arresting at a specified altitude, and then a descent to the start position within a specified time while maintaining heading, longitudinal, and lateral position within specified desired and adequate limits. Guidance again was provided via simulated traffic cones, targets, and target boxes oriented in front of and laterally to the right of the pilot.

3. Depart/Abort Maneuver; Low/Partial
   a. The depart/abort maneuver began with the aircraft in a hover at a predetermined fixed location. Using the nacelle rotation, the pilot accelerated to 40 knots. At 40 knots, using nacelle control, the pilot decelerated to stop at a hover within a predetermined area. The time to complete the maneuver, stopping position, and vehicle attitude were used as performance measures/metrics.

4. Nap-Of-the-Earth; High/Partial
   a. Performance of the inceptors in low level flight was evaluated using a simulated Nap-Of-the-Earth (NOE) task through the NASA Ames campus. Speed was controlled via nacelle rotation and throttle position. Speeds ranged from 0 to 85 knots. Figure 11 depicts the simulated NOE course.
5. Brown-Out Landing; High/Partial
   a. The brown-out landing was a straight in visual approach. At 35-50 ft. above the runway and at speeds slower than effective translational lift, a brown-out condition would be simulated by occluding all visual references except for the view out of the pilots lower right chin window. The pilot was instructed to continue the descent to a full touchdown.

6. Aborted VFR “normal” approach; High/Full
   a. The aborted VFR “normal” approach was identical to the brown-out maneuver except that instead of a brown-out condition being presented, the pilot was instructed to execute a go-around at the 200ft agl decision height. The task was complete once the aircraft was converted to full airplane mode with the vehicle in a climbing ascent at 200 knots or more. No objective performance metric was utilized for this task.
7. Instrument Guidance Approach; High/Full

   a. The instrument guidance approach task was the longest of the seven maneuvers and was a full visual approach to land with the pilot beginning on a $45^0$ entry to left downwind for Moffett field. The pilot was required to convert the aircraft from airplane to helicopter mode and execute a landing at the runway number markings. No objective performance metric was utilized for this task.

   Pilots flew each course a minimum of three times for practice followed by one trial data run. At the completion of the run pilots were asked to provide comments based off of an 18 item questionnaire (Appendix 5) and assign a Handling Quality Ratings (HQR) score to the task. The HQR Scale was developed by Cooper and Harper after World War II and was designed to provide ratings on the systems being evaluated. The scale, as depicted in figure 44, is designed to be used only by formally trained test pilots and is broken down into 4 levels.
During the experimental trials, after the TCL was tested first with all pilots, the VMS T-Cab was moved to the motion beam. As the testing time on the VMS was given under donation by NASA, the initial test protocol had the TCL and RTI being tested without motion. The primary reason for this being cost impact as the VMS with motion can cost upward of $250K per week. Due to a variety of serendipitous circumstances, midway through the testing of the TCL, the T-Cab was moved to the motion beam and the RTI was able to be tested both in stationary and motion configurations.
5.6 Results

From a flight perspective, control was possible throughout helicopter, fixed-wing, and transition modes with both the baseline TCL and experimental RTI. However, some data illustrated some deficiencies with the RTI that were reflected in the pilot’s comments and HQRs. Pilots reported three predominant concerns with the thrust control operating the RTI:

1. The rotation of the RTI with nacelle angle during transition created some confusion in which way to move the grip to control the throttle.

2. Pilots were not able to distinguish between fine changes in the RTI’s housing angle making interpretation of exact nacelle position angle difficult. While this did not have an effect on overall task performance, it was an unexpected finding.

3. Precise throttle control with the RTI was difficult due to an unanticipated binding of the system along the throttle axis.

These concerns are discussed further in the following sections.

5.7 HQR Results

There were some initial issues with the data collection routine that did not allow for full collection of all HQR data points. The data presented below is the same data presented at the 67th American Helicopter Society forum at Virginia Beach (Rozovski & Theodore, 2011). Presentation at this conference was a requirement by NASA in order to use the VMS.
In total there were three experimental test pilots that completed the experiment with both the TCL and RTI configurations in fixed-base simulation (RTI-F), and the RTI in motion-base (RTI-M) as well. The fourth pilot was not able to complete all tasks on motion and fixed-base due to time constraints.

Table 1 shows the handling qualities ratings results for the Mission Task Elements (MTEs) for which handling qualities ratings were collected. The TCL results shown in this table were collected with the VMS cab on a fixed platform (no motion). The RTI results were collected both with the cab fixed and with motion. “RTI-F” refers to the results with the cab on a fixed-platform, and “RTI-M” refers to the results with motion.

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<th>Hover</th>
<th>Vertical</th>
<th>Depart/Abort</th>
<th>IFR</th>
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<td>5</td>
<td>4</td>
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<tr>
<td></td>
<td>RTI-F</td>
<td>5</td>
<td>3</td>
<td>4</td>
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<tr>
<td></td>
<td>RTI-M</td>
<td>4</td>
<td>3</td>
<td>4.5</td>
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<tr>
<td>Pilot 2</td>
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<td>RTI-M</td>
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<td></td>
<td>RTI-M</td>
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Table 1. Handling Quality Rating Results
Pilot 2 was a fixed wing pilot with Harrier experience and was not accustomed to helicopter flight and collective control systems for hover and low speed tasks, specifically the rate command attitude hold. The HQ ratings of 7 could therefore be explained by the pilots training and inexperience with helicopters.

The hover and vertical maneuver task results shown in table 1 did not require any nacelle angle change and therefore did not include any effects of RTI transition. The results for these two tasks show a slight degradation in the handling qualities ratings with the RTI when compared with the TCL. This degradation is also reflected in the pilot comments to the questions listed in the appendix. The differences in ratings were not a result of RTI transition as it did not rotate during the hover and vertical maneuvers. The differences however can be explained by the following:

1. The physical positioning of the RTI is a compromise between a collective and throttle due to its combination of the two and its transformation via rotation. Pilots commented that the RTI did not feel as natural as a standard collective, throttle, or TCL which is also a collective effectively. The reasoning for this is that the linear displacement of the RTI in either collective or throttle mode does not and cannot replicate a collective or throttle.

2. All pilots noted some binding or stiction of the RTI’s throttle travel making it difficult to precisely set and adjust the throttle grip position. Pilots were asked to comment on the binding, but to try to limit its effects on the handling qualities ratings. It is still suspected that some of the degradation in HQ ratings with the
RTI is still due to the binding. The reason for the binding was due to a manufacturing error. The RTI’s throttle is a sled that moves along two parallel bars. Due to anodization issues, the travel bars had a center distance that was shorter than the center distance of the receiving race on the throttle sled assembly. Due to this mismatch, binding would occur at the extreme points of the throttle travel due to a wedging effect. The RTI’s throttle, however, experienced little to no binding in the center ranges as the bars were able to flex to the appropriate center distances set by the throttle sled assembly.

Binding or high breakout forces can have severe effects on precision control, requiring very high initial force with low continual force after, something that is very hard to modulate if not properly supported. This is believed to have contributed to the degradation in the associated HQRs.

3. A third possible reason was that the orientation of the grip and amount of travel available between the TCL and RTI grip were different. The TCL motion axis is also angled slightly aft of vertical, while the RTI motion axis is slightly forward to match the nacelle trim pitch attitude of 86 degrees for this aircraft on vertical takeoff as to ensure that the mains always touch first during landing and to mitigate nose wheel loading on takeoff. The RTI’s straight upward vertical throw was the focus of many comments regarding ergonomics or comfort, which is believed to have driven the HQRs downward. Based on the RTI design drivers, this was not a negotiable feature of the system.
For the depart/abort and instrument guidance approach tasks that involved nacelle angle changes and corresponding rotation of the RTI, HQ ratings were generally worse with the RTI than with the TCL. One factor to keep in mind when considering these results is the influence of the binding or stiction that was seen with the RTI. As previously mentioned, pilots were asked try to limit the effect of binding on their handling qualities ratings, or essentially to provide a handling qualities rating for the RTI if binding had not been present. Even with this instruction, it is still believed that the binding issue accounts for some of the degradation with the RTI HQRs and is reflected heavily in the comments.

Another important factor in the degradation of the handling qualities ratings with the RTI is that pilots experienced some confusion as to which direction to move the grip to add and remove power during nacelle transition as the flight condition and nacelle angle changed. This will be discussed in more detail later in this section.

In order to more fully assess the effects of the RTI, it is important to consider the pilot comments in the evaluation. Typically pilot comments provide a much richer set of data than just the handling qualities ratings alone. With respect to the binding, the predominant effect was that it was more difficult to make fine power adjustments along the throttle axis. Subjective pilot comments further indicated that the magnitude of this effect was tightly coupled to the aggressiveness of the maneuver. One pilot reported in the brownout maneuver for the 2nd question inquiry, “not an aggressive maneuver but able to be as aggressive as wanted to be, precision for RTI was fine.” In contrast, in a similarly aggressive maneuver, another pilot indicated, “just following the guidance, aggressive to follow the guidance… with RTI tended to put in too big an input which was
a function of the binding.” Unfortunately, correction of the binding issue was not possible during this test, however it was resolved after and is not considered to be a technical hurdle of the system. While pilots were asked to try to disregard the binding in the system, it still affected HQR ratings and comments throughout the entire evaluation.

For the depart/abort and instrument guidance approach tasks, the RTI vibrated slightly while the inceptor was converting due to a slight misalignment of the internal gear mechanisms that controlled the rotation. This was not intended, but did give a positive outcome where the pilots received a haptic indication that the nacelles were actually moving via the inceptor vibration, this was noted particularly by the pilots who had no prior tiltrotor flight. The single pilot with tiltrotor experience was more familiar with the response of other cues in the cockpit (e.g. outside visuals, motion, and cockpit cues) as to whether the nacelles were moving. For pilots that are unfamiliar with these vestibular/visual cues, the only indication of nacelle angle and movement is from an indicator on the PFD; an example of this symbology can be found in the upper left corner of the displays in figures 41 and 42.

Pilots commented that neither the rotational position of the RTI nor the RTI grip provided a precise reading of the nacelle position. Pilots were able to distinguish between gross position changes and major orientations such as vertical or horizontal, however, they were not able to sense RTI position with greater than ~20 degrees of accuracy.
Pilots also commented that they often found themselves trying to move the throttle grip in the wrong direction to increase and decrease thrust against the direction of travel, particularly during conversion. Pilots commented that they were often trying to push the grip in the wrong direction. One possible reason for this issue could be attributed by the method in which rotary-wing pilots manipulate power settings verses fixed-wing pilots.

In a conventional helicopter, the pilot adds power by pulling with their fingertips, while in an airplane, power is added by the pilot pushing with their palm. Because the RTI combines both of these inceptors into a single device, the confusion may lie in that midway through, the proprioceptive aspect of the control strategy reverses.

One pilot commented that it may be better if the pilot was able to manually control the conversion of the RTI between helicopter and airplane mode rather than having it automatically tied to the nacelle angle. This way the pilot would be able to control when the inceptor transitioned from vertical (helicopter) and horizontal (airplane) modes. This may eliminate the confusion in which way to move the inceptor in the intermediate (transition) positions.

5.8 Conclusions

Pilots indicated some deficiencies in the RTI partly due to an unintended binding issue along the throttle axis. Non-linear binding along the throttle axis causes significant detriment to the pilots ability to accurately set power control. The conclusions gained from this study were valuable in understanding the critical components of the design, construction, execution, and testing of the RTI. The main lessons learned were:
1. Pilots were able to perform all of the tasks with the RTI throughout helicopter, airplane, and transition flight modes.

2. The 1:1 mapping of the inceptor angle to the nacelle angle did cause some confusion during nacelle rotation as to which direction to move the RTI grip to control power.

3. Fine angular sensitivity was not possible in the RTI within better than 20 degrees resolution.

4. Haptic feedback from the RTI during nacelle rotation provided an additional beneficial cue of nacelle movement.

5. Physical placement of the RTI was difficult due to a compromise in fixed-wing throttle and rotary-wing collective positioning differences.

5.9 Major Findings, to the Design Principle Hierarchy

During testing, deficiencies with the RTI were discovered. Two deficiencies in particular were noted: first, the pilot was unable to distinguish between small angle changes of the RTI during RTI movement, and second, the pilot suffered control reversals. While angular sensitivity is understandable, the control reversal occurrence was not anticipated.

The control reversal appears to be driven by a violation of a previously un-described phenomenon, proprioceptive consistency.

Proprioceptive consistency is defined here as the individual's use of specific and consistent haptic cues that guide them through the proper control strategy. For instance,
in an automobile, with the individual’s hands at the 10 and 2 o’clock position, the control inputs to make the car turn left or right remain consistent as well as the haptic or proprioceptive sensation the individual experiences. This is to say, the force and direction of force a person perceives on their hand during this event is consistent for each respective action. Violations to this principle may to drive control reversals, as the individual erroneously relies on the cue in order to execute their control strategy.

This finding suggests that an additional principle is needed within the DPH for proper inceptor design: Proprioceptive consistency. To accommodate this new principle, one would have to make the haptic feel the device consistent across the flight envelope. However, in order to accommodate this principle, the RTI would have to be placed above and forward of the individual’s lateral axis shoulder point, which would then violate the first level of design; ergonomics. The new structure of the design theory would appear as follows:

1st level: Ergonomics

2nd Level: Proprioceptive Consistency

3rd level: SR compatibility

An alternate solution to resolve this issue is to discretize the RTI’s transition envelope (Figure 45), reducing the amount of time the pilot spends in the portion of flight where the proprioceptive inconsistency occurs. Specifically, when the tiltrotor is operating in helicopter mode, the RTI would represent a helicopter collective, and when the tiltrotor is
operating in airplane more, the RTI would represent a throttle, the transition between the two would occur quickly and automatically based on a separate parameter such as flight envelope state (i.e. helicopter vs. airplane).

Figure 45. RTI transition corridor with associate hysteresis (Rozovski, 2008a)

By driving the RTI this way, the hypothesis is that angular sensitivity will not interfere, since the RTI is not indicating nacelle angle but rather flight envelope mode. It is because of this that it is thought that the proprioceptive consistency could be eliminated as there would now be a discrete and clear indication of what control strategy to use. The purpose of this new mode is based on an identification that in order to provide a true Rotational Throttle Interface, it is simply not possible to adhere to all three principles. To mitigate the effects of this, the pilot would be cued according to the vehicle’s mode: either aircraft or helicopter, as opposed to the original variable of nacelle angle. This method effectively
replicates the design of the XC-142 inceptor configuration, except that there is one control system, not two, and the pilot does not need to remove his or her hand from the controller during flight.
CHAPTER 6 NATIONAL RESEARCH COUNCIL OF CANADA’S FLIGHT RESEARCH LAB SIMULATOR EXPERIMENT

After completion of the flight simulation tests at NASA, the binding was reduced by approximately 90% by realigning the guide rails. To test the RTI without the majority of the binding issue, and to evaluate the “two-mode” recommendation from the NASA evaluation, a second set of flight simulation evaluation were designed and conducted at the National Research Center of Canada’s Flight Research Laboratory. The experiment was designed to test the hypothesis of the Proprioceptive Consistency criticality and the proposed solution of discretization of the RTI control modes (collective vs. throttle) by reducing the amount of time the pilot spends within the transition mode.

6.1 Experimental Design

The primary question the second follow up experiment was designed to answer was:

1. Does automating the motion of the RTI according to the vehicle’s flight envelope mitigate or eliminate control confusion? Alternatively does the new mode possibly increase confusion and control reversals?

Handling Quality Ratings about the inceptor proper were the primary metric used to evaluate whether the automated transition of the RTI result in superior handling qualities when compared to the conditions in which the RTI position matches nacelle angle or is
fixed vertical mode. All three conditions will be carried out without (almost all of) the mechanical binding that was present in the previous trial using the NASA VMS.

6.2 Approach

In the initial experiment, the RTI was driven using a 1:1 correlation to the vehicle’s engine nacelle angle (Figure 46).

In addition to this mode, a fixed vertical mode will also be implemented. In the original VMS study, the nacelle driven mode was tested against the NASA Thrust Control Lever (TCL). The TCL moves similar to a collective found in helicopters. As the configuration in the current simulator does not provide the rapid flexibility of control changes as in the VMS, the RTI will attempt to mimic the TCL by being locked in the vertical position. It is understood that the throw angle of the TCL and RTI do not match.
In the present experiment, a new method named “flight envelope” driven mode controls the RTI via the vehicle's flight envelope as opposed to the nacelle angle. While the figure depicts a vertical and horizontal position, it does not show the intermediate angle positions that occur automatically through the transition. Transition would occur at the following speeds:

1. Collective => Throttle: 120kts
2. Throttle => Collective: 80kts

These speeds were chosen based on feedback during pilot evolutions of the simulated vehicle's flight envelope.

The rationale behind this new mode is to reduce the ambiguity of the intermediate nacelle ranges by reducing the allowable time within these ranges and allowing the pilot to operate in a familiar collective or throttle inceptor style environment. It is important to note that while the RTI does convert automatically at a predetermined range, the nacelles are still controlled by the pilot through the standard thumb switch and the RTI does not move until commanded by the flight envelope, rather than the nacelle angle.

In addition to the automation of the transition between flight modes, work to eliminate the majority of the binding has been completed. The binding described earlier occurred due to a manufacturing error. Since then, the majority of the binding has been removed by readjustment of the guide-rails.
6.3 Equipment

Testing was conducted at FRL using NRC’s fixed-base flight simulator displays. The simulator consists of a center stick, rudder pedals, and the RTI. Four displays are configured to provide a forward, 45° left, 45° right, and left chin-window. X-Plane™ v9.70 will drive both the flight model and graphics for the experiment. The flight model itself is an off the shelf freeware version of the Bell XV-15. The reason for this selection was that the flight and drag model was determined through pilot testing to form the closest match to that of a V-22 sized transport aircraft, which is what was utilized in the prior VMS study. The flight model, RTI control, and data acquisition will be provided via a Lenovo W700ds ThinkPad while FRL’s flight simulator AMD 64 Athlon X2 3U computing systems will provide the visuals.

6.4 Design

The independent variables (IV) was the mode in which the RTI operated which consisted of three levels:

1. Nacelle driven RTI; In this mode the RTI is matched 1:1 with the vehicle’s nacelle angle. The max nacelle transitions speed is 7.5 degrees per second with a max range of 95°. While the max transition speed is 7.5 degrees for the nacelles, 2.5 degrees per second is typically used as anything above this causes vehicle controllability issues. This is 2.5 degrees per second is commanded as a max rate through the digital rocker thumb switch on the RTI. At the minimal 2.5 degree per second rate, the RTI will remain in transition for 38 seconds in order to fully
travel the 95 degree range. At maximum 7.5 degrees per second, a full transition will take ~12.7 seconds in order to fully travel the 95 degree range.

2. Flight Envelope driven RTI: In this mode the RTI is driven by the flight envelope using the vehicle’s speed. The max RTI transition speed is also 7.5 degrees per second but occurs independently of the nacelles which do not transition faster than 2.5 degrees per second. The total RTI 95 degree transition time would be ~12.7 seconds.

3. Vertical Fixed Mode: In this mode the RTI remains fixed vertically and does not move via the envelope nor the flight controls. This is similar to a collective style inceptor.

The course will consist of one racetrack circuit at Ottawa (YOW) International Airport from runway 14 marked using a modified Highway-In-The-Sky (HITS) symbology set (Figure 47 & 48 respectively). A standard 15° departure angle and 3° approach glide slope was used in the course design. The number of gates and distance between the gates was designed by subject matter experts with the requirement to minimize visual clutter and provide sufficient cueing during all phases of flight. A total of 34 gates were used.

The course will be divided into three sections:

1. Hover Flight => Forward Flight (11 gates)

2. Cruise Flight (8 gates)

3. Forward flight => Hover Flight (15 gates)
Figure 47. Circuit Model (Green barbell depicts start, red barbell depicts finish. Start to beginning of downwind leg is hover flight => forward flight, end of downwind leg to finish is forward flight => hover flight.

Final depiction of the HITS gate is depicted in Figure 48. The center dot indicates the ideal path through the course.

Figure 48. Proposed HITS symbology

The gate sizing was modified and validated through pilot testing using an in-house (NRC) licensed pilot volunteer.
The participants were five research pilots from the NRC. All pilots were military trained and held either research or experimental pilot qualifications. Dependent measures will consist of:

1. Cooper-Harper Handling Quality Ratings (HQRs) (Appendix 2)
2. Modified NASA VMS questionnaire (Appendix 3)

6.5 Procedure

The evaluation runs were organized as shown in table 2:

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pilot 1</strong></td>
<td>Practice</td>
<td>V</td>
</tr>
<tr>
<td><strong>Pilot 2</strong></td>
<td>Practice</td>
<td>V</td>
</tr>
<tr>
<td><strong>Pilot 3</strong></td>
<td>Practice</td>
<td>V</td>
</tr>
<tr>
<td><strong>Pilot 4</strong></td>
<td>Practice</td>
<td>V</td>
</tr>
<tr>
<td><strong>Pilot 5</strong></td>
<td>Practice</td>
<td>V</td>
</tr>
</tbody>
</table>

*Legend: V=Fixed Vertical, N=Nacelle Driven, F=Flight Envelope*

*NOTE: During day one, no physiological data will be recorded*

During day 2, as per HQR protocol, the participant had the option to redo a data run if they chose to do so.
6.6 Analysis
As this study is a follow up to the first evaluation done at the NASA Vertical Motion Simulator (VMS), the same modified NASA VMS questionnaire and Cooper-Harper Handling Quality Ratings (HQR) scale will be used. The analysis of the HQRs and questionnaire will be reported in raw format in accordance with the original study.

6.7 Results
In the end, only three of the five NRC test pilots were able to complete the task. One test pilot indicated after beginning the experiment that he had no rotary wing experience and was not able to maintain control of the aircraft in the low speed flight regime. Another pilot was not able to complete the trials due to an RTI failure. The failure rendered the RTI unavailable to continue further testing and the failure details are discussed in Appendix 6.

The remaining three evaluation test pilots all had a combination of fixed and rotary wing backgrounds. HQR results are shown in Table 3:

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Fixed</th>
<th>Vertical Flight</th>
<th>Envelope Driven</th>
<th>Nacelle Angle Driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot 1</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Pilot 2</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Pilot 3</td>
<td>4.5</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
In pilot comments, it was suggested that the RTI in Nacelle Angle Driven Mode would be the most desirable if further training was permitted. One of the confounding factors within this evaluation was the problematic flight model. Creating a proper tiltrotor flight model is problematic in that it requires not only a rotary and fixed wing flight model, but a transition between the two models as well. Due to the complexity of such models, there are intensive US ITAR regulations that are imposed on them. As the simulation test was conducted in Canada, it was not possible to obtain a fully compliant model. Instead, a generic, off-the-shelf model was used.

As proper tiltrotor models are complex, commercially available models get around this complexity by using a piece-wise model. The deficiencies in these models do not come from the individual pieces themselves, but the discontinuity between them. In the evaluation, pilots commented on the increased workload during the transition times. As the course was relatively short and transitions were the focus of the evaluation, this is believed to have significant effect on HQR results and pilot comments.
CHAPTER 7 DISCUSSION AND CONCLUSIONS

The initial drive for this follow on work was to address the control confusion reported in the VMS phase I experiment by implementing a new control mode called the Flight Envelope Driven (FED) Mode. By driving the RTI using the flight envelope as a metric as opposed to the nacelle angle, it was hypothesized that the time in the confusion causing intermediate area would be reduced, thereby mitigating potential control input errors.

In distilling the pilot comments, however, it was reported that the FED mode was considered the least favorable and most confusing of the three. Pilots stated that the FED mode caused confusion as to where they were in the nacelle range, although comments did not suggest control movement confusion.

Pilots stated that the FED mode did not provide any new information to them and caused confusion. The hypothesized reason for this is that the RTI moved in the same manner as when being driven by the nacelles, but was in fact being driven by an entirely different variable; airspeed. In one instance a pilot flew the entire course at 73° nacelle because they stopped transitioning the nacelles forward after the FED mode completed its conversion to fixed-wing mode. It is this that made me believe that even in the FED
mode the pilot still considers the RTI to be driven by the nacelles and not the flight envelope mode.

While the fixed vertical mode provides additional information over the Nacelle Angle driven mode, it did not provide incongruent information like the FED. Pilots commented that with additional practice, the Nacelle Angle Driven mode would be the preferred mode. The reasoning behind this is that the back driven movement may cause confusion initially because the pilot is not used to it, but through learning, the movement of the RTI could provide desired additional information about where the nacelles are. In contrast, the FED mode caused confusion because the movement was not only confusing, but counter indicative of what the pilot believed to be happening.

The final suggested rank order from comments and HQRs appeared to favor the following order:

1. Nacelle Angle Driven
2. Fixed Vertical
3. Flight Envelope Driven
7.1 Discussion

Over the course of the two experiments conducted, no changes were made to the RTI’s mechanical system itself except to eliminate binding. However, the Design Principle Hierarchy (DPH) Theory did undergo major changes. Initially the DPH consisted of a single level:

1. S-R Compatibility

However, a review of other power control inceptors indicated that there was an additional level that was primary to the S-R Compatibility design constraint, which was ergonomics. The new DPH was structured as follows:

1. Ergonomics
2. S-R Compatibility

The RTI initially was built using the 2 level structure seen above. At the completion of the functional prototype build, the RTI underwent phase I testing the NASA VMS. The testing, indicated that there was confusion during the RTI transitions phases possibly due to the way pilots add or reduce power with a helicopter collective or airplane throttle. Through this finding the DPH was updated once again adding a third level. The 3rd iteration of the DPH was structured as follows:

1. Ergonomics
2. Proprioceptive Consistency
3. S-R Compatibility

Using the understating garnered from the VMS study, a third mode called Flight Envelope Driven (FED) mode was created in which the RTI transitioned based on the
flight envelope as opposed to the nacelles. It was believed that this mode would reduce the amount of time the pilot was in the range of ambiguity, which caused the reported initial confusion. In testing this new mode, the evaluation test pilots reported that the new FED mode, the one created to address the shortcomings of the nacelle angle driven mode, was in fact less desirable than the nacelle angle driven mode or the fixed vertical mode in which the RTI did not move. It appears the mismatch of the RTI movement given the nacelle angle resulted in confusion. Because of this the DPH was updated for a fourth time to the following structure:

1. Ergonomics
2. S-R Compatibility
3. Proprioceptive Consistency

7.2 Consistency of the DPH with other Power Control Interfaces

The change was initiated after an ordinal effect was noted in mapping the RTI modes and other existing control systems to the DPH. Table 4 shows the tested RTI modes and other control systems with respect to the DPH Requirements:

<table>
<thead>
<tr>
<th></th>
<th>Ergonomics</th>
<th>Mental Model</th>
<th>Proprioceptive Consistency</th>
<th>Notes</th>
<th>Rank Ord.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTI Nacelle Angle Driven</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
<td>2 of 3 met in order</td>
<td>1</td>
</tr>
<tr>
<td>RTI Fixed Vertical</td>
<td>✔</td>
<td>✗</td>
<td>✔</td>
<td>2 of 3 met out of order</td>
<td>2</td>
</tr>
<tr>
<td>RTI Flight Envelope Driven</td>
<td>✔</td>
<td>✗</td>
<td>✗</td>
<td>Only 1 req met</td>
<td>3</td>
</tr>
<tr>
<td>Voith Schnieder Integrated Prop Control</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>3 of 3 met in order</td>
<td>1</td>
</tr>
<tr>
<td>Voith Schnieder Separated Prop Control</td>
<td>✗</td>
<td>✔</td>
<td>✔</td>
<td>2 of 3 met out of order</td>
<td>3</td>
</tr>
<tr>
<td>Diesel-Electric Locomotive Throttle</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>3 of 3 met in order</td>
<td>1</td>
</tr>
<tr>
<td>Steam Locomotive Throttle</td>
<td>✗</td>
<td>✗</td>
<td>✔</td>
<td>Only 1 req met out of order</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 4 we see seven different control systems, including the three separate RTI modes. The rank order (1 being most desirable, 3 being least) is parsed by control grouping (separated by border boxes). There are three control groups:

1. RTI
2. Voith Schnieder prop control (used for tugboats)
3. Train throttle system

It is believed that both the order in which the three levels are met and the number of total achieved requirements dictates how suitable the inceptor is. In the case of the RTI, we can see a positive correlation to the rank order, the DPH ordinal and value effect, and the comments the pilot’s made concerning the nacelle angle driven mode being the most desirable while the FED mode was the least. Similarly, the DPH can be applied to currently existing inceptors such as the Voith Schnieder prop controller and train throttle systems. In doing so we see that the newer Voith integrated controller fares better over the separated legacy system and that diesel electric throttle systems are better suited than the legacy steam controllers.

The reordering of the DPH was not simply done to suit the ordinal and value based structure of the current theory but was done as a result of the findings on the phase II work. Initially the current proprioceptive consistency 3rd level, which was previously level 2, was organized that way because it was thought, due to the elicited comments in the phase I VMS work that proprioceptive consistency superseded the S-R Compatibility. This was thought due to the confusion being caused as a result of the intermediate
transition phase where the RTI switches from a helicopter collective to a throttle. It was noted that there was a possible bias in the phase I experiment which may have resulted in to some of the comments. In the phase II experiment the suggested rank order changed significantly and S-R Compatibility superseded proprioceptive consistency.

### 7.3 Conclusions Regarding the DPH

In further review of the levels, potential effects can be seen in control system use:

1. **Ergonomics**: If the ergonomic level is not met, system adoption typically will not be seen unless there is nothing else to replace it. The reason for this is that the system would be uncomfortable to use, causing it to be rejected it prior to mainstream adoption.

2. **S-R Compatibility**: If the S-R Compatibility requirement is violated, adoption is possible, although control reversals seem likely. Additional training may be able to reduce the problem. However, stress reversion can occur, such as seen in USAF vehicle 5, if negative transfer of training from other systems exists.

3. **Proprioceptive Consistency**: Much like S-R Compatibility violation, if proprioceptive consistency is violated, the potential for control reversal also exists. This, however, is not due to negative transfer of training but instead the inability to distinguish of which way to move the interface. It is believed however that with proper training this too can be overcome. It is important to note that in order to have proprioceptive inconsistency, a third DoF needs to be present. Most control systems in the world only possess two DoFs making this type of violation rare.
The DPH prescribed here is a first cut definition of a potential design guidance principle. The two evaluations are not exhaustive and caution in interpreting these results is warranted. The DPH itself is an outline and further research is required to validate it. The purpose of the DPH is to be used to evaluate future and existing control system designs from a human factors perspective.
CHAPTER 8 CONTRIBUTION, CONCLUSIONS, AND FUTURE WORK

8.1 Contribution

The practical impact of this work is expected to be significant. Tiltrotors are part of military aviation, and will soon be utilized in commercial and general aviation. Until now, it was not possible to create a functional control inceptor that met the Direction and Magnitude Framework found in all existing certified western aircraft. The RTI not only demonstrated this ability but it did so with a ~18% weight savings in the prototype alone and an estimated 50% weight savings in a production model system. Furthermore, new variable thrust vehicles are being developed such as the Eurocopter X3, Sikorsky X2, and the Piasecki SpeedHawk. A fully developed and tested inceptor for such vehicles, with evidence suggesting its superiority to existing inceptors, would be of great practical significance.

The theoretical contribution centers on the design principles hierarchy described above. The identification of the ergonomic consideration, along with the S-R Compatibility and proprioceptive compatibility requirements, is expected to add clarity to new controller interface design, particularly for vehicles. In addition, the identification of a new principle, proprioceptive consistency, is a critical finding not previously described in the
literature. The resulting three-level set of principles for inceptor/controller design should provide fundamental guidance to human factors practitioners involved in controller and inceptor design.

8.2 Conclusions

This work encompasses two significant contributions:

1. Creation of the first DMF conformal power inceptor for tiltrotor aircraft

2. Creation of the first movement specific control design criteria to assist designers, the DPH.

In completion of the work to this point, it is evident why a conformal tiltrotor power interface was such a challenge. Work needed to be accomplished in the areas of mechanical, electrical, and human factors engineering prior to it being possible to create such a system. While the developed mechanical system is robust, and may even seem obvious, it took years of work to understand how to provide and relinquish control of distinct Degrees of Freedom within the system without violating existing design principles.

While the RTI only possess 3 DoF total, the use of the CPTA principle is generalizable and can be transferred to other multi DoF designs. This contribution is significant in that prior to this, power density was the identified technical hurdle and has still yet to be overcome. The CPTA removed this barrier.
Tiltrotor flight test is considered by some to be one of the riskiest of all flight test types. The creation and implementation of the RTI not only trends with the DMF established as early back as 1910, but also with the direction of the industry. Much like the progression of early instruments to modern glass displays, the move from a single DoF tiltrotor power inceptor to a 3 DoF RTI follows this suit in that it also provides additional and relevant information to the pilot, with the similar goal of reducing workload and increasing safety. It is believed that the RTI has benefits yet it will take further redesigns and evaluations to perfect the system for use in tiltrotor aircraft.

In parallel to this design and evaluation effort, a structured approach was developed. While the RTI could have been designed in a void, its integration not only into the flight deck, but the knowledge base as well was deemed important if not critical. Lack of a structured approach was necessary, and its importance is evident in the past history of tiltrotor control interfaces.

There are a number of approaches in control design methodology and evaluation such as from an aerospace perspective on control harmony, or a mechanical engineering standpoint on linkage complexity and hysteresis. However, there are none that approach control design from a human system perspective specifically to the movements of the control itself. While each perspective may be important by itself, if a control system fails outside of the existing designed evaluation criteria, the flaw will not only go undiscovered, but the system could suffer detrimental consequences during its use.
Much like other design and evaluation methods, the DPH is not intended to be all encompassing. The focus of the DPH is designed to add an additional layer of evaluation to augment existing design metrics hopefully leading engineers one step closer to a systematic and fully encompassing multi-part approach for human in the loop control design.

8.3 Future Work

Much like the work of this paper, the future work has two focuses that need further examination. While the RTI suggested benefit, the testing utility of the system itself has believed to have been exhausted. In order to gain additional data and further evaluate a conformal throttle interface for tiltrotor aircraft, a new RTI would have to be built and subsequent flight testing would have to be performed.

Work from a mechanical engineering standpoint needs to be undertaken in order to identify and address all failure modes. During this the complexity of the RTI needs to be reduced. The current inception of the system is comprised of over 350 individual parts. In initial analysis, it is believed that a second generation of RTI could reduce that count down to less than a hundred. This decrease in mechanical complexity is directly correlated to the types of failures the system could sustain, a critical factor in flight worthy systems.

Due to the cost of the RTI and the initial development being primarily self-funded, a passive counter-weight system was used. In order to implement the RTI in a dual-pilot
flight deck, an active counterweight and connection system would need to be developed to conformally link both systems. These systems already implemented in a similar fashion on the BAE active stick systems, typically cost >$100K per axis on their own without the full control system itself. In contrast, the RTI cost was ~$60K. The implementation of an active system would allow each pilot to have an understanding of what the other was doing by having their RTI mimic the others movements. This is currently not possible in the RTI’s current inception as the complex rotations do not allow for a purely mechanical cross linkage.

In order to validate these advancements, additional high-fidelity flight simulations and actual tiltrotor flight tests would need to occur. This is problematic in that the US military is the only operator of certified tiltrotor aircraft and with the vehicle being used heavily in operational theatres, using one for flight test is difficult at best at this time.

In addition to the RTI, the DPH needs further evaluation. The current inception of the hierarchy has been developed solely under the pretense of tiltrotor power inceptors. While the DPH is designed to evaluate such inceptors, the true test of the DPH would be evaluations for current and future inceptor designs with operational testing and longitudinal tracking of said inceptors performance.

While entirely new control designs are rare, NASA is currently looking at new control concepts for the lunar and mars lander vehicles, each of which have multiple DoF systems. Earthbound, both Sikorsky and Eurocopter are developing new multi-DoF
VTOL aircraft that will require new control interface systems. Any of these new systems could be evaluated by the DPH to see if it holds up to non-tiltrotor systems.

Regardless of what system it is tested on, the DPH will need to be evaluated further on both new and existing ones in order to validate its claims. Even through the design process and two evaluations, the DPH changed its form each time. Without the understanding of how other evaluations would affect its structure, it is not possible to say if the qualities and order of them are properly laid out.
REFERENCES


Appendix A

Pilot Questionnaire

Task Performance

1. Describe ability to meet DESIRED / ADEQUATE performance standards.

2. Describe aggressiveness / precision with which task is performed.

3. If trying for DESIRED performance resulted in unacceptable oscillations, did decreasing your goal to ADEQUATE performance alleviate the problem?

Aircraft Characteristics

4. Describe any objectionable controller force or motion characteristics, particularly with the Thrust Controller (TCL).

5. Describe predictability of initial aircraft response and ability to precisely control thrust.

6. Describe any objectionable oscillations or tendency to overshoot.

7. Describe any non-linearity of TCL response.

Demands on the Pilot

8. Describe overall TCL control strategy in performing the task (cues used, scan, etc.).

9. Describe any control compensation you had to make to account for deficiencies in the aircraft or TCL.

10. Describe any modifications you had to make to what you would consider “normal” Thrust control technique in order to make the aircraft behave the way you wanted.

Miscellaneous

11. How natural were the TCL inceptor motions required to perform the task?

12. Were there any undesirable characteristics of the Thrust Controller?
13. (RTI only) Did the rotation of the RTI with nacelle angle make it easier or harder to accomplish the maneuver?

14. (RTI only) Comment on the suitability of using position of the RTI arm and grip as a cue of nacelle position.

15. Comment on anything else related to the TCL.

Assign HANDLING QUALITIES RATING for overall task.

16. Using the Cooper-Harper rating scale, please highlight your decision-making process and adjectives that are best suited in the context of the task. If assigned HQR is Level 2, briefly summarize any deficiencies that make this configuration unsuitable for normal accomplishment of this task, i.e., justify why the procuring activity should reject this configuration as a means to accomplish this task.

17. What was the critical sub-phase of the task (e.g., entry, steady-state, exit) or major determining factor in the overall Handling Quality Rating (HQR) – with respect to the Thrust Controller?

18. Did the Thrust Controller have a significant impact on the assigned HQR?
Handling Qualities Rating Scale

Adequacy for Selected Task or Required Operation

Is it satisfactory without improvement?
- Yes
- No
  Deficiencies warrant improvement

Is adequate performance attainable with a tolerable pilot workload?
- Yes
  Improvement mandatory
- No
  Deficiencies warrant improvement

Is it controllable?
- Yes
- No
  Control will be lost during some portion of required operation

Aircraft Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Demands on the Pilot in Selected Task or Required Operation*</th>
<th>Pilot Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent Highly desirable</td>
<td>Pilot compensation not a factor for desired performance</td>
<td>1</td>
</tr>
<tr>
<td>Good Negligible deficiencies</td>
<td>Pilot compensation not a factor for desired performance</td>
<td>2</td>
</tr>
<tr>
<td>Fair - Some mildly unpleasant deficiencies</td>
<td>Minimal pilot compensation required for desired performance</td>
<td>3</td>
</tr>
<tr>
<td>Minor but annoying deficiencies</td>
<td>Desired performance requires moderate pilot compensation</td>
<td>4</td>
</tr>
<tr>
<td>Moderately objectionable deficiencies</td>
<td>Adequate performance requires considerable pilot compensation</td>
<td>5</td>
</tr>
<tr>
<td>Very objectionable but tolerable deficiencies</td>
<td>Adequate performance requires extensive pilot compensation</td>
<td>6</td>
</tr>
<tr>
<td>Major deficiencies</td>
<td>Adequate performance not attainable with maximum tolerable pilot compensation</td>
<td>7</td>
</tr>
<tr>
<td>Major deficiencies</td>
<td>Considerable pilot compensation is required for control</td>
<td>8</td>
</tr>
<tr>
<td>Major deficiencies</td>
<td>Intense pilot compensation is required to retain control</td>
<td>9</td>
</tr>
</tbody>
</table>

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.
Appendix C

Modified NASA Questionnaire

Cooper-Harper Handling Quality Rating (HQR) Assessment

Using the HQR decision tree, please assign an HQ rating to the task you just completed.

Task Performance
1. Describe ability to meet DESIRED / ADEQUATE performance standards.

2. Describe aggressiveness / precision with which task is performed.

3. If trying for DESIRED performance resulted in unacceptable oscillations, did decreasing your goal to ADEQUATE performance alleviate the problem?

Aircraft Characteristics
4. Describe any objectionable controller force or motion characteristics, particularly with the Rotational Throttle Interface (RTI).

5. Describe predictability of initial aircraft response and ability to precisely control thrust.

6. Describe any objectionable oscillations or tendency to overshoot.

7. Describe any non-linearity of RTI response.

Demands on the Pilot
8. Describe overall RTI control strategy in performing the task (cues used, scan, etc.).

9. Describe any control compensation you had to make to account for deficiencies in the aircraft or RTI.

10. Describe any modifications you had to make to what you would consider “normal” Thrust control technique in order to make the aircraft behave the way you wanted.

MISC.
11. How natural were the RTI inceptor motions required to perform the task?

12. Were there any undesirable characteristics of the RTI?

13. (RTI only) Did the rotation of the RTI with nacelle angle make it easier or harder to accomplish the maneuver?
14. (RTI only) Comment on the suitability of using position of the RTI arm and grip as a cue of nacelle position.

15. Comment on anything else related to the RTI.

**Assign HANDLING QUALITIES RATING for overall task.**

16. Using the Cooper-Harper rating scale, please highlight your decision-making process and adjectives that are best suited in the context of the task. If assigned HQR is Level 2, briefly summarize any deficiencies that make this configuration unsuitable for normal accomplishment of this task, i.e., justify why the procuring activity should reject this configuration as a means to accomplish this task.

17. What was the critical sub-phase of the task (e.g., entry, steady-state, exit) or major determining factor in the overall Handling Quality Rating (HQR) – with respect to the RTI?

18. Did the RTI have a significant impact on the assigned HQR?
NRC-FRL Performance Standards
RTI Trial HQR Criteria

1. **Gate Criteria**: There is a 4-gate tolerance over the entire course.
   Desired: < 4 Gates Missed
   Adequate: ≥ 4 Gates Missed

2. **Pitch Attitude Criteria**: There is a vehicle pitch attitude tolerance over the course of the flight.
   Desired: Pitch Attitude = 10 Deg.
   Adequate: Pitch Attitude = 15 Deg.

3. **Downwind Leg Velocity Criteria**: There is a flight velocity tolerance for the downwind leg.
   Desired: Velocity = 250 kts ± 2 kts.
   Adequate: Velocity = 250 kts ± 4 kts.

4. **Cyclic control stop criteria**: There is a time based tolerance for cyclic control over the flight.
   Desired: 3 seconds at cyclic stop
   Adequate: 8 seconds at cyclic stop

5. **Landing Criteria**: There are both landing spot and landing success tolerances for the flight.
   **A. Landing Spot**
   Desired: Before threshold markings
   Adequate: Between threshold marking and runway intersection
   **B. Landing Success**
   All Crash Scenarios: HQR > 7
Appendix E

NRC-FRL Questionnaire

**Task Performance**
1. Describe ability to meet DESIRED / ADEQUATE performance standards.

2. Describe aggressiveness / precision with which task is performed.

3. If trying for DESIRED performance resulted in unacceptable oscillations, did decreasing your goal to ADEQUATE performance alleviate the problem?

**Aircraft Characteristics**
4. Describe any objectionable controller force or motion characteristics, particularly with the Thrust Controller (TCL).

5. Describe predictability of initial aircraft response and ability to precisely control thrust.

6. Describe any objectionable oscillations or tendency to overshoot.

7. Describe any non-linearity of TCL response.

**Demands on the Pilot**
8. Describe overall TCL control strategy in performing the task (cues used, scan, etc.).

9. Describe any control compensation you had to make to account for deficiencies in the aircraft or TCL.

10. Describe any modifications you had to make to what you would consider “normal” Thrust control technique in order to make the aircraft behave the way you wanted.

**MISC.**
11. How natural were the TCL inceptor motions required to perform the task?

12. Were there any undesirable characteristics of the Thrust Controller?

13. (RTI only) Did the rotation of the RTI with nacelle angle make it easier or harder to accomplish the maneuver?

14. (RTI only) Comment on the suitability of using position of the RTI arm and grip as a cue of nacelle position.

15. Comment on anything else related to the TCL.
Assign HANDLING QUALITIES RATING for overall task.
16. Using the Cooper-Harper rating scale, please highlight your decision-making process and adjectives that are best suited in the context of the task. If assigned HQR is Level 2, briefly summarize any deficiencies that make this configuration unsuitable for normal accomplishment of this task, i.e., justify why the procuring activity should reject this configuration as a means to accomplish this task.

17. What was the critical sub-phase of the task (e.g., entry, steady-state, exit) or major determining factor in the overall Handling Quality Rating (HQR) – with respect to the Thrust Controller?

18. Did the Thrust Controller have a significant impact on the assigned HQR?
This document outlines the initial findings of the RTI failure that occurred during testing. Three discrepancies were found in total:

1. The main arm bevel gear has separated from its primary attachment point. It appears the set screw either sheared or separated leaving the gear loose.
2. Unidentified metal debris has been found along the main arm bearing race and lower bearing cup. The debris origin is unknown but could stem from the bearing itself, the lost set screw (though unlikely), or other particulate blown in as the case does have airflow.
3. The pneumatic tube that controls grip friction when in place has separated and appears to have been pinched and mauled by a set of gears. The cascading effect from this is that the shafts that hold the suspect gears could have deflected and possibly been damaged (though unknown) and the tube itself is most likely punctured though this has no effect on the current RTI functionality and can only be tested through a separate pressure test.
Each item has a different scope of required resources in order to address the anomaly:

1. This can be fixed though Fabrication would need to assist as the set screw is missing and the gear must be retentioned as to seat properly prior to installation of the set screw.
2. The metal debris is an effect of a possible failure and not direct in nature. Due to this, there is no action needed on this item at this time.
3. The hosing can be moved out of the way in order to mitigate further instances of this though a second set of eyes would assist in making sure that it does not happen again once the reposition is complete.

To address the questions forwarded prior, they are listed below:

*Could you provide an update on the RTI Functional state?* Please see above for background information. Regarding the RTI’s ability to function here on out, the above fixes would need to be made in order to accomplish this.
Has the device been assessed and a failure-mode identified? Yes

How long will it take to repair it? If these are the only issues, I estimate one (1) to two (2) weeks.

Can the repaired device be utilized reliably for NRC simulator trials assumed to require another 25-hours of operation? I honestly do not know the answer to this. I am surprised that the RTI has both made it this far and has had the failures it has. None of the issues listed above were in my immediate scope of concern, I was more concerned about the shaft flex and breakage so it is hard to make an estimation on this question. I can say I certainly hope so.

Please let me know if you have any further questions. Thank you.

Sincerely,

David Rozovski
VITA
VITA

David Rozovski

Academic Education
Ph.D. Industrial Engineering – Aviation Human Factors
Purdue University - West Lafayette, IN, USA, December 2013

- **Doctoral Thesis**: Human Factors Engineering & Control Design Research;
  "Design, Development, and Testing of a Conformal Power Control Interface for Thrust Vectoring Aircraft"

M.S. Human Factors
University of Illinois - Urbana-Champaign Urbana, IL, USA, May 2008

- **Master's Thesis**: Human Factors Engineering & Control Theory Research;
  "Control-Reversal Mitigation and Situational Awareness Improvement for Tiltrotor Aircraft Pilots via Redesign of the Thrust/Power Control Interface"

B.S. Psychology
Linfield College - McMinnville, OR, USA, January 2005

- **Senior Thesis**: Aviation Psychology and Human Factors Research: "Vacuum Failure Detection and Visual Factors that Affect Pilot Recognition Times in IMC Conditions for Single Engine Aircraft"

Aeronautic Education

- Multi-Engine Commercial Rating - West Lafayette, IN, USA, October 2010
- Commercial (Fixed-Wing) Certificate - West Lafayette, IN, USA, October 2010
- Chilean Fixed-Wing Instrument Rating Validation - Santiago, Chile, May 2010
- Complex Endorsement - West Lafayette, IN, USA, June 2009
- Instrument (Fixed-Wing) Rating - West Lafayette, IN, USA, May 2009
- High-Performance Endorsement - Hayward, CA, USA, July 2006
- Chilean Helicopter PPL Validation - Santiago, Chile, March 2006
- Helicopter Private Pilot Certificate - Newberg, OR, USA, September 2005
- Chilean Fixed-Wing PPL SEL Validation - Santiago, Chile, March 2005
- Tail-wheel Endorsement - McMinnville, OR, USA, September 2004
- Basic Aerobatics Maneuver Course - McMinnville, OR, USA, May 2004
- Fixed-Wing Private Pilot Certificate SEL - McMinnville, OR, USA, April 2004
Aircraft Flown To Date
33 Distinctive Types (28 fixed-wing / 5 rotary-wing)
515 Hours (385 hours fixed-wing / 130 hours rotary-wing)

Military Aircraft
Bell TH-57B/C Sea Ranger
Beechcraft T-6A Texan II
North American T-28 Trojan
North American T-6 Texan
Naval Aircraft Factory N3N

Experimental Aircraft
Bell 205 NRC Fly-By-Wire
Bell 206 Instrumented Platform
Extra 300L Instrumented Platform

Rotary-Wing
Eurocopter EC-120
Schweizer 300C/CBi
Hughes 269

Multi-Engine Fixed-Wing
Ford 5-AT-B Tri-Motor (1933)
Beechcraft Baron B-58E
Piper Seneca PA-34

Aerobatic Fixed-Wing
Yakovlev Yak-52
American Champion Citabria

Fixed-Wing Civilian Single Engine Land
Cirrus SR-20
Beechcraft Bonanza BE-36
Piper Tomahawk PA-38
Cherokee PA-28
Arrow PA-28
Archer PA-28
Diamond DA-40
Cessna C-150
C-152 Aerobat
C-172 Skyhawk
C-182 Skylane
C-185 Skywagon
C-206 Super Skywagon
C-T-210 Turbo Centurion

Fixed-Wing Gliders
Grob G 103 Twin Astir
Xiamango Motor Glider
Schweizer 2-33