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A Conceptual Design of a General Aviation Hands-on-Throttle and Stick (HOTAS) System.

Mark N. Callender
University of Tennessee - Knoxville

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To the Graduate Council:

I am submitting herewith a thesis written by Mark N. Callender entitled "A Conceptual Design of a General Aviation Hands-on-Throttle and Stick (HOTAS) System.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Ralph D. Kimberlin, Major Professor

We have read this thesis and recommend its acceptance:

U. Peter Solies, Alfonso Pujol, Jr.

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew

Vice Provost and
Dean of Graduate Studies

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A CONCEPTUAL DESIGN OF A GENERAL AVIATION HANDS-ON-THROTTLE AND STICK (HOTAS) SYSTEM

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Mark N. Callender
August 2003

DEDICATION

This thesis is dedicated to my wife and children
who have supported and inspired me
in writing this paper
and in life in general.
Thank you, Sarah, Eli, and baby-to-be.

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This paper and my other graduate achievements would not have been possible without the guidance and support of the faculty and staff of the University of Tennessee Space Institute. Special mention must be made of Betsy Harbin and Gail Wells who kept the Aviations Systems department running smoothly. Their assistance was invaluable in completing this degree.

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My final thanks go to my Lord and Savior, Jesus Christ, for the abilities He has given me and allowed me to use and for the relationships with the aforementioned individuals.

ABSTRACT

In this project the concept of Hands-on-Throttle and Stick (HOTAS) was applied to a general aviation (GA) aircraft. HOTAS had seen limited use in GA aircraft, but nothing that would compare to its use in military or commercial aircraft. The purpose of incorporating HOTAS was to give the pilot the ability to quickly and efficiently operate specific functions of the aircraft's avionics units without having to remove his/her hands from the stick (or control wheel) or throttle.

This project followed the systems engineering approach to accomplish the conceptual design of the GA HOTAS system. Two representative GA aircraft were chosen along with the avionics units to be controlled. In-flight functions of the units were determined and broken down into their most basic functions. Hardware was identified for each function, and the best alternative was chosen for each function. A control layout was achieved and then integrated into the aircraft's existing controls. The project resulted in a conceptual GA HOTAS system that could be integrated into existing GA aircraft with existing avionics.

Throughout the course of this project, the design proceeded with the needs and abilities of the pilot in mind. The HOTAS system was designed to be operable by pilots of various sizes and experience levels. The system was meant to be intuitive so that any pilot with experience in the aircraft's avionics could operate it; however, training and experience with the system was also required.

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LIST OF ABBREVIATIONS

ASD	Anthropometric Simulation Device
ATC	Air Traffic Control
cm	Centimeters
COMM	Communication Radio
DO	Document
DOD	Department of Defense
ENT	Enter
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GA	General Aviation
GPS	Global Positioning System
GPS SEQ	GPS Waypoint Sequencing
HDBK	Handbook
HFDG	Human Factors Design Guide
HOTAS	Hands-on-Throttle and Stick
IDENT	Identification
IFR	Instrument Flight Rules
kHz	Kilohertz
LOC	Localizer
MHz	Megahertz

MIL	Military
MKRB	Marker Beacon
MSG	Message
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAV	Navigation Radio
NAVAID	Navigational Aid
NRST	Nearest
OBS	Omni Bearing Selector
PRN	Pseudorandom Noise
PTT	Push-to-Talk
RAIM	Receiver Autonomous Integrity Monitoring
RNAV	Area Navigation
RTCA	Radio Technical Commission for Aeronautics
SHELL	Software-Hardware-Environment-Liveware-Liveware
SID	Standard Instrument Departure
SRP	Seat Reference Point
STAR	Standard Terminal Arrival Route
STD	Standard
TSO	Technical Standard Order
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	Very High Frequency Omnidirectional Range

WPT SEQ	Waypoint Sequencing
Đ→	Direct-To

CHAPTER 1

INTRODUCTION

Background

One of the definitions of general aviation (GA) is “all civil aviation operations other than scheduled air services and nonscheduled air transport operations for remuneration or hire” [1]. Over 300,000 aircraft and over 500,000 pilots are included in this group [2]. The pilots range from the newly licensed pilot to the highly experienced commercial pilot. The hours flown in GA account for over half the yearly totals worldwide [3]. Along with the large numbers of aircraft, pilots, and yearly hours flown, GA also accounts for more than half of the yearly flight fatalities [2]. These numbers testify to the importance of GA and the need for continuing improvements in flight safety. The stated cause for the majority of all aircraft accidents is human error. Several ways to remedy this problem include removing humans from the equation, improved training, and improved design. The first alternative is not feasible for general aviation since general aviation is driven by humans and their desire to fly. Improved training is a feasible alternative; however, general aviation pilots currently undergo hours of training along with review flights every two years to check proficiency. Even with improved or increased training, design flaws have the potential to induce pilots to make mistakes. Improved design to accommodate the human operator is the first step to reducing pilot error in GA. Improved or increased training should follow the human centered design effort; however, with a system designed for and with the human operator in mind, the system should become more intuitive decreasing the need for additional training.

Statement of Need

This design project was focused on the GA cockpit in an effort to create a more pilot centered flight environment. The method selected to accomplish this goal was through the incorporation of a Hands-on-Throttle and Stick (HOTAS) control system. In this type of control system, functions of the aircraft's avionics units and other systems were operated remotely by controls incorporated into the throttle and/or stick (control wheel). This kept the pilot from taking his/her hands off of the necessary flight controls to operate other controls in the cockpit. This system had been used extensively in military and commercial aircraft to place aircraft systems controls at the pilot's fingertips. Automobile manufacturers had even begun using the system to allow drivers to operate radios, cellular phones, and cruise control from the steering wheel. GA aircraft had seen limited use of HOTAS with push-to-talk (PTT) switches, electric trim switches, autopilot disconnect switches, and transponder identification (IDENT) switches placed on the control wheel. These controls differed from aircraft to aircraft in placement and control type. There were also many other possible controls that could have been incorporated into a HOTAS system. This constituted the need that drove this project: to develop the conceptual design for a GA HOTAS system capable of controlling the necessary in-flight functions of specified avionics and aircraft systems. This human centered design effort was conducted using the systems engineering approach.

CHAPTER 2

SYSTEM DESCRIPTION

General

General aviation encompasses aircraft from the single engine trainer to the multiengine corporate jet. In order for this design effort to benefit the majority of general aviation, an aircraft was identified which was representative of the majority of general aviation. Following is a description of this aircraft along with its engine, flight controls, and the avionics to be controlled by HOTAS.

Representative General Aviation Aircraft

In September of 1999, the National Aeronautics and Space Administration (NASA) published a report entitled “The Typical General Aviation Aircraft” [4] in which it defined certain aspects in common to the majority of general aviation aircraft. To define traits about these aircraft, NASA first had to define the term general aviation. The definition they gave was as follows: “…any fixed wing aircraft operating under Part 91, 125,135 (non-scheduled), or 137, excluding experimental aircraft, gliders, or any aircraft that is a known commuter or commercial air carrier aircraft” [4]. The information used in the NASA report was derived from the 1996 General Aviation and Air Taxi Activity Survey [5]. Out of the 187,312 aircraft that responded to the survey, 160,577 fit the above definition of general aviation [4]. Of these aircraft, 150,980 or 94% were piston-powered aircraft [4]. The remaining 6% were made up of turboprop and turbojet aircraft [4]. NASA also compiled a list of the most numerous aircraft by make and model. The

Cessna 172 was the most numerous composing 12.3% of the total general aviation market, and the Piper PA28 was the second most numerous with 11.18% of the total market [4]. NASA also determined several characteristics that most general aviation aircraft had in common. The majority of general aviation aircraft were four seat, horizontally opposed four to six cylinder single engine aircraft with fixed tricycle landing gear, had an aluminum frame with aluminum skin, and were controlled using cables, bellcranks, and push-pull tubes [4]. Both the Cessna 172 and the Piper PA28 aircraft fit this description. The fact that there were over 200 different general aviation aircraft and that these two aircraft combined to almost 25% of the total led to their selection, for this project, as the representative general aviation aircraft. Further descriptions of each aircraft's components necessary for this project were made; however, no further general description of the aircraft were made since both aircraft fit the above description. The only notable differences between the aircraft that needed to be mentioned was that the Cessna 172 was a high wing aircraft that used an elevator for longitudinal control, and the Piper PA28 was a low wing aircraft that used a stabilator for longitudinal control. The aircraft can be seen in figures A-1 and A-2[1].

Powerplant Controls

Power Control

The power control was the main powerplant control which gave the pilot the ability to control the rpm of the engine (or the manifold pressure in aircraft equipped with constant speed propellers). Power control for the Cessna 172 was accomplished through

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[1] All figures are located in the Appendix.

the use of a flexible push-pull control mounted to the instrument panel. Some models of the Piper PA-28 also utilized the flexible push-pull control; however, many used a lever operated flexible push-pull control mounted in a control quadrant on a centrally located pedestal. FAR 23.779(b)(1) required that the operation of power control be such that forward motion of the control corresponded to an increase in either rpm or manifold pressure [6]. The power control's location was required (FAR 23.777(c) and (d)), along with all powerplant controls, to be centrally located, and to be the left most powerplant control [6]. The power control was to be at least one inch longer or taller than the other powerplant controls to distinguish it from other powerplant controls (FAR 23.777(d)) [6]. The shape of the power control knob also distinguished it form other powerplant controls. Power control knob shape is shown in figure A-3 for both quadrant and panel mounted controls.

Propeller Control

The propeller control was the secondary powerplant control for aircraft equipped with constant speed propellers. The propeller control gave the pilot the ability to control engine rpm by varying the pitch of the propeller blades. By increasing the pitch of the blades, the drag on each blade was increased which decreased the rpm of the engine for a constant power setting. Cessna 172's were not equipped with constant speed propellers, unless modified by the owner/operator, and therefore were not equipped with propeller controls. Piper PA-28's had certain models with constant speed propellers and others with fixed pitch propellers. The Piper PA-28 used for this project was equipped with a constant speed propeller. Due to the fact that Cessna 172's and certain Piper PA-28's were not equipped with constant speed propellers, propeller controls were not considered for this project.

Mixture Control

The mixture control allowed the pilot to control the amount of fuel being introduced by the carburetor or fuel control unit into the cylinders. By adjusting the mixture control the pilot was able to either increase or decrease the fuel to air mixture that was combusted by the engine. The mixture control allowed the pilot to operate the aircraft most efficiently by “leaning” the mixture to the point where the least amount of fuel possible was being burned while suitable power and acceptable engine temperature were maintained. Mixture control for the Cessna 172 was accomplished through the use of a flexible push-pull control mounted to the instrument panel. Mixture control for the Piper PA28 was accomplished through the use of a lever operated flexible push-pull control mounted in a control quadrant on a centrally located pedestal. FAR 23.779(b) required operation of the mixture control so that forward motion of the control corresponded to a “rich” mixture (higher fuel to air ratio) [6]. The mixture control was required (FAR 23.777(c) and (d)) to be centrally located and to be to the right of both the power control and the propeller control, if equipped [6]. Mixture control knob shape is seen in figure A-3 for both panel and pedestal mounted controls [6].

Miscellaneous Powerplant Controls

Other engine controls included carburetor air heat, superchargers, turbochargers, cowl flaps, and oil coolers. These controls had functions such as warming air which was introduced into the carburetor to prevent carburetor icing, “boosting” the pressure of the air entering the engine to maintain, or increase, it to above sea level pressure, and engine cooling. For the purpose of this project, these functions were considered secondary and were not considered during design.

Flight Controls

Roll and Pitch Control

Ailerons were aerodynamic control surfaces located on the outboard section of the wing that controlled the rotation of an aircraft about the longitudinal axis. An upward deflection of one aileron corresponded to a downward deflection of the opposite aileron. This asymmetric deflection of ailerons resulted in greater lift on the wing with the downward deflected aileron and decreased lift on the wing with the upward deflected aileron. This caused the aircraft to roll about the longitudinal axis in the direction of the upward deflected aileron. Aircraft roll could also have been accomplished by flaperons and spoilerons. These were combinations of ailerons and secondary flight controls such as flaps and spoilers. The Cessna 172 and Piper PA28 utilized ailerons for roll control. Control of the ailerons themselves was accomplished through the use of a floor or side mounted stick controller or a panel or column mounted control wheel. Right and left movement of the stick or clockwise and counterclockwise rotation of the wheel corresponded to aileron deflection that caused a roll in the direction of movement of the control. The Cessna 172 and the Piper PA28 utilized a panel mounted control wheel for aileron control.

The elevator was an aerodynamic control mounted on the horizontal stabilizer which controlled aircraft rotation about the lateral axis. Upward deflection of the elevator caused increased downforce on the horizontal stabilizer resulting in the nose of the aircraft pitching up. Downward deflection of the elevator caused decreased downforce on the horizontal stabilizer resulting in the nose of the aircraft pitching down. Aircraft pitch could also have been accomplished by stabilators. A stabilator was the combination of the elevator and horizontal stabilizer. The Cessna 172 utilized an elevator for pitch control. The Piper PA28 utilized a stabilator for pitch control. Control of the elevator or stabilator was accomplished through the use of a floor or side mounted stick controller or a panel or column mounted control wheel. Forward movement of the stick or wheel corresponded to control surface movement which caused a nose pitch down while rearward movement of the control corresponds to a nose pitch up. The Cessna 172 and the Piper PA28 utilized a panel mounted control wheel for pitch control. Control wheels for both aircraft are shown in figures A-4 and A-5.

Yaw Control

The rudder was an aerodynamic control located on the vertical stabilizer which controlled aircraft rotation about the vertical axis. A deflection of the rudder to the right caused a leftward sideforce on the vertical tail which yawed the nose to the right. A deflection of the rudder to the left caused a rightward sideforce on the vertical tail which caused the nose to yaw to the left. Control of the rudder was accomplished through floor mounted pedals. Forward movement of the right pedal corresponded to a right yaw of the aircraft, and forward movement of the left pedal corresponded to left yaw of the aircraft.

Control of the rudder could also have been accomplished through incorporation of rudder control into the aileron control mechanism removing the need for pedals; however, precise coordination in turns, purposeful slips, and compensation for crosswind takeoffs and landings were lost in this type of control system making pedals the most common type of rudder control. The Cessna 172 and the Piper PA28 used pedals for rudder control.

Avionics Equipment

General

Avionics are designed by many manufacturers and differ from company to company; however, each unit is required to perform certain functions as prescribed by the Federal Aviation Administration and the Radio Technical Commission for Aeronautics. The following are general descriptions of the avionics used in this project and their associated functions.

Audio Control Equipment

Aircraft audio systems managed the sending and receiving of transmissions and the routing of those transmissions to and from the pilot. The audio control panel was the pilot's interface with the aircraft's audio system. The control panel was the means by which the pilot selected which radio was used to transmit outgoing transmissions, which radio was monitored over the headsets or aircraft speakers, and the volume of the audio transmitted to the headphones or speakers. Most audio systems have a push-to-talk switch (PTT), separate from the control panel, located on the pilot's control wheel. This switch allows the pilot to activate the outgoing radio when outgoing transmissions are sent. Aircraft audio systems, including audio control panels and PTT's, are regulated by FAA TSO-C50c, Audio Selector Panels and Amplifiers [7] and RTCA/DO-214, Audio Systems Characteristics and Minimum Operational Performance Standards for Aircraft Audio Systems and Equipment [8]. Examples of several current audio control panels are shown in figures A-6, A-7, and A-8.

Global Positioning System (GPS)

The Global Positioning System (GPS) is a highly accurate navigational system used by military and civil aviation. GPS is composed of three segments: space segment, control segment, and user segment. The space segment of GPS is composed of 24 satellites that orbit the earth in six orbits of three to four satellites per orbit at an inclination of 55° to the equator and an altitude of approximately 10,900 miles [9]. These satellites complete a full orbit approximately every twelve hours. The GPS satellites each contained two highly accurate atomic clocks stable to approximately 0.003 seconds every 1000 years [9]. It is based upon the frequency of the clocks that each satellite produces a pseudorandom noise (PRN). Each satellite has a unique PRN which contains timing data, ephemeris data (orbital data), and almanac data (information concerning the complete GPS constellation) [9]. The control segment of GPS is made up of ground stations located in Hawaii, Kwajalein, Diego Garcia, Ascension, and Falcon Air Force Base in Colorado Springs, CO [9]. These ground stations monitor the GPS satellites and the information that each satellite transmits. Corrections to the satellites orbital position and data messages are calculated at the master control station in Colorado Springs, CO and sent to the satellites via the control stations [9]. The user segment of GPS consists of the receivers and associated processors that receive the GPS satellite transmissions and use those transmissions for timing, navigation, and other purposes. When the receiver receives a transmission from a GPS satellite, it duplicates that satellite's PRN code. After doing this, the receiver is able to align the two identical codes to determine the amount of phase shift that exists between the two codes. The phase shift corresponds to the time of travel of the satellite's transmission. By multiplying this time by the speed of light (approximately 186,000 miles per second), the receiver determines its distance from the satellite sending the signal. Once the receiver has locked onto transmissions from four satellites and performed the time-of-arrival calculations, it accurately determines its position in three dimensions. The receiver's internal processor gives this position in latitude, longitude, and altitude above the earth's surface. Aviation GPS receivers overlay this position onto a stored database of airports, navigational aids, cities, rivers, and other landmarks. By doing this, the GPS receiver guides the pilot from airport to airport directly without unnecessary diversions. Aviation GPS receivers are regulated by FAA Technical Standard Order (TSO) C129a, Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS) [10] and by the Radio Technical Commission for Aeronautics (RTCA) document number RTCA/DO-208, Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS) [11]. The GPS receivers used for this project are classified by TSO-C129a as Class A1. Class A1 receivers include GPS sensors, receiver autonomous integrity monitoring (RAIM), and are capable of en route, terminal, and non-precision approach navigation [10]. Class A1 receivers are instrument panel mounted with externally mounted antennas. Data presentation to the pilot is in a digital alpha-numeric or graphical format. Most current receivers use a combination of the two with alpha-numeric data presented alongside a moving map display. Examples of several current Class A1 certified receivers are pictured in figures A-9, A-10, and A-11.

VHF Communication and VOR Navigation (NAV/COMM) Equipment

General

VHF communication and VOR navigation equipment are separate systems that performed different functions. Some models combine the control units for these two systems into one control unit. These units are called NAV/COMMs. They combine all the functionality and control of the individual systems but require less space on the instrument panel. Following are descriptions of the separate systems.

Communication Equipment

VHF communication equipment provides a means of communication for aircraft with: other aircraft, ATC, weather services, and other provided services. The airborne communication equipment consists of a receiver, a transmitter, and an antenna. The pilot is able to select the desired frequency within the range 117.975 – 137.000 MHz. The pilot is then able to transmit and receive on that frequency. Communication equipment is regulated by FAA TSO-C37d, VHF Radio Communications Transmitting Equipment Operating within the Radio Frequency Range 117.975 to 137.000 Megahertz [12]; TSO-C38d, VHF Radio Communications Receiving Equipment Operating within the Radio Frequency Range 117.975 to 137.000 Megahertz [13]; and RTCA/DO-186a, Minimum

Operational Performance Standards for Airborne Radio Communications Equipment Operating within the Radio Frequency Range 117.975 – 137.000 MHz [14]. According to TSO-C37d and TSO-C38d, NAV/COMMs are classified based in part upon the smallest increment that the frequency can be adjusted. Different models ca be adjusted in 50, 25, or 8.33 KHz increments [12, 13]. For the purposes of this project, NAV/COMMs for which the communication radios were adjustable in 25 KHz increments are chosen. This classified the receivers as Class C or D and the transmitters as Class 3 or 4 [12, 13]. The selected frequency is displayed to the pilot in a digital format. Active and standby frequencies are displayed. Examples of several NAV/COMMs are pictured in figures A-11, A-12, and A-13.

VOR Navigation Equipment

The VOR system is the most widely used means of navigation for general aviation. The VOR system consists of ground stations and the airborne equipment. The ground station transmits an omnidirectional signal and another signal which is increasingly out of phase with the first signal for each radial degree around the station. The airborne equipment, consists of a receiver, an antenna, and course deviation display, when tuned to the ground station's frequency, receives the combined signal and, depending upon the type of display, displays the aircraft's current radial to or from the station or the deviation from the desired radial. This system has for many years been the navigation standard for general aviation when used alone or in conjunction with other systems allowing navigation from station to station or point to point when augmented by RNAV. Airborne VOR receivers and related equipment are regulated by FAA TSO-

C40c, VOR Receiving Equipment Operating within the Radio Frequency Range of 108-117.95 Megahertz (MHz) [15] and RTCA/DO-196, Minimum Operational Performance Standards for Airborne VOR Receiving Equipment Operating within the Radio Frequency Range of 108-117.95 MHz [16]. VOR receivers may also have a localizer (LOC) converter that allows the receiver to receive the localizer signal for instrument approaches and display that signal with the appropriate sensitivity for a precision instrument approach. The localizer signal is transmitted from a localizer ground station, which is aligned with the runway centerline and extended from the departure end of the runway [1]. The signal is directional, along the runway centerline, which when received provides horizontal guidance for precision approaches. VOR/LOC converter equipment can be tuned in increments of 50 kHz [15]. VOR receivers can also contain glideslope receivers which receive the glideslope signal and display that signal for precision instrument approaches. The glideslope signal is transmitted from the glideslope transmitter at the approach end of the runway [1]. The signal is projected at a 3° angle from the transmitter which when received provides for vertical guidance for precision approaches [1]. Glideslope signals ranged from 329.15 to 335.00 MHz and are adjustable in 150 kHz increments [15]. Each glideslope signal is paired with the associated localizer frequency for the specific precision approach. When the pilot selects the localizer frequency for a particular precision approach, the glideslope receiver is automatically tuned to the paired glideslope frequency for the approach [1]. VOR/LOC frequency is displayed to the pilot in a digital format. Active and standby frequencies are displayed. The VOR receivers used for this project have LOC converters and glideslope receivers. Examples of several current VOR receivers are shown in figures A-11, A-12, and A-13.

Airborne Air Traffic Control (ATC) Transponder

The air traffic control (ATC) transponder system is used by ATC to identify, track, and maintain separation between aircraft in the National Airspace System (NAS). The transponder system consists of two segments: ATC ground interrogation-receiver-processor segment and airborne transponder segment. The ground segment transmits a directional interrogation signal by a rotating antenna. The interrogation signal, when received by the airborne transponder unit, causes the airborne unit to send a reply signal. This reply signal contains information identifying the aircraft from which it was sent along with the aircraft's pressure altitude to the nearest 100 feet (if mode C equipped) [1]. The ground station receives the reply signal from which it obtains the aircraft's pressure altitude. The aircraft's range from the station is calculated by the total time taken for the interrogation signal to be received plus the time taken to receive the reply signal from the airborne unit. The aircraft's direction from the station is determined by the direction of the ground station's transmitting antenna at the time of transmission of the interrogation signal. The transponder system uses a four digit code for aircraft identification. Each digit ranges from 0 – 7 with 4096 different codes possible. Aircraft operating under visual meteorological conditions are assigned the code 1200. While operating under instrument meteorological conditions, each aircraft's transponder code is assigned by ATC and manually entered by the pilot. It is by this code that ATC maintains positive identification and separation of every aircraft under its control. The normal transmission mode of civil aircraft is Mode A. Transponders with altitude encoding ability also operates in Mode C. Airborne transponder units are regulated by FAA TSO-C74c, Airborne ATC Transponder Equipment [17] and by RTCA/DO-144, Minimum Operational Characteristics for Airborne ATC Transponder Systems [18]. Airborne transponder units are classified as A1, B1, A2, or B2 [17]. Class A transponders are designed for use at or above 15,000 feet; class B transponders are designed for use up to but not including 15,000 feet [17]. A1 and B1 transponders must meet the requirements of TSO-C74c. A2 and B2 transponders had to meet the requirements of TSO-C74c and section two of part two of RTCA/DO-144. Transponders used for this project have been classified as any or all of the above, the requirement being that the transponder must be Mode A and Mode C capable. Airborne transponders are instrument panel mounted with externally mounted antennas. Transponder reply code settings are displayed to the pilot in a digital format. Examples of several current airborne transponders are shown in figures A-14, A-15, and A-16.

CHAPTER 3

SYSTEMS ENGINEERING

General

The systems engineering process is a top-down approach to the design of any system under consideration. The premise of systems engineering is to begin with an identified need for a particular system, usually identified by the customer, and to determine the requirements of the overall system. The identified need for this project was a HOTAS control system for general aviation aircraft. With the overall system requirements in mind, the system was then divided into subsystems. This decomposition continued until the system was reduced to its most basic elements. Alternatives were then generated for elements which met the needs of the system. The most desirable elements were chosen and synthesized into the various subsystems. Systems engineering is opposed to the bottom-up approach of design in which the elements of the system are chosen in a specified configuration at the beginning of the design process and tested to see how well the chosen system performed against system requirements. With the systems engineering approach, system requirements are considered throughout the design process at each subsystem level and only after this process had been completed is the system as a whole tested against requirements. Systems engineering can be utilized to design an entirely new system or as in this case to modify an existing system.

Aircraft Systems

“A system is an assemblage or combination of elements or parts forming a complex or unitary whole…; any assemblage or set of correlated members…; an ordered and comprehensive assemblage of facts, principles, or doctrines in a particular field of knowledge or thought…; or a coordinated body of methods or a complex scheme or plan of procedure…” [19]. Air transportation formed a system according to the previous definition. Upon the decomposition of this system, several major subsystems were seen to make up air transportation: air subsystem (aircraft and pilots), ground subsystem (airports, maintenance facilities, ATC facilities, and all associated personnel), regulatory subsystem (FAA regulations and personnel). Each one of these subsystems can be further broken down into its individual components. Of particular interest in this project are the general aviation aircraft and pilot components of the air transportation system. Although the aircraft is a component of a larger system, it is itself a system. The aircraft was divided into subsystems: airframe, powerplant, controls, and avionics. Important components of these subsystems are powerplant controls, control wheels, and avionics equipment.

SHELL Model

When considering systems, subsystems, and components, the interfaces are of particular importance. The HOTAS system in this project is hardware, but its purpose is to accommodate the pilot in performing certain in-flight tasks. Therefore, not only were the interactions between hardware and hardware evaluated, but the interfaces between the pilot and the hardware was of primary importance. When designing with the human user in mind, the SHELL model provided a framework for evaluating the interfaces between human, hardware, regulations, environment, and other humans [20]. The SHELL model is shown in figure A-17. The SHELL model was used in evaluating the requirements of the system.

Feasibility Analysis

After the need was stated, a feasibility analysis was performed. The purpose of the feasibility analysis was to determine if the appropriate technology existed or soon would exist to fulfill the need of a general aviation HOTAS system. It was known that the military had utilized HOTAS for many years in rotary and fixed wing aircraft. Figure A-18 shows an example of the F-16 and Mig-21 HOTAS controls. General aviation has seen limited use of HOTAS with the PTT switch, electric trim, autopilot shutoff, and several other controls mounted on the control wheel. Based upon this knowledge and the commercially available supply of switches, buttons, wheels, and joysticks, it was determined that the hardware did exist to meet the needs of a general aviation HOTAS system. The hardware had to be able to interface with the avionics it was to control. The technology to connect the HOTAS controls to current avionics units was assumed to exist since application of HOTAS was evident in military, commercial, and general aviation. With the technology in place the system design proceeded.

CHAPTER 4

REQUIREMENTS ANALYSIS

General

After the need was stated and the feasibility of the project was established, system requirements were determined. System requirements as with all parts of systems engineering are top down in nature. First the requirements of the overall system were determined followed by subsystem requirements and component requirements. System requirements were required to be met at all levels of the design effort. The overarching system requirement followed from the statement of need: to design a HOTAS system capable of controlling the in-flight functions of the audio panel, GPS, NAV/COMM, and transponder. Therefore the system was required to allow the pilot to control the in-flight functions of the above avionics without removing his/her hands from the flight and/or powerplant controls. A decomposition of the requirements began by determining the operational requirements.

Operational Requirements

General

Operational requirements were requirements that dealt with who would use the system, where will the system be used (environment), when and how often would the system be used, and what functions would the system perform. Each question was addressed separately.

User

The proposed user for the system is the general aviation (GA) pilot. The licensed GA pilot may have as little as thirty hours of flight time to tens of thousands of hours of flight time. The experience level of GA pilots obviously varies a great deal; however, all pilots are required to be able to communicate and navigate regardless of the amount of experience they have. This gave the project relevance to all GA pilots. The system was designed to aid all general aviation pilots, but it has the possibility of being more advantageous to the instrument rated pilot. The instrument rated pilot not only is required to perform all of the functions of any other licensed pilot, but he/she must perform more complex operations involving instrument approaches/departures, more frequent communications with various ATC facilities, and navigation within stricter tolerances. Any GA pilot is the identified user of the system; however, special consideration was given to the instrument rated pilot.

Environment

The environment in which the system will be used was determined to be in the representative general aviation cockpit. As stated previously, this is the cockpit of either the Cessna 172 or the Piper PA-28. The altitude range seen in these cockpits is from sea level to approximately 14,000 feet (aircraft's service ceiling); however, the altitude was restricted to 10,000 feet for the purposes of this project since the aircraft under consideration are not pressurized and are not normally equipped with supplemental oxygen [1]. Temperature may vary widely from well below freezing at 10,000 feet to well over 100 degrees Fahrenheit on the ground. These temperatures are capable of being controlled to a certain extent by the pilot through the use of cabin heat or cabin air; however, during the initial portions of a flight and in situations where the temperature cannot be adequately controlled, the above stated temperatures were used. Depending upon which part of the country the aircraft was to be flown and the time of the year and day, the system can be exposed to high relative humidity air. Ambient light levels range from bright sunlight to darkness. These environmental requirements directly affected the makeup of the HOTAS system. Since the human pilot is to operate the system, the environmental requirements will indirectly affect the system as well. Not only does the system, which includes all HOTAS hardware, have to operate within these environmental requirements, the pilot is also required to operate the HOTAS system in this environment. This was one portion of the SHELL model. Several operator requirements were created due to environmental requirements. During flight in low light conditions, HOTAS controls must be easily identifiable by the pilot. Since the pilot's hands would be on the controls and since the pilots eyes and attention were considered to be elsewhere, this meant that the controls would have to be intuitive, relying as little as possible on pilot memory. During flight in relatively cold temperatures, pilots are expected to wear the appropriate clothing to include gloves. Therefore, the HOTAS controls should be operable by a pilot wearing light gloves, meaning that the controls had to be distinguishable to the extent that a gloved operator could tell the controls apart by touch. This also meant that operation of one control could reasonably be expected not to affect or actuate any other HOTAS control.

Duration and Frequency of Use

When the HOTAS system was to be used was determined primarily to be in flight which includes takeoff, climb, cruise, descent, approach, and landing. Functions utilized on the ground but not required for flight were excluded from the system in order to decrease the complexity of the HOTAS design. The frequency of use of the system may vary widely; however, for this project the frequency of use of the HOTAS system was considered high since the pilot was to have access to the HOTAS controls at all times.

Functional Requirements

General

The functional requirements of the system are dependent upon the in-flight requirements of the pilot to control the audio panel, GPS, NAV/COMM, and transponder. These requirements are not necessarily critical to flight safety; however, they are intended to cover the majority of expected in-flight uses of the above avionics. The functional requirements of each unit were investigated separately.

Audio Panel

As described previously, the audio panel gives the pilot the ability to control the audio traffic sent and received by the aircraft and that audio information's presentation to the pilot. In-flight requirements for use and control of the audio panel were determined to be the following: audio volume control, active transmitting radio selection, received audio to be heard over the headsets or speakers, and cueing the radio for transmission.

GPS

The GPS provides for the pilot's ability to navigate more accurately and precisely in the enroute, terminal, and approach modes of flight. The following functions were determined necessary for in-flight control of GPS units: selection of groups and pages within the GPS unit; the ability to input and/or verify selections such as user defined waypoints, flight plans, standard terminal arrival routes (STARs), non-precision approaches, and standard instrument departures (SIDs); the ability to increase/decrease the precision of the display (zoom in/out); the ability to initiate direct-to navigation; the ability to enable/disable manual waypoint sequencing; the ability to initiate the nearest airport/waypoint/navigation aid function; the ability to view messages; and the ability to view menus.

NAV/COMM

The NAV/COMM is the unit which allows the pilot to communicate with other aircraft, airports, and ATC facilities. The unit also provides a means of VOR navigation. The communication portion of the NAV/COMM was identified as providing the following in-flight functional requirements to the HOTAS system: volume control, selection of communications frequency, and selection of the active frequency. The navigation portion of the NAV/COMM was identified as providing the following in-flight requirements: volume control, selection of navigation frequency, and selection of the active frequency.

Transponder

The transponder is a required item for flight in certain airspace. It gives ATC the ability to positively identify and track the aircraft along with all other aircraft in the ATC coverage area. The following requirements were determined to be necessary for in-flight control of the transponder: selection of transponder code and the identification feature.

CHAPTER 5

FUNCTIONAL ANALYSIS

General

Functional analysis is the process of decomposing the system into its most basic functions. This process began by examining the functional requirements of the individual avionics units. Each functional requirement was decomposed into the basic functions required to meet it. Since no specific make or model of avionics were chosen for this project, the functional requirements were meant to be applicable to the majority of each type of avionics. However, to decompose each functional requirement into its most basic functions, specific models of each avionics unit were considered. Specific models were cited when they were used as the basis for the functional decomposition.

Audio Panel

1. The first audio system functional requirement was that of volume control. Volume control for the majority of audio panels is accomplished through the use of a single knob. Control of the volume is attained by either clockwise or counterclockwise rotation of the knob. The basic function of the knob is that of either increasing or decreasing the volume.

2. The next audio system functional requirement was that of selecting the communications radio over which the pilot could transmit. Some aircraft are equipped with only one communications radio that negates the need for this requirement; however, many aircraft are equipped with dual communications radios. Dual radios are used for

redundancy and convenience. When configured with dual communication radios, the pilot must choose over which radio to transmit. On most audio panels, a knob with a detent corresponding to each radio is used to select the active transmitting radio. Either the first communications radio (COMM 1) or the second communications radio (COMM 2) is selected. There is not an option for neither or both radios to be selected for transmitting. The basic function for choosing the transmitting radio is that of an either/or selection of COMM 1 or COMM 2.

3. The next functional requirement for operation of the audio panel is that of selecting the desired communications and navigation radios to be heard over the headsets or speakers. The communications radio that is selected as the transmitting radio is automatically monitored over the headsets or speakers (this is an automatic function of audio panels). If equipped with a navigation radio and second communication radio (both of which this project assumed to be true), the pilot could choose to monitor each or all of these along with the primary radio for communications. The ability to monitor the marker beacon (MKR) is included on most audio panels as well. The majority of audio panels have differing types of push buttons for the selection of devices to be monitored. Each communication or navigation radio has a separate button. In some cases the pilot may want to briefly monitor a selected frequency on a secondary radio, receive the necessary information, and then remove the secondary audio source from being monitored. The functions the pilot must perform are those of selection and deselection of the desired radio(s).

4. The final functional requirement for operation of the audio panel is that of cueing the radio for transmission. The pilot, whether speaking into a handheld microphone or

into a headset microphone, must press a button to transmit at the desired time. If the button is mounted on the stick, it was called a push-to-talk (PTT) switch. When communication on the active frequency is desired, the pilot must press and hold the switch for the duration of the communication. Releasing the button ends the communication. The basic function for cueing the radio is that of continuous selection for the desired duration.

GPS

1. The first functional requirement for operation of the GPS is that of movement from on group of information to another within the GPS unit. In able to organize the vast amounts of information that GPS units contain, most GPS units have their functions and information separated into several distinct groups. The pilot must select a given group to view the desired information in that group. Group selection on current units is accomplished by either a designated push button for the specific group, concentric knobs used to scroll up/down and left/right to highlight the desired group, or a small joystick used to scroll up/down and left/right or to move an on screen pointer to the desired onscreen group. Within groups, further selection is possible between the pages of the group. Pages allow different information within a group to be displayed in a more manageable fashion. Page selection is accomplished in the same manner as group selection. Selection within a given page is also possible, i.e. menu selection. Group and page selection by designated push button was automatically ruled out as an option due to the relatively large number of buttons required and due to their reliance upon labeling and memory for proper operation. Based upon the remaining current methods of navigation

within GPS units, the basic function in navigating between groups and pages was that of scrolling (either left/right or up/down) to the desired group or page and accepting the selection.

2. The next functional requirement follows from the previous requirement in that for certain GPS units the group or page must be accepted once selected. Acceptance of groups and pages is one of many reasons for this requirement. Some GPS units would display questions to the operator that required the operator's acceptance. When entering or retrieving data such as stored waypoints, acceptance is required to store the entered data or to retrieve the stored data. Regardless of what is to be accepted, most current GPS receivers utilize an "ENT" button to accept selections. The basic function for selection acceptance is a discrete selection action.

3. The next functional requirement is that of inputting alpha-numeric data into the GPS unit. Most current GPS units rely upon concentric knobs for inputting data. The data input portions of the GPS screen consists of underlined blanks to be filled in by the operator. The first blank is automatically highlighted signifying that data must be input first into that blank. The following blanks are highlighted by rotating the outer knob, which moves the highlighted region to the next blank. To select the alpha-numeric symbol to enter for each blank, the operator rotates the inner knob, which scrolls through the alphabet, Arabic numerals, and commas, periods, and spaces. The first basic function for entering data is scrolling left/right to the desired space to enter data. The next basic function is scrolling through the alpha-numeric choices to find the desired character.

4. The next functional requirement is the ability to manually select the display sensitivity (to zoom in/out). This requirement comes from TSO-C129a, section

a.(3)(viii)3 [10]. Most current GPS receivers equipped with this ability have either a rocker type switch or two separate buttons to affect the zoom control. For receivers equipped with the rocker type switch, zooming in is accomplished by rocking the switch in one direction while zooming out is accomplished by rocking the switch in the other direction. When two buttons are used, one button zooms in and the other zooms out. The rocker switch design and the two-button design are oriented either horizontally or vertically and are labeled with either up and down arrows or the words "in" and "out". The basic function for zooming in/out is either a discrete or continuous selection of the zoom in/out control.

5. The next functional requirement is the ability to engage/disengage manual waypoint sequencing. This requirement comes from TSO-C129a section a.(3)(xi) [10]. This allows the pilot to fly holding patterns and procedure turns about a given waypoint with the ability to return to the flight plan and automatic waypoint sequencing at any time. Current GPS receivers utilize a dedicated push button for selection of manual waypoint sequencing. Pressing the button once disables automatic waypoint sequencing. Pressing the button a second time reactivates automatic waypoint sequencing. Some current receivers have the button as a part of the unit while other receivers have an external push button separate from the main unit. The buttons are labeled in various ways to include "OBS", "WPT SEQ", and "GPS SEQ". The basic function to engage/disengage manual waypoint sequencing is a discrete selection/deselection of the option.

6. The next functional requirement is the ability to navigate directly to any selected waypoint from the aircrafts current position. This is called direct-to navigation.

According to TSO-C129a section a.(3)(xi)1 [10], direct-to navigation must be accessible by a single action of the pilot. All current models utilized a push button with the symbol Đ→ to activate the direct-to feature. The basic function for initiating direct-to navigation is that of a discrete selection of the option.

7. Although not a requirement by regulation, the ability to quickly locate the nearest airport, NAVAID, or other waypoint was determined to be a functional requirement. Current GPS receivers utilize either a single push button to access the feature or a separate group or page set aside for this purpose. If the latter is used, then the group and page selection and selection acceptance functions from previous paragraphs are used. If the single push button, labeled "NRST", is used, the basic function for initiation of the nearest function is a discrete selection of the option. Following selection of the option, if the pilot chooses to navigate to one of the listed waypoints, the direct-to function is used to initiate navigation.

8. The next functional requirement is that of viewing messages. By TSO-C129a section a.(3)(xiii) [10], GPS receivers must be able to give failure and status indications for various reasons and at various times. These and other indications, warnings, and alerts are all given to the pilot by means of the message function. Current receivers employ a single push button labeled "MSG" to access the message feature. Either an indicator light flashes near the message button or an on screen indication of "MSG" is shown which prompts the pilot to check for current messages. To leave the message screen the pilot must push the message button a second time. The basic function for accessing and leaving the message feature is a discrete selection/deselection action.

9. Another functional requirement is the ability to view a menu for a specific page. Some current GPS units have on screen menus which are accessed by a “MENU” button. These menus contain page specific information and options. The menu can be accessed by pressing the menu button and hidden by pressing the menu button a second time or by making a selection from the menu. The basic function for accessing and hiding the on-screen menu is a discrete selection/deselection action.

NAV/COMM

Communication Radio

1. The first functional requirement for the operation of the communication radio is that of volume control. The pilot must be able to adjust volume of the communication radio along with overall audio system volume control. The functionality of the communication radio’s volume control is similar to that of the audio panel’s volume control. A knob (single or concentric) is turned either clockwise or counterclockwise to increase or decrease the volume of received transmissions over the communication radio; therefore, the basic functions are increasing and decreasing the volume.

2. The next functional requirement for operation of the communication radio is that of frequency selection. The pilot must select the appropriate frequency for the airport, geographic location, or ATC facility to which he/she is in communication. The available frequency range for VHF communication is 117.975 to 137.000. For most communication radios, concentric knobs are used to select the MHz and kHz. MHz are selected by rotation of the outer knob, and kHz are selected by rotation of the inner knob. Clockwise rotation causes an increase in frequency; counterclockwise rotation causes a

decrease. The basic functions required to select a communications frequency are increasing and decreasing the MHz and kHz.

3. The next functional requirement for operation of the communication radio is that of activating the selected frequency. Current models of communication radios have an active frequency and a standby frequency. The active frequency is the frequency in use, and the standby frequency is the frequency that is to be used next. When the pilot selectes a desired frequency by tuning the MHz and kHz, the frequency change is always made to the standby frequency so as not to interrupt the current frequency being monitored (this is the procedure for all current communications radios). When the pilot desires to monitor this new frequency a button is pushed causing the active and standby frequencies to swap places. The desired frequency is then active, and the next frequency can now be entered in the standby frequency position to await later activation. The basic function to accomplish the desired frequency activation can be described as a single-action frequency “flip-flop”.

Navigation Radio

1. The first functional requirement for operation of the navigation radio is that of volume control. To identify the station, the pilot should be able to adjust the volume of the navigation portion of the NAV/COMM radio, which is adjusted separately from the communication radio’s volume. The functionality of the navigation radio’s volume control is identical to the communication radio’s volume control. A knob is turned clockwise or counterclockwise to either increase or decrease the navigation radio’s

volume. The basic functions for the navigation radio's volume control are increasing and decreasing the volume.

2. The next functional requirement for in-flight operation of the navigation radio is that of frequency selection. Frequency selection for the navigation radio is similar to frequency selection for the communication radio. The frequency range for VOR stations is 108.00 through 117.95. The pilot must select the appropriate VOR/LOC frequencies for navigation during all phases of flight, in particular enroute and approach. A concentric knob is used to tune the MHz (outer knob) and kHz (inner knob). Clockwise rotation increases the frequency and counterclockwise rotation decreases the frequency. The basic functions for selecting the frequency of the navigation radio are increasing and decreasing the MHz and kHz of the frequency.

3. The final functional requirement for operation of the navigation radio is that of activating the selected frequency. The navigation radio functions in much the same way as the communication radio in that the frequency can only be entered as the standby frequency. The frequency then must be activated by pushing a button that "flip-flops" the active and standby frequencies. The basic function for activating the desired frequency is that of a single action frequency "flip-flop".

Transponder

1. The first functional requirement for operation of the transponder is that of transponder code selection. The pilot enters the transponder code whenever ATC assigns a new code or when transitioning from instrument flight rules (IFR) to visual flight rules (VFR) or vice versa. Most current models of transponders use four knobs to select the

desired code. Each knob is used to select a separate digit in the four-digit code. Clockwise rotation of a knob increases the digit from 0-9; counterclockwise rotation decreases the digit. When selecting a digit, continuous rotation of a knob causes the series of 0-9 digits to repeat. An alternate method of selecting the transponder code is through the use of a numeric keypad. The keypad consists of ten buttons numbering 0-9. When selecting a code, the first button pressed is automatically entered into the first digit of the code. The next button pushed is entered into the next digit with the remaining two digits entered in like manner. Transponders of the four-knob type were used for this project. The basic function for selection of the transponder code is that of increasing/decreasing each digit in a four digit code.

2. The next functional requirement is that of identifying your aircraft when requested by ATC. The pilot must use the identification feature on the transponder in order for ATC to distinguish the aircraft from other aircraft on the ATC radar screen. On all current models of transponders, the identification feature is activated by pressing a push button labeled "IDENT". When pressed, the IDENT button increases the intensity of the outgoing signal for 15-30 seconds after which the signal intensity automatically returnes to normal [17]. The basic function for operation of the IDENT feature is a discrete selection action.

CHAPTER 6

SYNTHESIS

General

After determining the functional requirements and their corresponding basic functions, according to the systems engineering process, alternatives were generated and evaluated in order to configure a system that met all of the system's requirements. Alternatives were compiled from multiple sources including the Federal Aviation Administration's (FAA) Human Factors Design Guide (HFDG) [21], various component manufacturers, and existing military and commercial aircraft HOTAS systems. Since basic functions are similar between several of the functional requirements, alternatives were first grouped according to basic functions. From these alternatives, the control was chosen for each functional requirement having that basic function.

Alternatives for Basic Functions

Increase/Decrease or Zoom In/Out

The following control alternatives provides the ability to increase/decrease a given parameter: thumb operated joysticks, hat switches, slide switches, rocker switches, thumbwheels, and knobs.

Select/Deselect

The following control alternatives provide the ability to select/deselect available choices: push buttons, rocker switches, toggle switches, and slide switches.

Scrolling

The following control alternatives provides the ability to scroll through selections: thumb operated joysticks, hat switches, slide switches, rocker switches, thumbwheels, and knobs.

Control Selection

Audio Panel

The following functional requirements were identified for HOTAS control of the audio panel: volume level, transmitting radio selection, audible radio selection, and radio cueing. Table 6-1 shows the comparison of the alternatives for audio panel volume adjustment. As can be seen in the table, knobs were not considered since they required the use of two fingers to be operated effectively. Similarity to existing controls was the primary reason that the thumbwheel was selected as the volume control. In order for the general aviation pilot to control the volume intuitively by the HOTAS system, the control had to be similar in operation to the existing volume control.

Table 6-1 Control Alternatives for Audio Panel Volume

	Similar to existing control	Movement Restricted to One Axis	Continuous Control over Large Range
Joystick			
Hat Switch			
Slide Switch		X	
Rocker Switch		X	
Thumbwheel	X	X	X

Current audio panels use knobs to control the volume. Knobs rotated around a single axis. Thumbwheels and knobs operate in much the same way; therefore, thumbwheels are the most intuitive control for volume.

Selection of the control used to select the transmitting radio was simplified by the fact that this project assumed the use of only two communications radios. If COMM 1 was selected on the audio panel as the transmitting radio before the flight began, there remained only the need for a single control to select COMM 2 from the HOTAS system. The control for COMM 2 would simultaneously deselect COMM 1 and select COMM 2 for transmission. Activating the control again would simultaneously deselect COMM 2 and select COMM 1. Push buttons and rotary selector knobs are used on current audio panels to select the transmitting COMM. Since only one control is needed, the push button was chosen as the transmitting COMM selection control.

For the selection of the audible radios, the push button was determined to be the best alternative. Push buttons are used on all current audio panels and are the most intuitive choice for the HOTAS system. Current models of audio panels automatically select the transmitting COMM as an audible COMM. The necessary selections are the remaining COMM, NAV 1 and 2, and the marker beacon. Pushing these buttons would select the desired audio. Pushing the button again would deselect the audio.

The standard control for cueing the radio for transmission is a momentary push button. The momentary push button was the control chosen for radio cueing in the HOTAS system due to its similarity to the existing control and its intuitive nature.

GPS

The following functional requirements were identified for HOTAS control of the GPS: group and page selection, selection acceptance, data entry, display sensitivity control, engage/disengage manual waypoint sequencing, direct-to navigation, nearest airport/NAVAID/waypoint locator, viewing messages, and viewing menus.

Selection of the groups and pages within the GPS unit was determined to be a scrolling action and is accomplished by ganged knobs on most current GPS units. Ganged knobs were not considered for HOTAS use; however, the thumbwheel operates in much the same manner without the need for two fingers. Two thumbwheels were chosen for group and page selection, one for group navigation and the other for subgroup or page navigation taking the place of the large and small knob respectively.

Data entry on current units consists of scrolling (left/right) to the appropriate data entry position and scrolling through the list of alpha-numeric choices for that position. This is accomplished by the use of ganged knobs. As stated previously, knobs were not considered for HOTAS use due to their reliance on the use of two fingers; however, thumbwheels are very similar in operation to knobs but require the use of only one finger. Based on the similarity of operation to current units, thumbwheels were chosen for data entry. One thumbwheel is for scrolling between data entry positions; the second thumbwheel is for scrolling through the list of alpha-numeric choices.

Display sensitivity control on current units is accomplished by the use of two push buttons or a combined control similar to a rocker switch. Two push buttons were considered; however, a rocker type switch was chosen in order to distinguish the control from surrounding HOTAS controls. The rocker switch also would allow the pilot to have control of both zooming in and zooming out with only one control.

Selection acceptance, engaging/disengaging manual waypoint sequencing, direct-to navigation, nearest airport/NAVAID/waypoint locator, viewing messages, and viewing menus are functions accomplished by push buttons on current units. These discrete actions were determined to be most effectively accomplished by a push button for the HOTAS system as well.

NAV/COMM

Communications Radio

The volume control for the COMM radio is no different than the volume control for the audio panel; therefore, the thumbwheel was selected for control of the COMM radio volume.

Frequency input requires the HOTAS system to afford control of selection of the MHz and kHz of the desired COMM frequency. Ganged knobs are used to select the frequency on all current models. The use of knobs was not considered due to the need for two fingers to effectively operate them. The need for the system to be intuitive led to the use of the controls most similar to knobs: thumbwheels. One thumbwheel is needed to input MHz and another thumbwheel to input kHz.

Current COMMs allow the user to input frequencies into the standby position only. A frequency “flip-flop” button is depressed to swap the active and standby frequency positions. The push button was chosen as the most intuitive control for HOTAS COMM frequency activation due to its similarity to the current control.

Navigation Radio

The following functional requirements were identified for HOTAS control of the NAV radio: volume control, frequency input, and frequency activation.

The volume control for the NAV radio is the same as the volume control for the audio panel and the COM radio; therefore, the thumbwheel was selected for control of the NAV radio volume.

Frequency input requires the HOTAS system to afford control of selection of the MHz and kHz of the desired NAV frequency. As discussed previously for the selection of the COM frequency input control, ganged knobs could not be used. Thumbwheels were chosen instead due to their similarity in operation to knobs. One thumbwheel is needed to input MHz and another thumbwheel to input kHz.

Current NAVs allow the user to input frequencies into the standby position only. A frequency “flip-flop” button is depressed to swap the active and standby frequency positions. The push button was chosen as the most intuitive control for HOTAS NAV frequency activation due to its similarity to the current control.

Transponder

The following functional requirements were identified for HOTAS control of the transponder: transponder code entry and IDENT activation. Transponder code entry on current units is accomplished by four knobs, each controlling the numeric data entry for each digit of the four-digit code. Knobs were not considered due to their requirement for two fingered operation; however, thumbwheels operate in much the same way with the requirement for only one finger. Due to the similarity of operation, thumbwheels were chosen as the HOTAS control for transponder code entry.

IDENT activation on current models is accomplished by a push button. This discrete action was determined to be most effectively accomplished by a push button on the HOTAS system as well.

CHAPTER 7

HOTAS CONTROL MOUNTING LOCATION

General

HOTAS control mounting locations were grouped into three possible categories: power control, aileron and elevator control, and alternate locations. The size, shape, and location of the different mounting positions varied from aircraft to aircraft. Cessna and Piper aircraft use control wheels for aileron and elevator control as shown in figures A-4 and A-5 or A-21 and A-22. Manufacturers such as Diamond and Cirrus use sidesticks or centersticks as shown in figures A-19 and A-20. Cessna utilizes a panel mounted push-pull control as shown in figure A-21 for power control. Piper utilizes a quadrant mounted, lever operated, push-pull control for power control as shown in figure A-22. Diamond and Cirrus aircraft use quadrant mounted, lever operated, push-pull controls located on a center console for ease of reach. These controls are shown in figures A-23 and A-24. In addition to the previous control mounting locations, alternate locations are possible such as the device shown in figure A-25. This particular device is used in the Gulfstream GV-SP for the mounting of various controls. Similar devices could be added to an armrest or seat of general aviation aircraft in order to serve as a mounting location for HOTAS controls.

Although many different control locations exist, this project was focused on the representative general aviation aircraft, i.e. Cessna 172 and Piper PA-28; therefore, the HOTAS system was designed with these aircraft's possible mounting locations in mind. Other considerations for choosing the appropriate mounting location were the mounting surfaces of the existing controls, the existing controls operation, the location of existing controls within the pilot’s reach envelope, and the frequency and duration of pilot contact with the existing controls.

Mounting Surface

Control Wheel

The mounting surfaces for the Cessna 172 and the Piper PA-28 are shown in figures A-4, A-5, A-21, and A-22. The control wheels in both aircraft varied slightly from one another; however, controls wheels from different model years of the same aircraft also differed slightly. The control wheel used for this project could have been that of the Cessna or Piper aircraft. Any control wheel chosen for this project must be modified to accept the HOTAS controls; therefore, either the Cessna or Piper control wheel can be used. This being the case, no specific control wheel was chosen. The only requirement for the control wheel is that the handgrip must be ergonomically correct and sized to accommodate the fifth percentile female through the ninety-fifth percentile male [21]. It was assumed for the remainder of the project that the handgrip fit this criterion.

Throttle

As can be seen in figures A-4 and A-5, the throttle controls differ greatly between the Cessna and Piper aircraft. The Cessna 172 throttle is a push pull control with a cylindrical knob oriented longitudinally [6]. The Piper PA-28 throttle is a lever operated push-pull control with a cylindrical knob oriented laterally [6]. Along with being oriented in different directions, the knob dimensions differ between Cessna and Piper

Aircraft. Knob dimensions also differ between different model years of the same aircraft; therefore, the knob used as a mounting surface for HOTAS controls was not necessarily a Cessna or Piper knob. If HOTAS controls were to be added to the throttle knob, modifications would had to have been made to both the Cessna and Piper throttle knobs; therefore, neither the Cessna or Piper throttle knobs were used for this project. The only requirement for the throttle knob is that it has to be ergonomically correct and sized to accommodate the fifth percentile female through the ninety-fifth percentile male [21]. It was assumed for the remainder of the project that the handgrip fit this criterion.

Alternate Location

As seen in figure A-25, alternate HOTAS control mounting locations exist. The mounting surfaces of these controls could be similar to that of the control used in the Gulfstream GV-SP, or they could be tailored to any size, shape, or location.

Control Operation

Control Wheel

The operation of the control wheel for both the Cessna 172 and the Piper PA-28 consists of a fore and aft translation and a left and right rotation. The control wheel is either pushed towards or pulled away from the control panel to affect pitch control. The range of translation is approximately 17cm for the Cessna and the Piper. The control wheel rotates around the control arm on which it is mounted in order to affect roll control. The range of rotation is approximately 180 degrees for the Cessna and the Piper.

Throttle

Operation of the throttle control for the Cessna 172 consists of fore and aft translation. The throttle translates through a range of approximately 7cm. The throttle control is also capable of being rotated; however, this rotation has no effect on engine rpm and ias due to the construction of push-pull control cables. Operation of the throttle control for the Piper PA-28 consists of the rotation of a lever about a lateral axis. The range of rotation is from a horizontal position with the control directed aft through slightly less than ninety degrees of rotation leaving the control oriented vertically.

Reach Envelope

A reach envelope investigation was conducted to determine where the control wheel and throttle were located in the pilot's functional reach envelope. Functional reach is the space surrounding the pilot through which the pilot can grasp a control. This investigation considered the 5% female pilot and the 95% male pilot. In order to determine the control wheel and throttle location within the reach envelopes of the targeted populations, seat positions were determined in the Cessna 172 and the Piper PA-28. Both aircraft have adjustable seats that allow for pilots of varying sizes. To determine the proper seat position DOD-HDBK-743A, Anthropometry of U.S. Military Personnel (Metric) was consulted to determine specific seated body measurements for both populations from United States Air Force personnel measurements taken in 1967 [22]. The measurements needed were as follows: buttock-knee length, knee height, and thigh clearance. These measurements were combined in order to simulate a seated pilot's position beginning with thigh clearance, measured from the seat's surface to the top of the thigh [22]. From this measurement extends the buttock-knee length, which is the distance from the back of the pilot's buttocks to the front of the knee [22]. From this measurement extends the knee height, which is the distance from the center of the knee to bottom the foot [22]. These three measurements combine to represent a pilot's leg reach as shown in figure A-26. From the measurements shown above, an anthropometric simulation device (ASD) was constructed using two standard yardsticks (see figure A-27). One yardstick represented the buttock-knee length, and the other represented the knee height. Each measurement was marked by a hole drilled through the center of the corresponding yardstick. The two yard sticks were then connected by a bolt and wing nut to simulate the knee joint. A 12-inch ruler was placed at the intersection of the seat back and seat pan, also known as the seat reference point (SRP), and extended along the seat back to represent the thigh height. The end of the ASD representing the back of the pilot's buttock was then placed at the corresponding thigh height along the seat back. The ASD was then extended along the seat pan and bent at the joint to place the end representing the bottom of the pilot's foot near a rudder pedal (see figure A-28). For proper seat placement, the pilot must be able to operate the rudder pedals to full displacement. With the ASD in place and full right rudder, the seat was positioned to allow the ASD to reach the displaced rudder pedal. Appropriate knee angles and foot placement on the rudder pedals were copied from those demonstrated by a participant in the opposite seat. With the seat adjusted for the given population, the horizontal distance from the SRP to the control wheel and throttle were measured in both the Cessna 172 and the Piper PA-28. Table 7-1 lists the measurements gathered using the ASD for the Cessna 172 and the Piper PA-28. These measurements were then compared with

Table 7-1 Cessna 172 and Piper PA-28 Cockpit Measurements

		Lateral Distance from SRP[1] (cm)	Vertical Distance from SRP (cm)	Longitudinal Distance to SRP (cm)	
				5% Female[2]	95% Male
Cessna 172[3]	Yoke Grip[4]	12.25	46	36	53
	Throttle Grip[5]	24	30	56	73
Piper PA-28[6]	Yoke Grip	12	41.5	37	55
	Throttle Grip	27	34.5	52	70

1. Seat Reference Point
2. Data gathered from 1967 United States Air Force Anthropometric Survey
3. 1967 Cessna 172H, Skyhawk
4. The control wheel was in an elevator neutral position. Grip measurements were taken from the middle fingers contact point on the front of the grip.
5. The throttle was at the 75% throttle forward position. Grip measurements were taken from the center of the throttle knob.
6. 1970 Piper PA-28-235-D, Cherokee

functional reach envelope diagrams obtained from NASA STD-3000, Man-Systems Integration Standards [23]. The diagrams are given for lateral distances from the SRP and depicted reach envelopes for the longitudinal-vertical plane. They are given in 15 cm increments laterally from the SRP. The yoke grips are located 12 and 12.25 cm laterally from the SRP's of the Cessna and Piper respectively; therefore, the 15 cm reach envelope diagrams were used for the yoke grips. The throttle grips are located 24 and 27 cm laterally from the SRP's of the Cessna and Piper respectively; therefore, the 30 cm reach envelope diagrams were used with the throttle grips. The reach envelope diagrams are shown in figures A-29 with yoke grip and throttle placements represented. The reach envelopes in figure A-29 are for forefinger and thumb grasp tasks; however, if full hand grasp are considered, the reach envelopes will decrease several cm depending upon the lateral displacement. As seen in the previous figures, the throttle grips are situated near or outside of the boundary for functional reach; however, the yoke grips are well within the reach envelopes for both populations in both aircraft.

Duration and Frequency of Use

Control Wheel

For aircraft with no autopilots such as the Cessna 172 and Piper PA-28 used in this project, the pilot is required to have a hand on the control wheel for the duration of the flight. The pilot’s left hand is used most often since the pilot sits in the left seat and operates several other controls with the right hand; however, during the cruise segment of a flight the pilot can use the right hand on the control wheel to relieve the left hand.

Throttle

Operation of the throttle begins with the takeoff portion of a flight at which time the power is set to full. During the climb portion of the flight the throttle may be adjusted, and during the cruise portion of the flight the throttle may be adjusted once more. Once set in cruise, usually 65-75% power, the throttle is held in place, using control friction, for the remainder of the cruise portion of the flight. Slight adjustments may be made in cruise to account for atmospheric changes or control slippage. During the descent portion of the flight, the throttle may be again adjusted as well as during the landing portion of the flight. The duration of time for which the pilot’s hand is on the throttle varies from pilot to pilot; however, the time taken to adjust the throttle to the desired setting is no more than several seconds after which the pilot can utilize the right hand for other cockpit tasks. Certain portions of the flight such as takeoff and landing require more adjustment of and attention to the throttle; however, frequency and duration of use of the throttle in flight were both considered low.

HOTAS Control Location Selection

Placement of the HOTAS controls was determined based upon the criteria discussed previously: mounting surface, control operation, reach envelope, and frequency and duration of use.

The mounting surfaces of the Cessna and Piper control wheels and throttles were assumed to have needed modification to accept the HOTAS controls, so the original mounting surfaces were of little importance since they were to be replaced or highly modified.

The operation of the control wheels for both aircraft, at first glance, was not desirable for HOTAS control mounting purposes. The control wheels are rotated in order to roll the aircraft; a situation in which the HOTAS controls would be oriented differently in relation to the pilot, adversely affecting the pilot's ability to operate the HOTAS controls. In reality the pilot would most likely not rotate the control wheel to its extremes; however, if such a situation arose requiring the pilot to deflect the ailerons sharply, the avionics equipment that the HOTAS system controlled would probably not be needed. This evaluation resulted in the control wheel's acceptance as a potential HOTAS mounting location based upon the control's operation.

The operation of the throttle in the Cessna 172 is a longitudinal translation and is acceptable for HOTAS control mounting. The throttle in the Piper PA-28 rotates about a lateral axis which causes the throttle grip to have a different orientation to the pilot depending upon where in the throttle range it is set. This causes difficulty since the pilot's hand would have to be oriented the same way on the throttle grip throughout the throttle's range of motion; however, the throttle usually remaines in the forward half of the throttles range throughout the flight and is only decreased significantly when in the landing pattern. The throttle for the Piper PA-28 was therefore determined to be acceptable as a HOTAS control mounting location with the throttle grip and HOTAS control placement optimized when the throttle is in the 65-75% of full power range.

Based upon the reach envelope information displayed in figure A-29, the control wheels for both the Cessna and the Piper are acceptable for HOTAS control mounting. Even with the reach envelopes adjusted for full hand grasp, bringing the reach curves in 5.5 cm, the control wheels still fell well within the 5% female's and 95% male's functional reach envelops [21,23].

The throttle in the Cessna is approximately 5 cm inside of the 95% male's functional reach envelope and 2 cm outside of the 5% female's functional reach envelope. The throttle in the Piper is approximately 9 cm inside of the 95% male's functional reach envelope and 4 cm inside of the 5% female's functional reach envelope. With the reach envelopes adjusted for full hand grasp, the reach envelope boundaries are even closer to the throttle positions. With the throttles being so close to the reach envelope boundaries, outside in the case of the 5% female in the Cessna, the pilot's arm would be outstretched to near the extent of his/her reach. This is not acceptable since the

HOTAS system needs to be mounted such that it can easily be reached, i.e. well within the pilot’s functional reach envelope; therefore, the throttle is not acceptable for HOTAS control mounting based upon its location within the pilot’s functional reach envelope.

The duration of time the pilot’s hand is on the control wheel and the frequency of the control wheels use are sufficiently high. This led to the control wheels acceptance as a mounting location for HOTAS controls. Although the throttle had previously been determined unacceptable for HOTAS control mounting, it was evaluated with respect to frequency and duration of use. The low frequency of use of the throttle during the majority of a given flight and the short duration of time the pilot’s hand is in contact with the throttle during each use resulted in the throttle once again being determined unacceptable for HOTAS control mounting.

The control wheel was determined to be the most suitable location for HOTAS control mounting based upon the four criteria discussed previously. The throttle was rejected on two of the four criteria: its placement within the pilot’s reach envelope and its frequency and duration of use. The third option for control mounting locations, alternate locations, was not included in the previous evaluation since the Cessna and Piper have no such alternate locations; however, this type of mounting location was reserved in case the control wheel alone was not adequate.

CHAPTER 8

HOTAS CONTROL INTEGRATION

General

With the mounting location determined, the HOTAS controls were placed in relation to one another on the control wheel. Factors such as the capabilities of the human hand, the importance of certain controls, and the purposeful grouping of controls were considered when arranging the HOTAS controls. All of these considerations culminated in the layout of the HOTAS control system on the control wheel. A proposed modification to the control wheel was deemed necessary to accommodate new controls.

Capabilities of the Human Hand

In order to integrate HOTAS controls into the control wheel, the capabilities of the pilot's hand and fingers were determined. The position of the pilot's hand on the control wheel is common to all control wheels as seen in figure A-30. With hand placement known, the range of motion of the fingers and thumb were determined in order for the HOTAS controls to be placed in the optimum positions. Extending from the wrist, there are 19 bones which made up the hand and fingers as shown in figure A-31 [24]. Five metacarpal bones extend from the carpometacarpal joint of the wrist. The metacarpal bones make up the palm of the hand. The carpometacarpal joint corresponding to the first metacarpal, which led to the thumb, is a saddle joint [24]. This type of joint consists of adjacent bones shaped somewhat like saddles that are 90 degrees apart. The bones fit together and are capable of movement in two axes. The movements are grouped into four primary categories: abduction, adduction, extension, and flexion [24]. Abduction usually corresponded to the movement of a body part away from the body's midline; however, in the case of the thumb's carpometacarpal joint, abduction is the movement of the thumb at a 90 degree angle to the plane of the hand (see figure A-32) [24]. Adduction is the reverse of abduction whereby the abducted thumb is returned to its original position (figure A-33) [24]. Extension consists of the thumb's movement in the plane of the hand away from the other fingers (see figure A-34) [24]. Flexion is the reverse of extension with the thumb returning to its original position adjacent to the index finger (figure A-35) [24]. The carpometacarpal joints of the 2nd, 3rd, and 4th metacarpal bones are described as "modified saddle joints" [24]. These joints allow for little motion apart from the motion of the wrist [24]. The 5th carpometacarpal joint corresponding to the metacarpal bone of the little finger is also a modified saddle joint allowing little motion; however, it is somewhat more similar to the joint of the thumb in that it allows slightly more movement than the other three fingers [24]. The lower ends of the metacarpal bones are connected to the phalanges by the metacarpophalangeal joints as seen in figure A-31 [24]. The metacarpophalangeal joint of the thumb acts as a hinge joint, allowing movement in only one axis [24]. Movement of the thumb towards the palm of the hand is called flexion while the reverse of this action is called extension [24]. The metacarpophalangeal joints of the four fingers are condyloid joints, consisting of the oval shaped convex end of one bone and the oval shaped concave end of the other bone [24]. These joints allow motion in two axes. The movements of the four fingers about their metacarpophalangeal joints are classified as abduction, adduction, flexion, and extension. Abduction is the spreading apart of the fingers within the plane of the hand (see figure A-36) [24]. Adduction is the return movement from abduction to the original position (see figure A-37) [24]. Flexion is the movement of the fingers toward the palm of the hand (see figure A-38) [24]. Extension is the return motion of the fingers from flexion to their original position (see figure A-39) [24]. Each of the four fingers has three phalanges; the thumb has only two phalanges [24]. The phalanges are connected by interphalangeal joints, which are hinge joints allowing motion in only one axis [24]. For the fingers and the thumb, movement towards the palm of the hand is flexion, and the reverse movement is extension [24]. The movement capabilities of the hand and fingers for this project were considered with the hand gripping a control wheel as seen in figure A-30. When the hand is in this position, the metacarpophalangeal and interphalangeal joints of the four fingers are at differing angles of flexion, depending upon the diameter of the control wheel grip and the size of the pilot's hand. When in flexion, the abduction of the four fingers about the metacarpophalangeal joints is limited, i.e. the vertical range of the four fingers on the control wheel grip is limited apart from movement of the wrist [24]. The carpometacarpal joint of the thumb is partially extended and abducted, and the metacarpophalangeal and interphalangeal joints of the thumb are partially flexed. In this position, the thumb retains full range of motion while the fingers are slightly restricted in abduction about the metacarpophalangeal joints. Greater range of motion for all fingers is obtained by slightly shifting parts of or the entire hand about the grip; however, the thumb retains the largest range of motion.

The three types of control devices chosen to accomplish the functions of the HOTAS control system were the thumbwheel, the rocker switch, and the push button.

Based upon the capabilities of the hand on the control wheel, the HOTAS controls were generally placed according to which finger(s) could control them. The thumbwheel could have been naturally placed in the control space of the thumb; however, a horizontally mounted thumbwheel, if needed, could have been placed in the control space of the fingers. In much the same way as the thumbwheel, the rocker switch could have been utilized by the thumb or the fingers. Push buttons are controllable by the thumb and fingers as well. With the pilot's hand gripping the control wheel, there was no space on the control wheel grip to mount HOTAS controls in the control space of the 3rd and 4th fingers without an increased risk of unintentional activation; therefore, placement of HOTAS controls in the control space of the 3rd and 4th fingers was excluded. The index and little finger are capable of abducting slightly to activate HOTAS controls located away from their gripping position.

Primary Controls

Primary controls are controls of high importance or controls that are used frequently [25]. These controls require placement in the optimum positions on the control wheel. According to the capabilities of the hand, the control space of the thumb is the optimum position for HOTAS control mounting. The index and little fingers are capable of operating controls; however, the thumb is capable of a larger range of motion and has a larger possible mounting surface on the control wheel grip. Primary controls were determined based upon the primary functions to be performed for each avionics unit. A control which was used frequently but that was not a focus of this project was electric trim control. Although not a focal control in this project, the electric trim control was considered a primary control and placed as such.

Audio Panel

The functions of the audio panel considered to be primary functions were volume control, selection of the transmitting radio, and COMM radio cueing.

GPS

The functions of the GPS considered to be primary functions were group and page selection, selection acceptance, data entry, and direct-to navigation.

NAV/COMM

The functions of the communication and navigation radios considered to be primary functions were volume control, frequency input, and frequency activation (frequency “flip-flop”).

Transponder

The functions of the transponder considered to be primary functions were transponder code entry and IDENT activation.

Control Grouping

Controls that are operated in a definite order or sequence were to be grouped together [25]. Controls on current avionics units are in close proximity to one another based on the limited size of the unit upon which they are mounted; however, this did not automatically necessitate the grouping of the controls in a HOTAS system. Only controls that were purposefully grouped together on existing avionics units were to be grouped together in the HOTAS system. The grouping of controls is a method by which the pilot could easily identify the position of controls based upon their relationship to other controls. Grouping also allows the pilot's actions to move in a definite flow without having to move back and forth to accomplish the different control actions required in a sequence.

Audio Panel

Several controls on current audio panels were purposefully grouped together. The transmitting radio and audible radio controls were grouped together. These controls were in two separate groups; one for transmitting radios and another for audible radios; however, these two groups are highly related in purpose and are located very close to one another. The HOTAS system in this project has only one control for transmitting radio selection, so grouping was not a concern for transmitting radio controls. The HOTAS system has four audible radio controls grouped together: COMM, NAV 1, NAV 2, and MRK. The audible radio controls group had to be in a definite group, and it had to be located close to the transmitting radio control.

GPS

Several controls on current GPS units are grouped together and operate in sequence. Group and page selection controls on current GPS units are grouped together in the form of ganged knobs. The large outer knob controls group selection while the smaller inner knob controls page selection. Group selection is made first followed by page selection within the group. These controls formed a sequence and were oriented left to right in the HOTAS system. The group control is located on the left, and the page control is located on the right. Data entry controls on current models are operated in sequence as ganged knobs as well. The large outer knob is used to scroll to the appropriate data entry position, and the small inner knob is used to scroll through the alpha-numeric choices. These controls were given left to right placement in the HOTAS system with the data entry position control on the left and the alpha-numeric choice selection control on the right. Once the data is entered, it is accepted by depressing a pushbutton; therefore, selection acceptance was in sequence with the data entry controls. The HOTAS selection acceptance control was located to the right of the HOTAS data entry controls. The direct-to navigation feature is often initiated after inputting a desired destination; therefore, it is also operated in sequence with the data entry controls. The direct-to navigation feature was located to the right of the selection acceptance control.

NAV/COMM

Controls on current NAV/COMMs are purposefully grouped together and operated in a sequence. On current NAV/COMMs the controls for input of the MHz and kHz are grouped together as ganged knobs. Depending upon the frequency change and the user, these controls are also operated in a sequence. When inputting a new frequency that requires both the MHz and kHz to be changed, it was expected that the MHz was entered first followed by the kHz. This assumed a left-to-right control flow that corresponded to the NAV/COMM’s display. The standard direction of flow of controls operated in a sequence was from left to right or from top to bottom [21, 25]. Since the displays on all current NAV/COMMs display MHz and kHz from left to right, the HOTAS controls for MHz and kHz input were grouped together with the MHz control on the left and the kHz control on the right.

Once the frequency is input, it has to be activated. This means that the frequency activation control is the last step in the sequence of inputting and activating a new frequency. On current NAV/COMMs the frequency activation control is to the left of the MHz and kHz input controls. Although this control placement is standard on all current NAV/COMMs, the HOTAS control system followed a left to right or top to bottom control flow. Top to bottom control flow was not used since the MHz and kHz controls were oriented left to right and the frequency activation control was in series with them. The HOTAS control layout for the NAV/COMM was, from left to right, MHz control, kHz control, and frequency activation control.

Transponder

Controls on current transponder units that are purposefully grouped together and operated in a sequence are the data entry controls for the four transponder code positions. Data entry for this four digit transponder code was assumed to follow the left to right standard; therefore, the HOTAS transponder code entry controls were given left to right placement corresponding to the placement of their associated displays.

Emergency Controls

For this project, emergency controls were considered to be those controls needed primarily in emergency situations. They are controls of high importance that are not expected to be used on a regular basis. Of the HOTAS controls, only one was considered to be an emergency control. The nearest function control of the GPS was considered an emergency control due to its ability to quickly aid lost pilots, pilots operating on critically low fuel, or pilots facing many other time critical situations that could arise. Emergency control placement was to be separate from other controls in order to distinguish the control from other controls of high importance. Emergency controls were also to be separate from other controls in order to reduce the number of controls in one location especially with emergency controls being used infrequently. Placement on the control wheel grip that fit these criteria was in the control space of the little finger. Due to the importance of this control and the limited control space of the little finger, this was the only control that was placed in the little finger's control space.

HOTAS Control Layout

General

From the above information, the HOTAS controls were placed on the control wheel. If the HOTAS system had included every control discussed in this project there would have been forty separate controls on the control wheel; this number included the additional controls from a second NAV/COMM. This system would have been difficult for a pilot to operate without constantly looking at the control wheel for visual control identification, the fingers would have been overloaded with controls, and the control wheel is not large enough to accommodate such a large number of controls. To reduce the number of controls on the control wheel, control functions were combined into shared controls by the use of a momentary “shift” button. The shift button operated in much the same way as the shift key on a computer keyboard. When a control was operated, one function was performed; however, when the shift button was depressed along with the same control, another function was performed. The shift key potentially doubled the functionality of every control. Even with the shift button used, the minimum possible number of controls was twenty. This was still too large a number of controls for the pilot’s capabilities and the physical space of the control wheel. The next measure to reduce the number of controls on the control wheel was to further increase the number of functions controlled by a shared control. This was accomplished by combining the controls from each avionics unit into a set of common controls. Each common control would control different functions depending upon the avionics unit selected. A selector control was added to the HOTAS system with positions for each avionics units to be controlled. For this project there were five selector control positions: audio panel, GPS, NAV/COMM 1, NAV/COMM 2, and transponder. With the selector control positioned, the common controls allowed the pilot to perform the functions necessary to control the particular avionics unit. A five-position slider switch was used as the selector control. The slider switch, unlike a rotary selector knob, is operated by a single finger, and it is capable of being oriented vertically, so the switch positions reflect the positions of the associated avionics units on the control panel. To create the set of controls common to all of the avionics units’ controls, each avionics unit’s controls were arranged based upon the information discussed previously. Similarities were then identified and combined into a common control. Control layout began with placement of the primary control followed by controls that were purposefully grouped or operated in a sequence. Emergency controls and any remaining controls were later placed.

Audio Panel

A preliminary control layout for the audio panel HOTAS controls is shown in figure A-40. Volume control on is on the left face of all current audio panels and was given left placement in the HOTAS system as a result. Volume control and transmitting COMM selection are primary controls that were placed in the control space of the thumb. The COMM radio cueing control is also a primary control and was tentatively placed to the right of the transmitting COMM selection control. The audible radio selection controls were grouped together as well as being located in close proximity to the transmitting COMM control.

GPS

A preliminary control layout for the GPS HOTAS controls is shown in figure A-41. The GPS group/page selection and data position/alpha-numeric choice selection HOTAS controls were grouped together and aligned from left to right to allow for sequential operation. The selection acceptance control and the direct-to navigation control were located to the right of the group/page and data position/alpha-numeric choice selection controls.

NAV/COMM

A preliminary control layout for the NAV/COMM HOTAS controls is shown in figure A-42. Volume control is on the left face of all current NAV/COMMs and was given left placement in the HOTAS system as a result. The MHz, kHz, and frequency activation controls were grouped together and aligned from left to right to allow for sequential operation.

Transponder

A preliminary control layout for the transponder HOTAS controls is shown in figure A-43. The transponder code entry controls were aligned from left to right to allow for sequential operation. The identification activation switch was placed to the right of the transponder code entry controls.

Primary Common Controls

From the preliminary HOTAS control layouts, a set of common controls was constructed. Both the audio panel and the NAV/COMM had a thumbwheel for volume control. Both the NAV/COMM and the GPS had two thumbwheels for control of various functions. All four avionics units had at least one pushbutton that was considered a primary control. From these similarities, the common controls were determined to be three thumbwheels and one pushbutton. Arrangement of the common controls was similar to the arrangement of the separate avionics unit's controls. The volume thumbwheel was on the left. Moving to the right, two thumbwheels were grouped together followed by the pushbutton. The functions of the common controls for each avionics unit are given in table 8-1. All of the functions of each avionics unit were not capable of being controlled by the common controls alone; therefore, the previously mentioned shift button was utilized to increase the functionality of the common controls. Table 8-2 lists the functions of the common controls when operated with the shift button depressed.

Remaining Controls

The only primary controls that were not incorporated into the common controls were the electric trim control, the COMM radio cueing control, the direct-to navigation control, the common control selector control, and the shift control. The common control selector control and the shift control are considered primary controls since they determined the functions of the other primary controls. The common control selector control is the first control in the sequence of controlling all of the common controls and was given placement to the left. However, the importance of the selector control warranted more central placement. It was placed between the volume control and the remaining common controls. The shift button is a primary control, but it must be operated simultaneously with other primary controls. Since the primary controls are operated by the thumb, the shift button had to be operated by another finger. The index finger was chosen to operate the shift button, since it is capable of depressing a button while the thumb operates other controls. The electric trim control was placed between the volume control and the common control selector control. This placed the electric trim control in an easily accessible location where pilots would expect it.

Table 8-1 Functions of the Common Controls

		Volume Thumbwheel	First Grouped Thumbwheel	Second Grouped Thumbwheel	Pushbutton
Audio Panel		Volume			Transmitting COM Selection
NAVCOM	COM		MHz	kHz	Frequency Activation
	NAV				
GPS			Group Selection/Data Entry Position Location	Page Selection/Alpha-numeric Choice Selection	Selection Acceptance
Transponder			Transponder Code Digit 1	Transponder Code Digit 2	IDENT

Table 8-2 Functions of the Common Controls with the Shift Button

		Volume Thumbwheel	First Grouped Thumbwheel	Second Grouped Thumbwheel	Pushbutton
Audio Panel		Volume			Audible COM Selection
NAVCOM	COM				
	NAV	Volume	MHz	kHz	Frequency Activation
GPS			Group Selection/Data Entry Position Location	Page Selection/Alpha-numeric Choice Selection	Menu Activation
Transponder			Transponder Code Digit 3	Transponder Code Digit 4	IDENT

The electric trim control used for this project is a miniature hat switch as seen in figure A-44. The radio cueing control had earlier been placed to the right of the frequency activation control of the COMM. This placement remained the same with the radio cueing control located to the right of the common control pushbutton that controlled the COMM's frequency activation. The direct-to navigation feature was operated by a push button located to the right of the COMM radio cueing control. Non-primary controls that had not been placed were the audible radio selection controls for NAV 1, NAV 2, MKR, the GPS's display sensitivity control, manual waypoint sequencing control, and message viewing control. All of the remaining controls were to be operated by pushbuttons except for the GPS's display sensitivity control that was operated by a rocker switch. In order to reduce the number of controls needed to accomplish these functions several of the control's functions were combined into shared controls by using the shift button. The remaining control's functions are listed in table 8-3. The remaining controls were placed in the control space of the thumb to the right of the primary common controls in the order shown in table 8-3.

Table 8-3 Functions of the Remaining Controls

	First Remaining Pushbutton	Second Remaining Pushbutton	Rocker Switch
Audio Panel	Audible NAV 1 Selection	Audible Marker Beacon Selection	
Audio Panel with Shift Button	Audible NAV 2 Selection		
GPS	Direct-to Activation	Message Selection	Display Sensitivity Control
GPS with Shift Button	Manual Waypoint Sequencing Selection		

Control Wheel Modification

Twelve controls were to be placed on the control wheel. Ten of the controls were to be placed in the control space of the thumb. The control wheel had to be modified to accept the controls and to allow sufficient spacing between them. Modification to the control wheel had to expand the control mounting locations within the thumb's reach. The thumb's reach boundary formed an arc about the control wheel grip as seen in figure A-45. This reach boundary was attained by abduction and adduction about the thumb's carpometacarpal joint. Shifting of the hand on the control wheel grip allowed further thumb reach; however, much of this additional reach was unusable for placement of controls that were to be operated along with the shift button. The proposed modification to the control wheel grip is shown in figure A-46.

Control Placement

Placement of the controls onto the modified control wheel grip followed the control layout determined previously. With such a large number of controls to be placed in the control space of the thumb, conserving and efficiently using space was of the utmost importance. The volume thumbwheel was placed in the leftmost position in the control space of the thumb. Since the volume thumbwheel was not operated with the shift button, it was placed so that the thumb could operate it with the hand slightly shifted about the control wheel grip. In this position, the volume thumbwheel rotated about a longitudinal axis as seen in figure A-47. The electric trim hat switch was placed to the right and forward of the thumbwheel. Thirteen millimeters is considered the minimum spacing between controls operated by one finger and was adhered to when possible [21].

The common controls slide switch was placed to the right and aft of the electric trim hat switches. The grouped thumbwheels were placed to the right of the slide switch. To preserve the close grouping of the thumbwheels while protecting against inadvertent activation of one thumbwheel while operating the other, the grouped thumbwheels were separated by a guard approximately 3 mm wide that extended 3 mm above the thumbwheels. The primary common control's pushbutton was located to the right of the grouped thumbwheels. The PTT switch was placed to the right of this pushbutton and towards the extent of the thumb's reach. To the right of the PTT switch but nearer in the thumb's reach envelope was placed the first of the three remaining controls. This was the pushbutton that had shared functions accessible by the shift button. This pushbutton was placed first to ensure the thumb's ability to operate it while the index finger simultaneously depressed the shift button. The next pushbutton was placed to the right of the shared function's button. The last control to be placed was the display sensitivity rocker switch. It was placed to the right of the last pushbutton and oriented vertically. The placement of the controls was described from left to right; however, when looking at the modified control wheel grip, it can be seen that this placement was "wrapped" around the modified control grip following the thumb's range of motion. Figure A-48 shows the proposed control placement. The two remaining controls were the shift pushbutton and the nearest airport/waypoint/navigation aid pushbutton. The shift pushbutton was placed in the control space of the index finger. The nearest airport/waypoint/navigation aid pushbutton was placed near the extent of the little finger's reach boundary slightly below the little finger's position on the control wheel grip.

CHAPTER 9

CONTROL IDENTIFICATION

General

The HOTAS control system was designed to be as intuitive as possible to enable any pilot, especially those experienced with the avionics units in a given aircraft, to control the system with little to no training. The shape, operation, and orientation of the controls was designed to promote the intuitive nature of the system; however, an additional form of control identification was needed to aid an inexperienced user until the HOTAS control functions became familiar. Control labeling was the obvious way to accomplish the needed control identification.

Control Labeling

To aid in control identification, the HOTAS controls were labeled according to their functions. Where possible, labeling of the HOTAS controls was consistent with the labeling on the avionics units. Since most of the HOTAS controls had several functions depending upon the avionics unit selected, these controls were given several labels. The size of the HOTAS controls, no larger than 1 cm wide, restricted the placement of labels to the area of the control wheel surrounding each control. Labels for each function of a HOTAS control were placed to the left of the control. The labels were arranged from top to bottom to correspond to the arrangement of the avionics units for which each label was applicable. Labels for each function that required depression of the shift control were placed to the right of each control. Theses labels were also arranged from top to bottom to correspond to their associated avionics unit. The volume control thumbwheel was placed on the left face of the control wheel grip making the area to its left difficult to see; therefore, its label was placed to the right to make it more obvious to the pilot. The electric trim switch was a miniature hat switch; however, it was large enough to accommodate labels around the outer edges of the control head. The radio cueing button, PTT, had only one function, and because of its size was recognizable as a PTT switch; therefore, no label was given for the radio cueing button. The display sensitivity control has only the functions of zooming in and zooming out; therefore, its label was placed on the control itself. The nearest airport/waypoint/navigation aid button is in the control space of the little finger where no label could be seen. Its label was placed on the backside of the control grip with an arrow leading to the button's location. The shift button was not labeled due to its forward placement on the control grip. Table 9-1 lists the all of the functions to be controlled along with their labels. Label character height was 2.3 mm with 1 mm spacing above and below adjacent labels [21]. Due to the number of labels for certain HOTAS controls, color-coding was used to distinguish between the controls operated alone and those operated with the shift button. White was chosen as the color for labels of controls operated without the shift button. This was the standard color for labels on most current avionics units. Yellow was chosen as the color for labels of controls operated with the shift button. The shift button itself was also colored yellow to make a definite link between its operation and the HOTAS control functions accessed by it. The specific shades of white and yellow follow the guidelines given in the Human Factors Design Guide section 6.3.5.5.2 [21]. The HOTAS control grip with labels is shown in figure A-49.

Table 9-1 HOTAS Control Labels

	Avionics Unit	Function	Label	
			Without Shift	With Shift
Volume Thumbwheel	Audio Panel	Volume Control	VOL	
	NAV/COMMs			
Electric Trim Hat Switch	N/A	Nose Up	U	
		Nose Down	D	
		Roll Left	L	
		Roll Right	R	
Common Control Selector Switch	Audio Panel		AP	
	GPS		GPS	
	NAV/COMM		N/C1	
	NAV/COMM		N/C2	
	Transponder		TPDR	
First Grouped Thumbwheel	GPS	Group Selection	GRP	
	NAV/COMM	MHz Entry	MHz	
	Transponder	Transponder Code First Digit	1	
		Transponder Code Third Digit		3
Second Grouped Thumbwheel	GPS	Page Selection	PAGE	
	NAV/COMM	kHz Entry	kHz	
	Transponder	Transponder Code Second Digit	2	
		Transponder Code Fourth Digit		4
First Pushbutton	Audio Panel	Transmitting COMM Selection	TCOM	
		Audible COMM Selection		ACOM
	GPS	Selection Acceptance	ENT	
		Menu Selection		MENU
	NAV/COMM	COMM Frequency Activation	C◀▶	
		NAV Frequency Activation		N◀▶
	Transponder	Identification Activation	IDENT	
Second Pushbutton	Audio Panel	Radio Cueing		
Third Pushbutton	Audio Panel	Audible NAV 1 Selection	NAV1	
		Audible NAV 2 Selection		NAV2
	GPS	Direct-to Activation	-D→	
		Manual Waypoint Sequencing		MAN
Fourth Pushbutton	Audio Panel	Audible Marker Beacon Selection	MRK	
	GPS	Message Viewing Activation	MSG	
Rocker Switch	GPS	Zoom In	▲	
		Zoom Out	▼	
Little Finger's Pushbutton	GPS	Nearest Activation	NRST	
Index Finger's Trigger Switch	All	Shift		

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This project began by expressing the need for a GA HOTAS system capable of controlling the necessary in-flight functions of specified avionics and aircraft systems. The avionics controlled were the audio panel, GPS, NAV/COMMs, and transponder. Control of the electric trim was also incorporated. The in-flight functions of each avionics unit were determined and separated into their most basic forms. HOTAS control hardware was chosen for each function and combined into an organized control layout. This control layout is made up of three thumbwheels, a miniature hat switch, a five-position slider switch, four pushbuttons, a PTT switch, a rocker switch, and a trigger switch. These controls were placed on the control wheel, which was chosen as the appropriate HOTAS mounting location, in the control space of the fingers that operate them. The capabilities of the hand were determined in order to place the controls with the appropriate finger. Design modifications to the control wheel grip were made in order to accept the large number of controls to be operated by the thumb. This was because the thumb has the largest range of motion. The controls were then labeled in order to aid in their identification until the pilot became familiar with them. Conclusions drawn from the design project are as follows:

1. A GA HOTAS system is feasible utilizing existing components for HOTAS controls. Modifications to the control wheel are necessary in order to incorporate the HOTAS controls. Modifications to current avionics units are also necessary to allow HOTAS control of their functions

2. The conceptual GA HOTAS design meets the identified need for the project.

3. Although the HOTAS system was designed to be intuitive, the number of controls and the multifunctionality of the controls would necessitate training on the system's operation prior to the system's use in flight.

Recommendations

The following recommendations are made concerning the project:

1. Avionics units should be designed with this HOTAS control system in mind to aid in the system's incorporation.

2. A prototype of the system should be constructed and tested as a simulation. This simulation should compare the HOTAS system to the standard non-HOTAS system.

3. A training program should be developed to familiarize pilots with the systems operation.

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APPENDIX

Figure A-1 1967 Cessna 172H, Skyhawk

Figure A-2 1970 Piper PA-28-235D, Cherokee

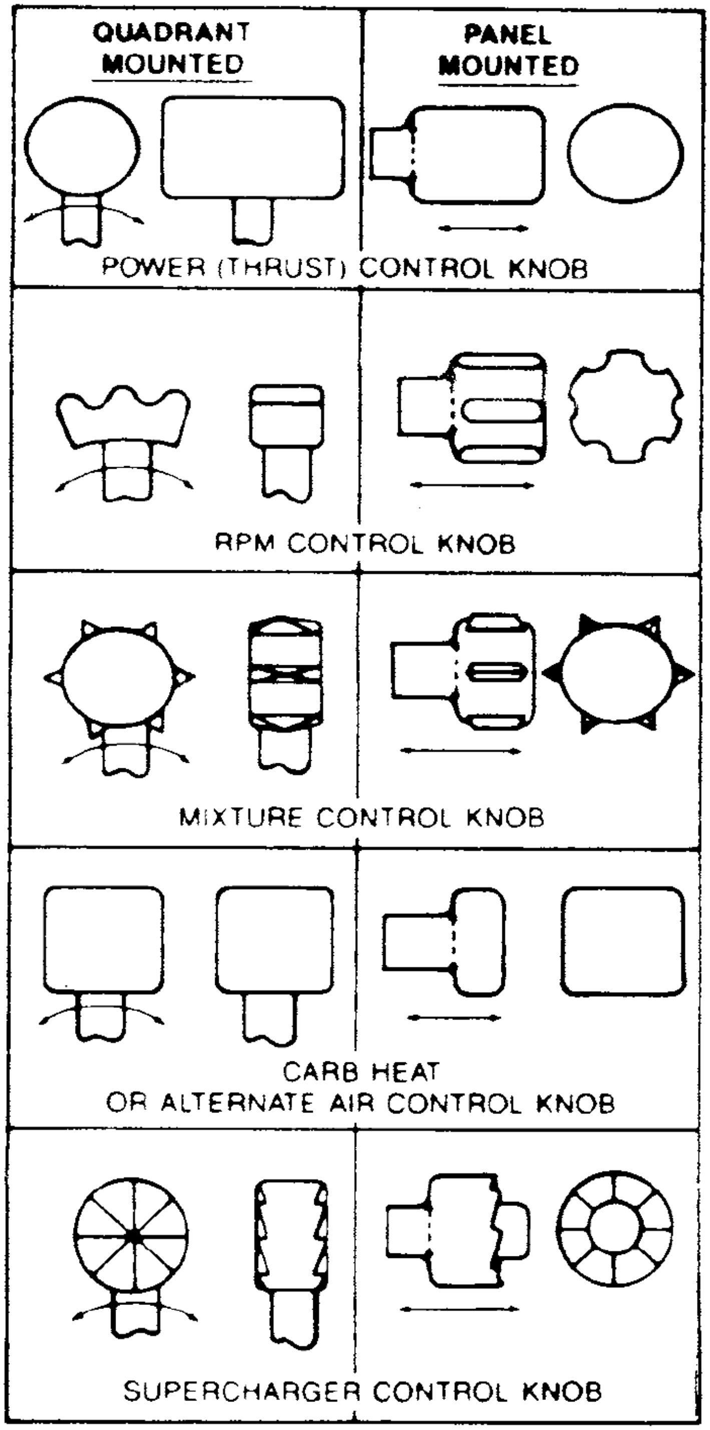

Figure A-3 Panel and Quadrant Mounted Knob Shapes

Source: United States Department of Transportation, Federal Aviation Administration (n.d.). *Electronic Code of Federal Regulations*. Retrieved September 10, 2002, from http://www.access.gpo.gov/nara/cfr/cfrhtml_00/Title_14/14cfrv1_00.html.

Figure A-4 Cessna 172 Control Wheel

Source: Retrieved from http://skyhawk.cessna.com/avionics.chtml.

Figure A-5 Piper PA28 Control Wheel

Source: Retrieved from http://www.newpiper.com/fleet/warriorIII/see_it/index.asp.

Figure A-6 Apollo SL15 Audio Panel

Source: Retrieved from http://www.upsat.com/sl15.shtml.

Figure A-7 Bendix/King KMA 28 Audio Panel

Source: Retrieved from http://www.bendixking.com/static/catalog/viewproductdetails.jsp?pid=48.

Figure A-8 Garmin GMA 340 Audio Panel

Source: Retrieved from http://www.garmin.com/products/gma340/.

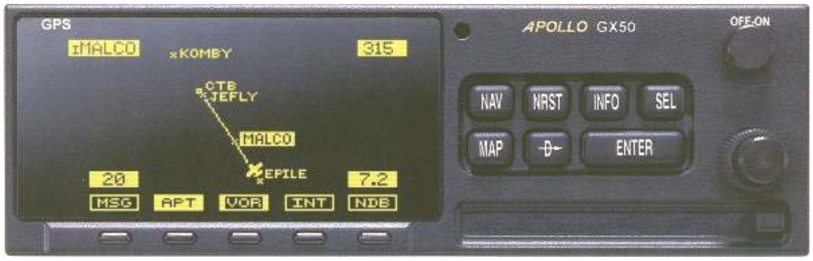

Figure A-9 Apollo GX50 GPS

Source: Retrieved from http://www.upsat.com/gx50.shtml.

Figure A-10 Bendix/King KLN 90B GPS

Source: Retrieved from http://www.bendixking.com/static/catalog/viewproductdetails.jsp?pid=120.

Figure A-11 Garmin GNS 530 GPS with integrated NAV/COMM

Source: Retrieved from http://www.garmin.com/products/gns530/.

Figure A-12 Apollo SL30 NAV/COMM

Source: Retrieved from http://www.upsat.com/sl30_gen.shtml.

Figure A-13 Bendix/King KX 155A NAV/COMM

Source: Retrieved from http://www.bendixking.com/static/catalog/viewproductdetails.jsp?pid=89.

Figure A-14 Apollo SL70 Transponder

Source: Retrieved from http://www.upsat.com/sl70.shtml.

Figure A-15 Bendix/King KT 70 Transponder

Source: Retrieved from www.bendixking.com/static/catalog/viewproductdetails.jsp?pid=139.

Figure A-16 Garmin GTX 330 Transponder

Source: http://www.garmin.com/products/gtx330/.

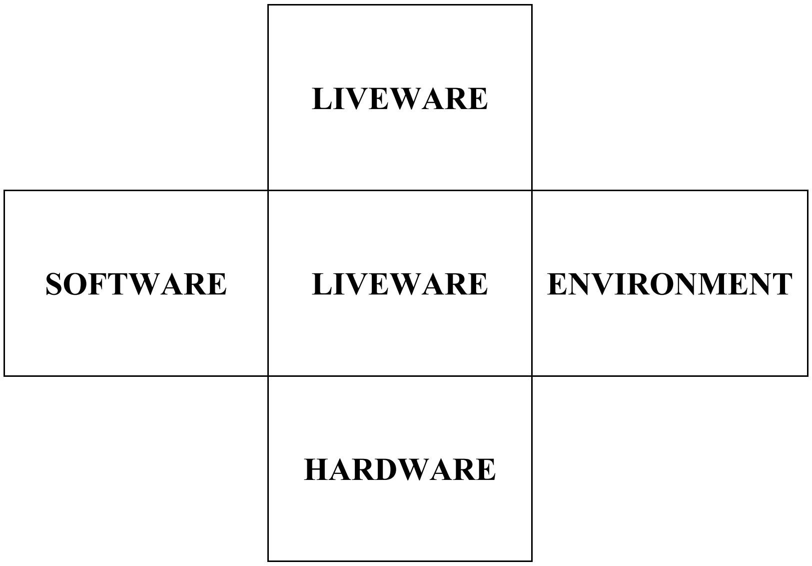

Figure A-17 SHELL Model

Figure A-18 F-16 HOTAS Throttle/Mig-21 HOTAS Throttle and Stick

Source: Retrieved from http://www.mason-electric.com/F16.htm and http://www.mason-electric.com/MIG-21.htm.

Figure A-19 Diamond Evolution Centerstick

Source: Retrieved from http://www.diamondair.com/contentc/Evolution.htm.

Figure A-20 Cirrus SR20 Sidestick

Source: Higdon, D. (2003, January 20). *Plastic Planes, Part Two: The Cirrus SR20*. Retrieved on March 10, 2003, from http://www.avweb.com/news/newacft/182428-1.html.

Figure A-21 Control Wheel from 1967 Cessna 172H, Skyhawk

Figure A-22 Control Wheel from Piper PA-28-235D, Cherokee

Figure A-23 Diamond Center-Mounted Throttle

Source: Retrieved from http://www.diamondair.com/contentc/Evolution.htm.

Figure A-24 Cirrus SR20 Center-Mounted Throttle

Source: Higdon, D. (2003, January 20). *Plastic Planes, Part Two: The Cirrus SR20*. Retrieved on March 10, 2003, from http://www.avweb.com/news/newacft/182428-1.html.

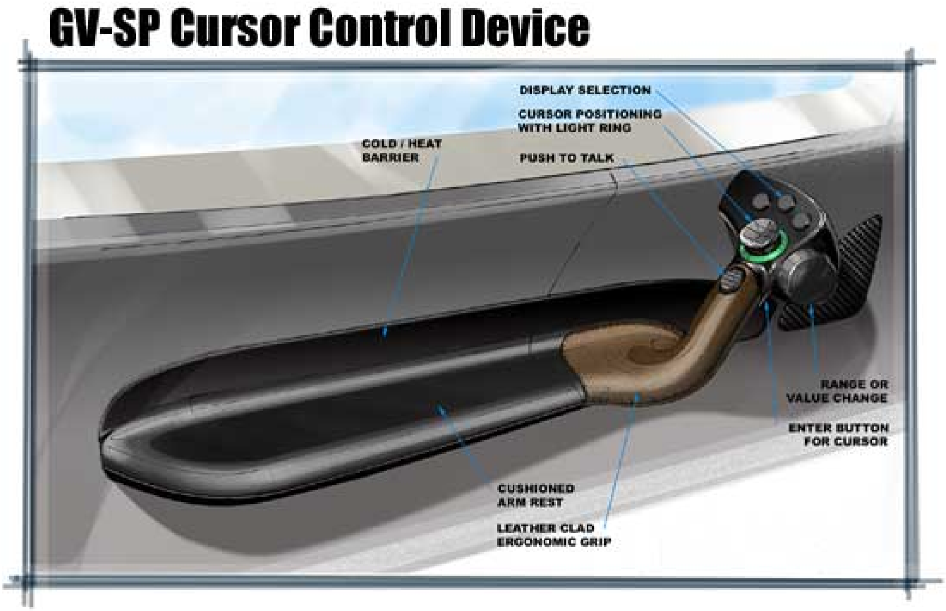

Figure A-25 Gulfstream GV-SP Alternate Control Mounting Location

Source: Retrieved from http://www.mason-electric.com/GVSPCCD.htm.

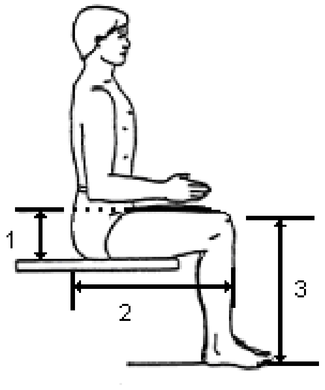

Figure A-26 Seated Measurements: 1) Thigh Clearance 2) Buttock-Knee Length 3) Knee Height

Source: United States Army Natick RD&E Center. (1991). *Anthropometry of U.S. Military Personnel (Metric)* (DOD-HDBK-743A). Retrieved September 10, 2002, from http://assist.daps.dla.mil/online/parms/mainframe.cfm.

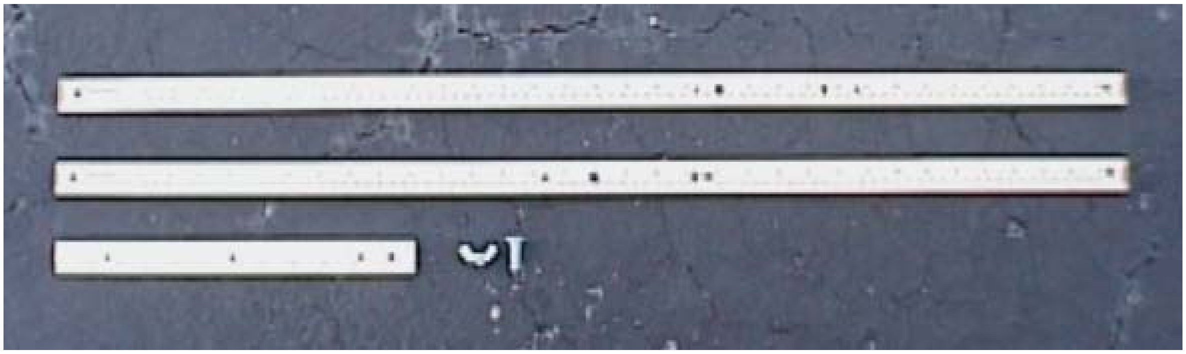

Figure A-27 ASD Components

Figure A-28 ASD in the Cessna 172

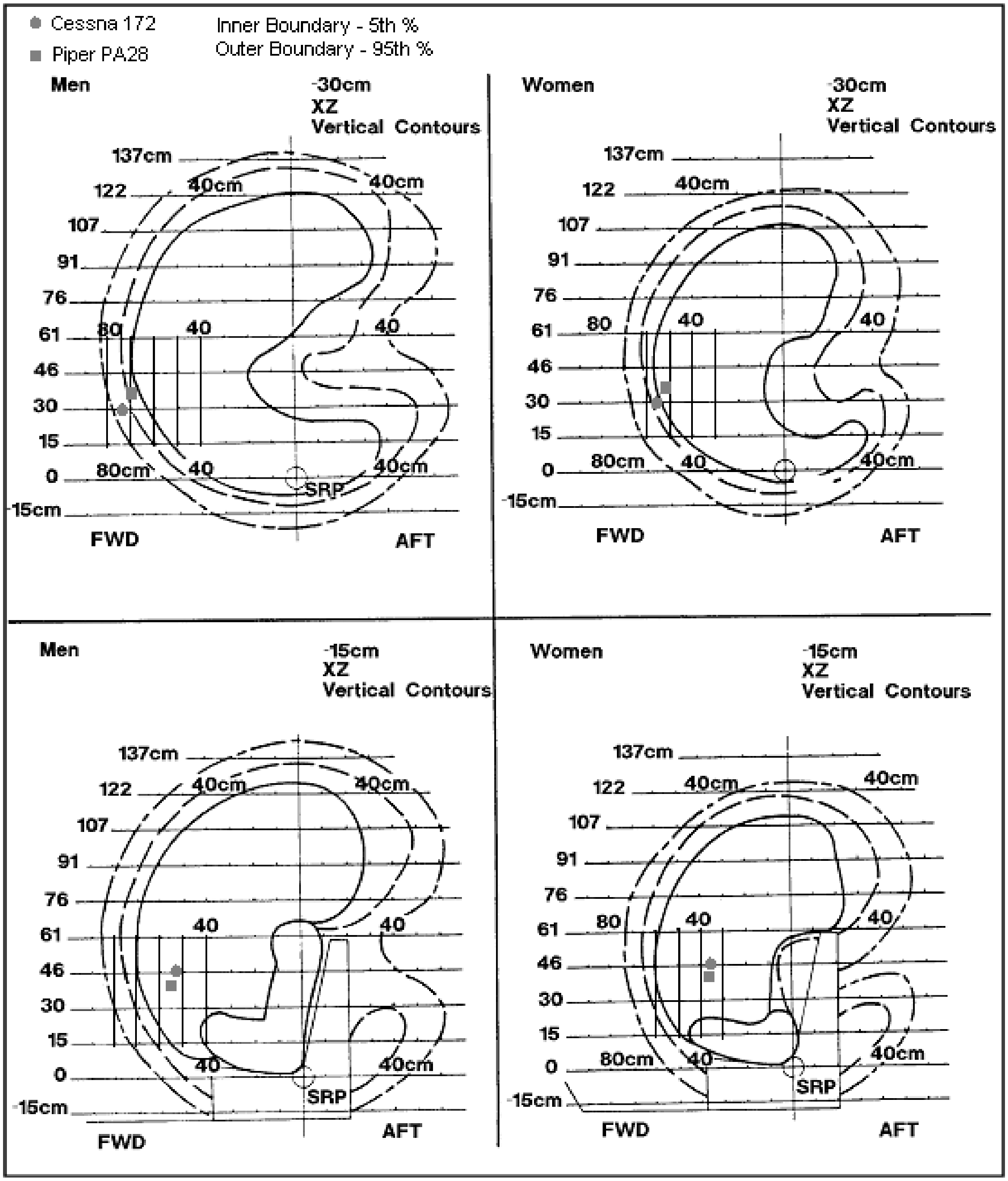

Figure A-29 Reach Envelope Diagrams for the 5th and 95th Percentile Pilot

Source: National Aeronautics and Space Administration. (1995). *Man-Systems Integration Standards* (NASA-STD-3000). Retrieved November 15, 2002, from http://msis.jsc.nasa.gov/default.asp.

Figure A-30 Hand Placement on the Control Wheel

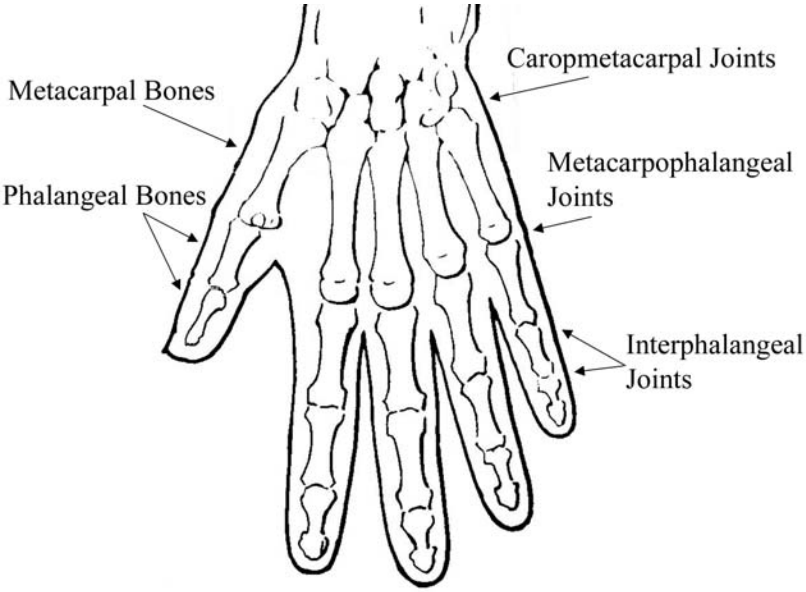

Figure A-31 Bones of the Human Hand

Source: Wells, K. F. (1966). *Kinesiology*. Philadelphia: W. B. Saunders Company.

Figure A-32 Abduction of the Thumb about the Carpometacarpal Joint

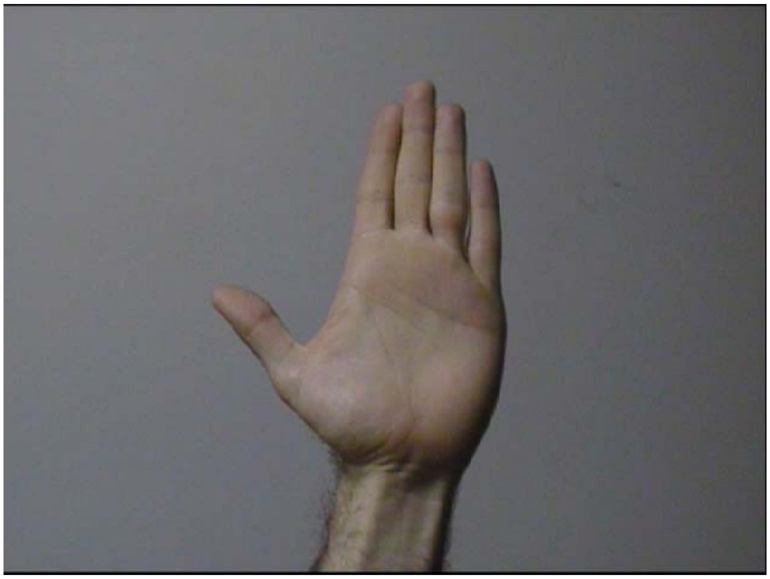

Figure A-33 Adduction of the Thumb about the Carpometacarpal Joint

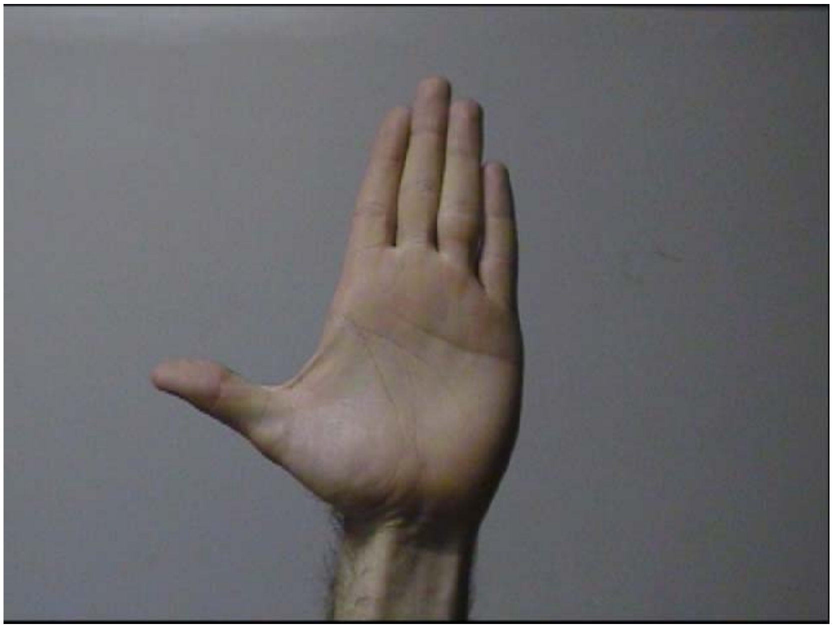

Figure A-34 Extension of the Thumb about the Carpometacarpal Joint

Figure A-35 Flexion of the Thumb about the Carpometacarpal Joint

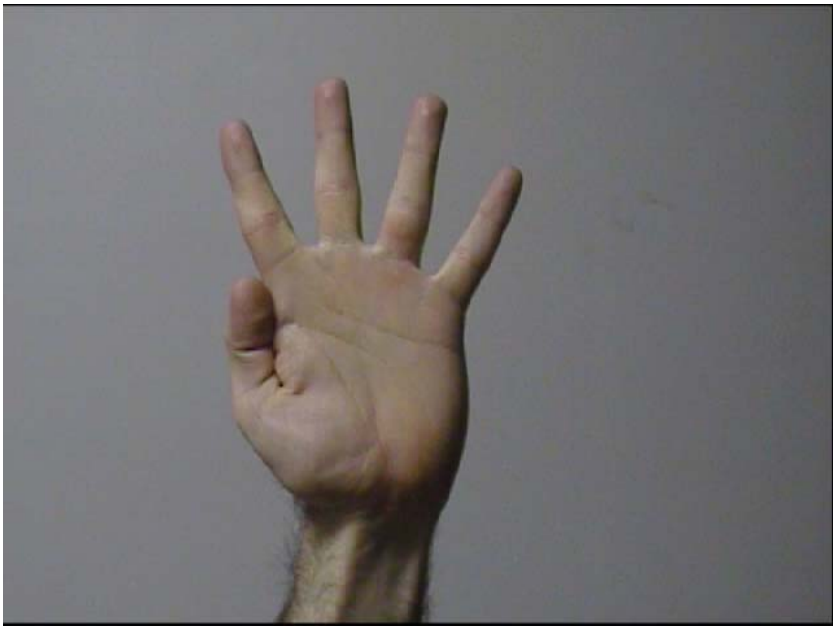

Figure A-36 Abduction of the Fingers about the Metacarpophalangeal Joints

Figure A-37 Adduction of the Fingers about the Metacarpophalangeal Joints

Figure A-38 Extension of the Fingers about the Metacarpophalangeal Joints

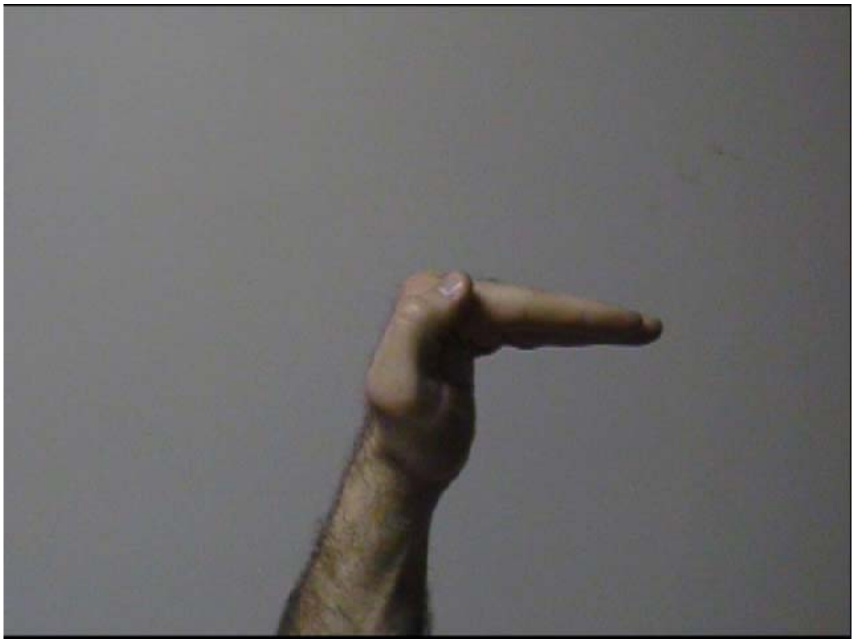

Figure A-39 Flexion of the Fingers about the Metacarpophalangeal Joints

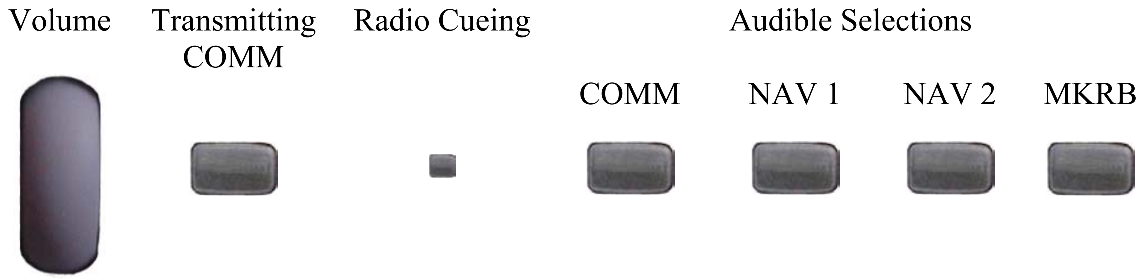

Figure A-40 Preliminary Audio Panel HOTAS Control Layout

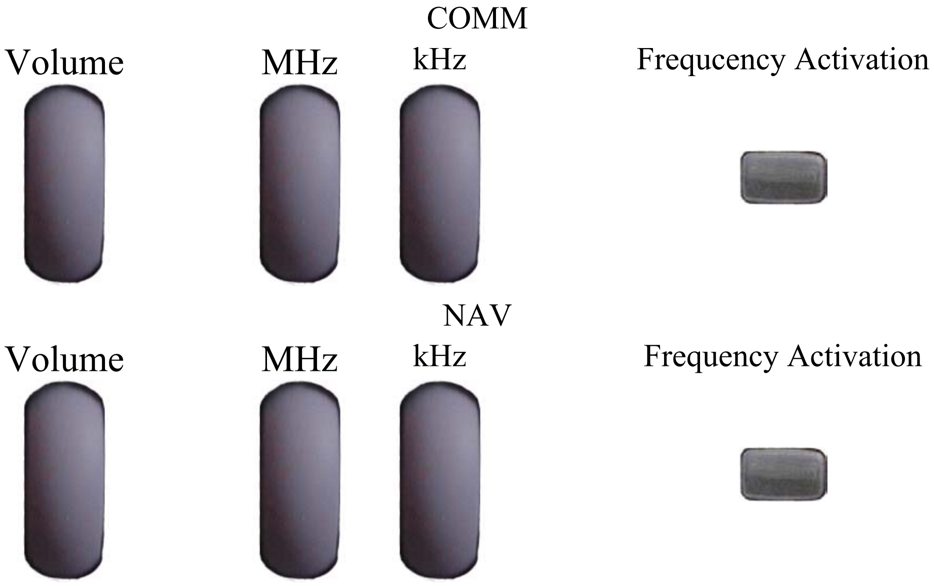

Figure A-41 Preliminary NAV/COMM HOTAS Control Layout

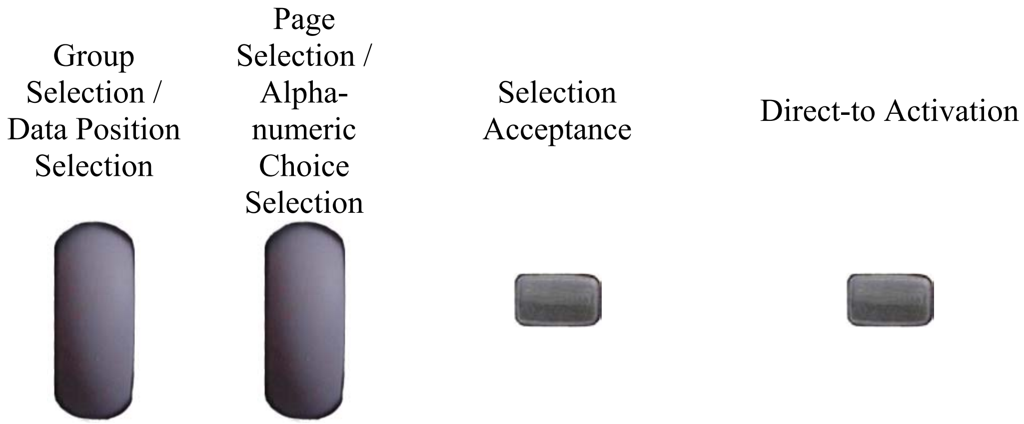

Figure A-42 Preliminary GPS HOTAS Control Layout

Figure A-43 Preliminary Transponder HOTAS Control Layout

Figure A-44 Miniature Hat-Switch for Electric Trim Control

Source: Retrieved from http://mason-electric.com/Raw/Switches/400mini.htm.

Figure A-45 Thumb Range of Motion Arc about the Control Wheel Grip

Figure A-46 Proposed Control Wheel Grip Modification

Source: Retrieved from http://www.infinityaerospace.com/infgrip.htm.

Figure A-47 Modified Grip with Volume Thumbwheel

Source: Retrieved from http://www.infinityaerospace.com/infgrip.htm.

Figure A-48 Proposed HOTAS Control Placement

Source: Retrieved from http://www.infinityaerospace.com/infgrip.htm, http://mason-electric.com/Raw/Switches/400mini.htm, and http://www.arcolectric.co.uk/2000S5.html.

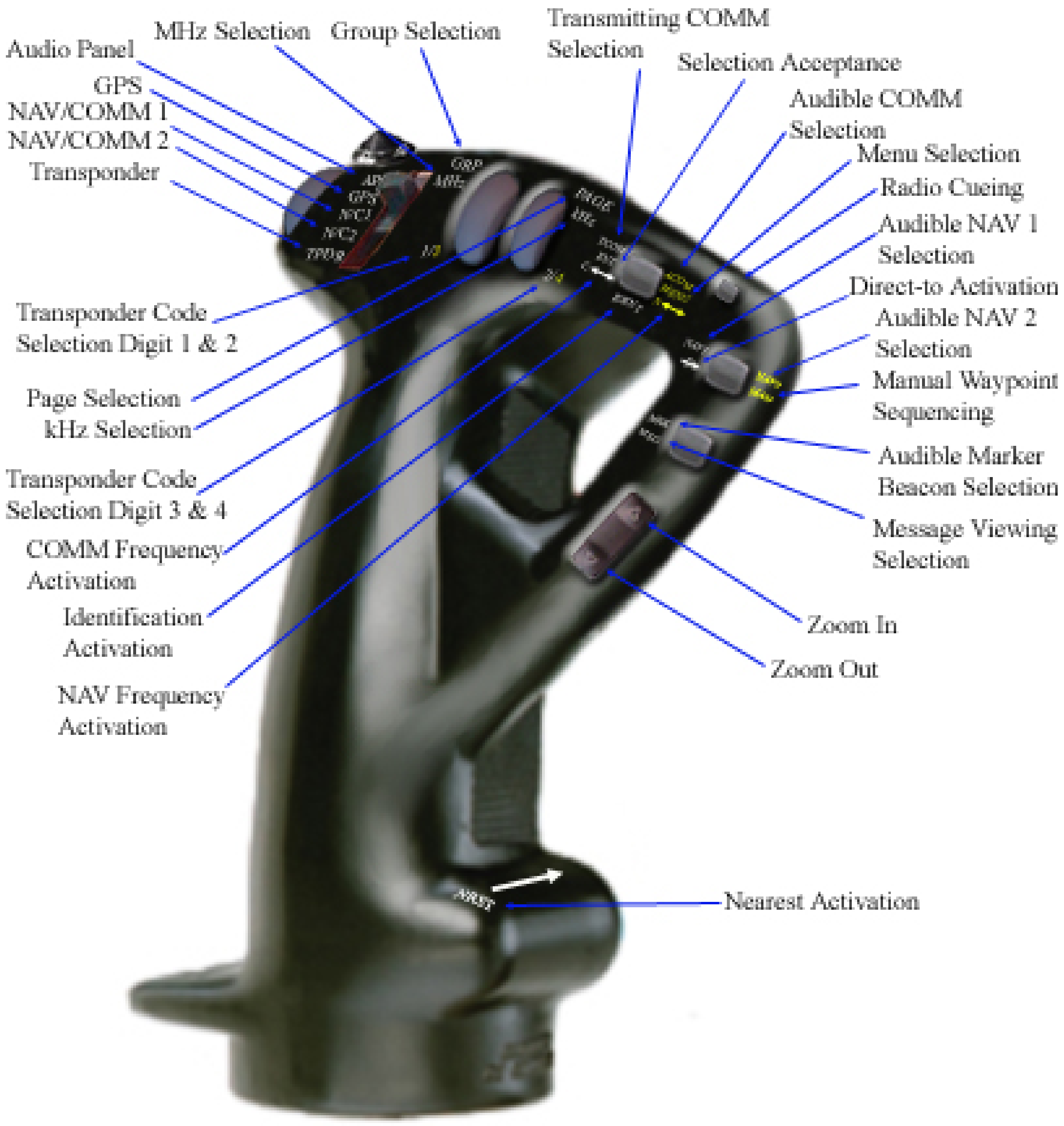

Figure A-49 HOTAS Control Grip with Labels

Source: Retrieved from http://www.infinityaerospace.com/infgrip.htm, http://mason-electric.com/Raw/Switches/400mini.htm, and http://www.arcolectric.co.uk/2000S5.html.

VITA

Nate Callender was born in Dyersburg, Tennessee on October 21, 1976. He attended schools in the Lauderdale County Public School System, where he graduated from Halls High School in May, 1994. He entered the United States Air Force Academy, Colorado Springs, Colorado in July, 1994 where he attended until December, 1995. He then entered Middle Tennessee State University, Murfreesboro, Tennessee in August, 1996 where in December, 1999 he received the Bachelor of Science degree majoring in Aerospace Technology. He entered the Master's program in Aviation Systems at the University of Tennessee Space Institute, Tullahoma in January, 2000. In January, 2001 he began working for Semcor Engineering, which later became Titan Aerospace, as an aerospace engineer contracted to the United States Army in Ft. Rucker, AL where he performed the duties of a flight test engineer for the Aviation Technical Test Center. He officially received the Master's degree in August, 2003.

He is presently working for Dyersburg State Community College as a Mathematics Instructor while pursuing a Master's degree in Mathematics from the University of Memphis.