Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Active Sidestick Design Using Impedance Control

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***Abstract*-- The active sidestick is a mechanical sidestick assembly for fly-by-wire flight control that uses motors, electronics and a high bandwidth closed loop control system to provide grip feel of spring return, breakout forces, and soft-stops. The grip feel characteristics can be user-configured. Also, advanced features such as two-stick cross-coupled operation can be implemented using only electronic feedback signals instead of a mechanical link connecting the two sticks. The goal of this project is to develop a proof of concept system that implements the most important functional requirements of the active sidestick. Safety-critical issues and other flight-worthiness issues are not considered here. The intention is to demonstrate the functionality of the active sidesticks to potential customers in order to generate interest in a request for proposal. This paper describes the system architecture and functional operation of the proof of concept system.**

***Index terms*—fly-by-wire, sidestick, haptics, force control**

I. ACRONYMS

ABL	Anti-backlash
ADC	Analog to Digital Converter
COTS	Commercial Off The Shelf
DAC	Digital to Analog Converter
PMSM	Permanent Magnet Synchronous Machine
RDC	Resolver to Digital Converter
VDC	Volts DC

II. INTRODUCTION

The active sidestick is a conventional mechanical sidestick assembly for fly-by-wire flight control, but uses motors, electronics and a high bandwidth closed loop control system to provide grip feel of spring return, breakout forces, and soft-stops. The advantage of an active sidestick is that these grip feel characteristics can be user-configured. In addition, advanced features such as two-stick cross-coupled operation can be implemented using only electronic feedback signals instead of a mechanical link connecting the two sticks.

In order to investigate the feasibility of this technology at Woodward MPC Corporation an R & D project was begun in January, 2006. The R & D project was a joint effort between the Flight Deck, Digital Systems and the Motors departments. The goals of the project are

1. Development, in a laboratory environment, of a proof of concept system that implements the primary functional requirements of the active sidestick.
2. Identification and reduction of the technological development risks.
3. Demonstration of the functionality of the active sidesticks to potential customers in order to generate interest in a request for proposal.

Safety-critical issues and other flight-worthiness issues are not addressed in the design for this R & D project.

In Woodward MPC's concept, the active sidestick mechanical assembly is essentially a two-axis gimbal with the grip shafts connected rigidly to the gimbals. For each axis, a motor drives the gimbal through a ball-screw. There is no inherent spring force, and the only significant damping force is due to the friction in the ball screw. Motor torque is produced in response to a command from the electronics, and this torque simulates a spring return force, a break out force or a soft-stop.

It was determined that the main functional requirements to implement for this project were:

1. Single stick spring return feel with adjustable spring rate
2. Single stick damping feel with adjustable damping rate
3. Single stick break out force feel with adjustable forces
4. Single stick soft-stop feel with adjustable soft-stop locations
5. Dual stick independent operation where each stick operates independently and implements the functional requirements 1 through 4.
6. Dual stick cross-coupled operation where each stick implements functional requirements 1 though 4 and in addition reacts to force feedback from the opposite stick. Details of this operation are described in section IV.

Due to the investigative nature of this project, the above requirements are not completely clear or quantifiable. In order to minimize risk in the concept development phase we decided to use COTS servo amplifiers for the power electronics, and a rapid control prototyping environment for the development of the control algorithms. One advantage of this approach is that it is easier to understand and then quantify the user requirements. If the user is not clear about the requirements, it is then useful to elicit the details of the requirement from the user by actually operating the concept system.

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978-1-4244-2794-9/09/$25.00 ©2009 IEEE

In this paper we describe the system architecture, design and functional operation of the proof of concept system. Due to lack of space the simulation and experimental results are not shown here; however, results from simulations and experiments on the test stand have been obtained and demonstrate the feasibility of this concept. The paper is organized as follows. Section III gives a description of the concept system that we developed. This starts with the system architecture that outlines the various subsystems and interfaces between them. Each subsystem is then described to the level of a major component. Section IV describes in more detail the control algorithms that are used. We conclude the paper in section V with a summary of the project.

III. SYSTEM ARCHITECTURE

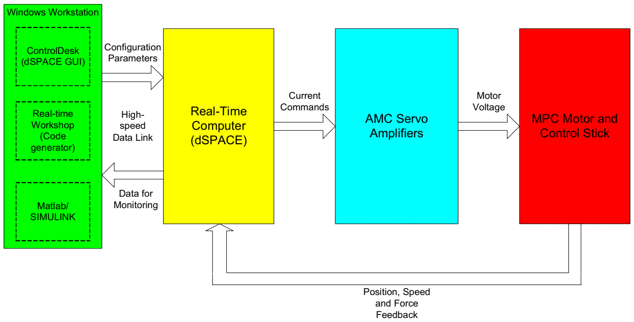

Figure 1: Block diagram of the Active Sidesticks concept.

Key sidestick components that are responsible for smooth operation are:

1. Ball screw drive actuator
2. 2-phase permanent magnet synchronous motor
3. Sinusoidal commutation
4. High bandwidth COTS servo amplifier
5. Speed feedback using drag-cup tachometer
6. Impedance control algorithm using force feedback

These components are discussed in more detail below.

3.1 Mechanical Subsystem

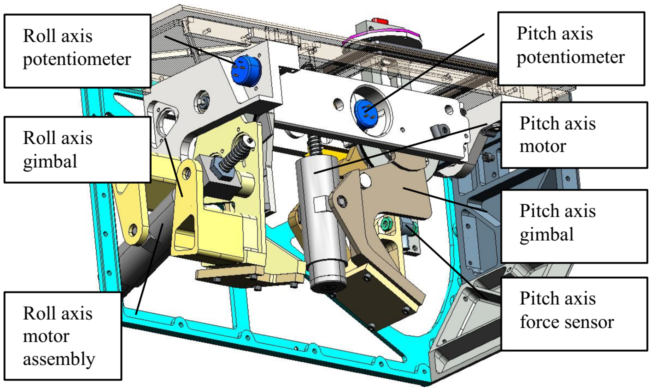

Figure 2: 3-dimensional view of the mechanical subsystem

3.1.1 Stick kinematics

The basic geometry of the sidestick is illustrated in figure 3. This is used to derive a relation between the motor angular position and the grip angle. The calculations for motor torque under static conditions can be found in [3].

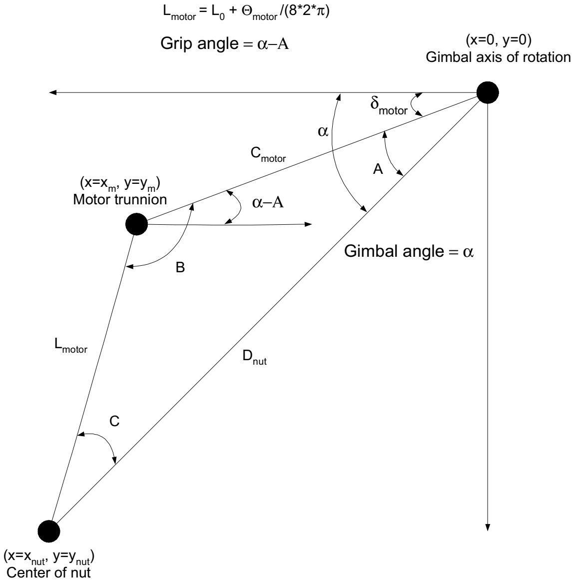

Figure 3: Active Sidesticks geometry

From figure 3 it can be seen that a linear force F along the screw shaft will produce a torque T along the gimbal axis of rotation equal to F*Dnut*sinC. The linear force in turn is given as F = P*Tm where P is the screw pitch and Tm is the motor torque. The average value of the gear ratio (θ_{motor} vs Grip angle) over the total range of travel for both the pitch and the roll axis is 145:1, and we call this the effective gear ratio. This is illustrated in figure 3 for the pitch axis. The effective gear ratio can be used in simple models of the drive train.

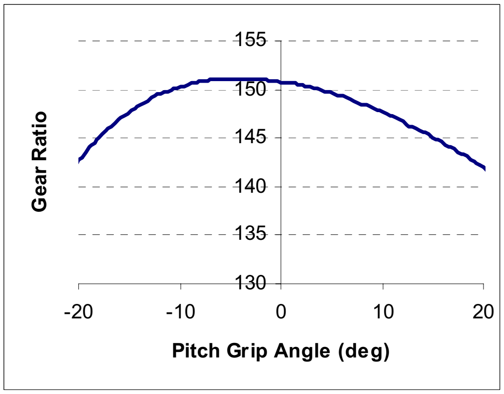

Figure 4: Pitch axis gear ratio

3.1.2 Motor

For this project we picked a 2-phase permanent magnet synchronous motor with sinusoidally distributed mmf for its low-cogging and low ripple torque properties. Motor sizing was determined using a load analysis. It was assumed that the nominal load at the grip is 30 lb and the nominal speed is 40 deg/sec along the pitch axis. The load and speed requirements for the roll-axis are less stringent. The analysis used the data from the stick design and determined the operating point for the motor to be 24.8 in-oz at 939 rpm. We verified that the proposed motor had a torque-speed characteristic that met the operating point requirements. The nominal current draw was calculated to be 8.269 A per motor.

3.1.3 Ball-screw

Since the inner loop of the control algorithm requires high bandwidth for accurate force regulation, we decided to use a ball screw drive since it has high stiffness and smooth back-drivability. The screw has a 3/8 inch diameter and a 8 rev/inch lead ratio. Efficiency in forward-drive and back-drive operation is very high. Friction in the ball screw was further reduced using a re-circulating ball return tube with a tangential lift off design.

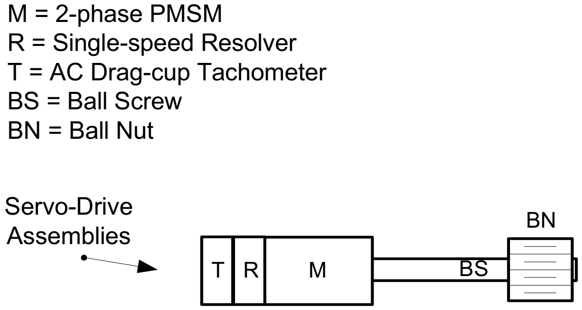

Figure 5: Active Sidesticks Ball-Screw

3.1.4 Force sensor

The force exerted along the pitch and roll axes are determined using load cells. The load cell selected has a range of +/- 120 lb and an output of +/- 2.695 V. The transducer was therefore located at the gimbal to present a greater range of force and therefore increase the resolution of the measurement. The transducer requires an excitation of +/- 18 VDC.

3.1.5 Position sensor

Potentiometers were attached to the gimbal shafts to provide position measurement. The potentiometers required an excitation of 40 VDC. The roll axis has a range of +/- 17 degrees from null and the pitch axis has a range of +/- 20 degrees from null. The potentiometer gear ratio is 8.875:1 so it will move +/-150.875 degrees in the roll axis and +/- 177.5 degrees in the pitch axis.

3.1.6 Resolver

The resolver used for commutation is a standard single-speed resolver. The resolver outputs were converted to an angle using a resolver to digital converter.

3.1.7 Tachometer

Motor angular speed was measured using AC drag-cup tachometers attached to the rotor shaft. These require a demodulation circuit to convert the tachometer output to a voltage proportional to speed.

3.2 Electronic Subsystem

3.2.1 Digital electronics

Figure 6 shows the layout of the digital subsystem for the Active Sidesticks concept. The blocks delineated are cards for the dSPACE real-time computer and they interface with the sensors and motor drives. The cards themselves communicate with each other and the host computer using a dSPACE-proprietary high speed data link.

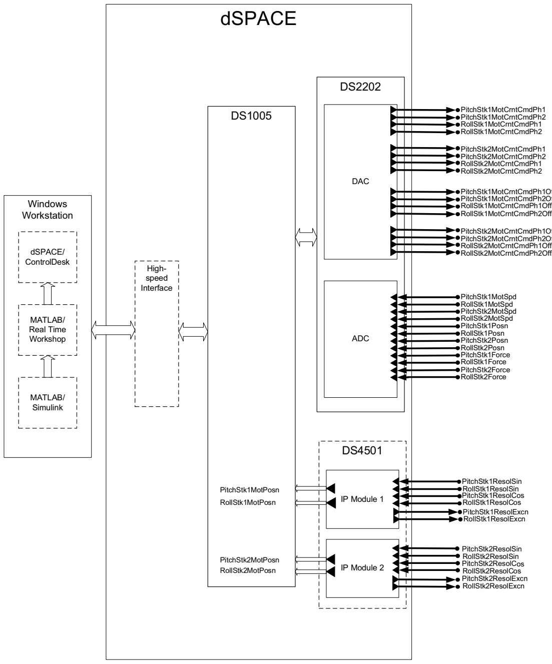

Figure 6: Active Sidesticks digital electronics.

3.2.2 Motor drive electronics

Figure 7 shows the motor drive electronics subsystem. Most of the functionality of this subsystem resides in the AMC servo amplifiers, but the motor resolver excitation and demodulation is done using the dSPACE resolver interface card. The tach output is demodulated using Woodward MPC designed electronics.

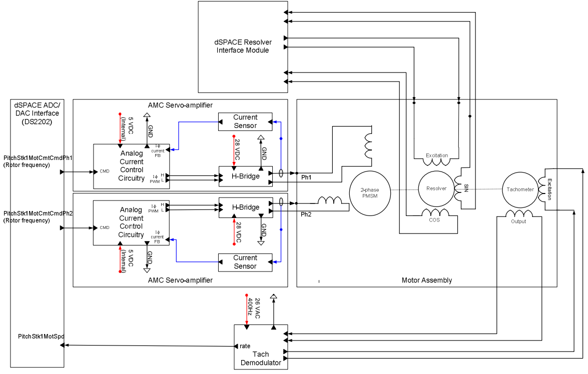

Figure 7: Active Sidesticks motor drive electronics.

3.2.3 Servo-amplifier

The servo amplifier regulates the current through the motor winding to the current command from the dSPACE digital controller. Since we are using a 2-phase PMSM, two servo amplifiers were needed for each motor, one for each winding. We selected the 25A8 brush type amplifier made by AMC that had a rating of 25 amps and a switching frequency of 22 kHz. The amplifier is capable of 4-quadrant operation. The bandwidth of the current control loop under locked rotor condition for our motor was determined to be

800 Hz. Although designed for brushed DC motor application, it is appropriate to use these amplifiers in pairs to control a two-phase PMSM. The amplifier is protected against over-voltage, over-current, over-heating, and short circuits across the motor, ground and power leads. The amplifier requires a single DC power source in the range of 20 to 80V. The operating voltage for this application is 28 V.

3.2.4 Tach demodulator

The output of the AC drag-cup tachometer consists of a signal whose amplitude is proportional to the speed of the rotor and whose frequency is the frequency of the excitation signal. In order to recover the speed from this signal it must be demodulated. This is done by synchronous rectification of the tachometer output signal. The tachometer excitation signal, which is 26 VAC at 400 Hz, is used to generate a square-wave timing signal and this is multiplied with the output signal from the tachometer. The resultant signal is filtered using a second order low-pass Butterworth filter. The filtered signal is offset by 5V and amplified so that it can be input to the dSPACE A/D card.

3.2.5 Resolver demodulator

Resolver signal demodulation is done using the dSPACE DS4502 interface card containing two demodulation modules. Each module is capable of demodulating the position signal from two resolvers. The output of the resolver consists of two signals; a signal whose amplitude is proportional to the sine of the rotor angle and a signal whose amplitude is proportional to the cosine of the rotor angle. The frequency of these signals is the frequency of the excitation signal. The sine and cosine signals must be demodulated to recover the rotor angular position. This is done using a tracking demodulator in the dSPACE DS4502 card.

3.2.6 Force sensor signal conditioning

The output voltage of the force transducer is in the range of +/- 2.695 V and we found it necessary to amplify this voltage and add an offset so it can be read with accuracy by the dSPACE A/D interface card. The circuit used consisted of two stages. In the first stage an adjustable reference voltage was generated. This voltage was summed with the signal from the transducer in the second stage and this was input into the A/D card. Since our application uses four force transducers, four such circuits were implemented.

3.3 Software Subsystem

Since we are using a rapid control prototyping environment, the Active Sidesticks software consists of three major parts:

1. The MATLAB/Simulink graphical model of the control system developed on the Windows workstation
2. The dSPACE ControlDesk GUI running on the Windows workstation
3. The real-time executable generated from the MATLAB/Simulink model running on the dSPACE DS1005 card.

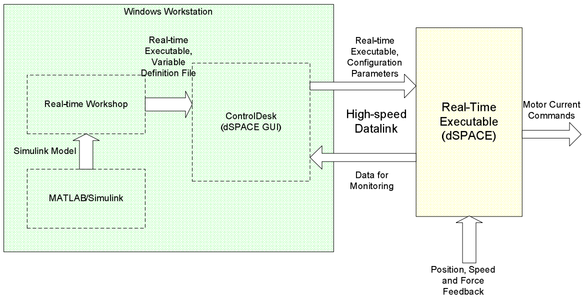

Figure 8: Block diagram of the software subsystem

Figure 8 shows the relationship between these major components. The complete system consisting of the controller and the plant is modeled in Simulink within the MATLAB integrated development environment. When the performance was found to be satisfactory, the control system model is extracted, and this is then discretized by converting all continuous time components to discrete time components. Using Real-time Workshop, C-code is generated from the control system model and compiled for the DS1005 PowerPC processor that is the target. The executable is downloaded to the target using the dSPACE ControlDesk application, which runs on the Windows workstation. This application is used for monitoring data and controlling the execution of the real-time executable.

3.3.1 Simulink Model

Using the MATLAB/Simulink graphical modeling environment we developed a system model for the Active Sidesticks and evaluated the performance in a simulation environment. Data for this model was obtained from the component groups. The actuator was modeled as a multi-body system consisting of the motor, the ball screw, the stick gimbal and the stick grip. Next, the control subsystem was extracted and discretized so that real-time workshop can be used to generate C-code from it. This was supplemented by blocks to perform scaling of the ADC and the RDC inputs, and the DAC outputs. The force control subsystem and the current control subsystem were selected to run at 10kHz and the impedance model to run at 1kHz. In order to allow the user to update the impedance model, a calibration algorithm was modeled in Simulink. This calibration algorithm accepts grip force values at various grip positions from the user, and converts it to force values at the force sensor. This modified look-up table is used by the control algorithm as the impedance model. The calibration algorithm is run at a rate of 1 kHz.

3.3.2 ControlDesk Application

The dSPACE ControlDesk application runs on the Windows workstation and provides an easy way to control the operation of the real-time executive on the dSPACE hardware. A user-interface similar to a LabView virtual instruments interface can be created so that data appearing on the screen is linked to variables of interest in the real-time executable. These data are updated through the high-speed data link between the dSPACE hardware and the Windows workstation.

The user interface windows fall into one of these categories.

Monitoring/Adjustments: Variables of interest selected by the user are displayed using numeric and analog display instruments, and through strip charts. Gains and offsets can be changed through knobs and numeric inputs.

Calibration: Numeric tables consisting of stick position and stick force are displayed that the user can change. Adjustments include breakout forces, soft-stops and the force gradient. The user then initiates calibration by selecting a button. The stick calibration data are updated in the real-time executive.

Mode Selection: The user may control the operation of the real-time executive by selecting the Independent mode or the Cross-coupled mode. The user may also run a calibration routine to modify the impedance model of either stick independently.

3.3.3 Real-time Executable

The real-time executable operates in a multi-tasking infinite loop. Since this is a concept system, floating point arithmetic was used in all algorithms to expedite control law development. The calibration functions and the force command generation functions run at a rate of 1 kHz, but the force control functions and the motor commutation functions run at a rate of 10 kHz. The current commands to the servo amplifiers may contain a constant but unknown offset. To remove this offset, a correction term which adjustable through ControlDesk, may be added to the command using software.

The function of the real-time executable is to implement the impedance control algorithm for the pitch and roll axes of both sticks. The operator can adjust the impedance model of either stick by entering a calibration mode. Once calibrated, it can operate in two modes: Independent mode or Cross-coupled mode. In the Independent mode the grip feel of each stick is independent of the other stick, and completely defined by its own impedance model. The real time executable reads the resolvers, potentiometers, the tachometers and the load cells, and calculates the current commands to be input to the servo amplifiers based on the feedback values and the impedance model. In the Cross-coupled mode the real-time executable adjusts the current command to each stick by adding a term proportional to the difference in the position feedback between the two sticks. This in effect "couples" the two sticks as though they were mechanically linked.

IV. CONTROL SYSTEM ANALYSIS

The Active Sidesticks application needs a control method that will not try to reject interaction forces such as disturbances, but respond to them in a prescribed way. Such a method is called force control. Force control methods are usually classified as explicit force control and impedance control methods. In explicit force control the desired interaction force with the environment is commanded. When such a method does not use force feedback it is called open-loop explicit force control, and this relies on accurate inverse models of the actuator. When it uses force feedback it is called force-based explicit force control. Such closed-loop methods generate a force error and use a high bandwidth force control loop to ensure fast response. They may also use a model of the actuator to generate a reference trajectory. In that case, a position control loop is then nested inside the outer force loop, and this ensures accurate force reproduction. This method is also called admittance control, and is closely related to the impedance control method. For the active sidesticks project, explicit force control did not seem feasible since the force command is not known directly, but is only specified as a function of the stick displacement and velocity. We therefore adopted the impedance control method that is described next.

4.1 Impedance control

Impedance control uses an impedance model to characterize the dynamic relationship between the state error and the interaction force with the environment. In the case of the active sidestick, the state error is the ordered tuple of the deviation of the sidestick's position from the commanded position, and the deviation of the sidestick's velocity from the desired velocity. The parameters associated with the state error are the spring constant and the viscous damping rate. The term impedance refers to the frequency domain representation of the electrical analog of the parameters associated with mechanical state error, namely, capacitance and inductance. The environment is of course the operator using the sidestick, and the interaction force is the reaction force provided to the operator by the active sidestick. The interaction force generated from the impedance model serves as the commanded force to an inner, high bandwidth, force control loop. This force control loop output is the sum of a feedback component proportional to the force error, and a feedforward component based on the inverse model of the actuator. The output of the force controller is a current command to the current control loop that is implemented within the COTS servo amplifier.

4.1.1 Topology

The topology used is called impedance control with force feedback. This is illustrated in figure 9 for single-stick single-axis operation.

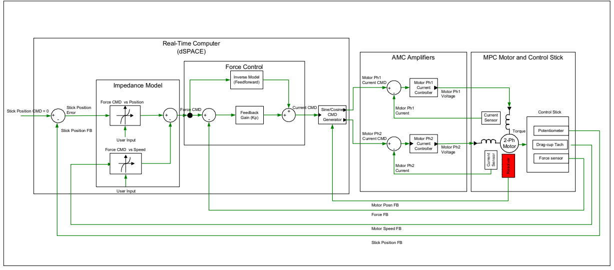

Figure 9: Active Sidesticks control system.

4.1.2 Impedance model

The impedance model consists of a pair of characteristics. The first gives the relationship between the sidestick displacement and the reaction force. The second gives the relationship between the sidestick velocity and the reaction force. These relationships are piecewise linear, and implemented as user-adjustable look-up tables. Features such features as breakout forces and soft-stops are implemented using discontinuous changes in the reaction force at specified stick positions.

4.1.3 Force control

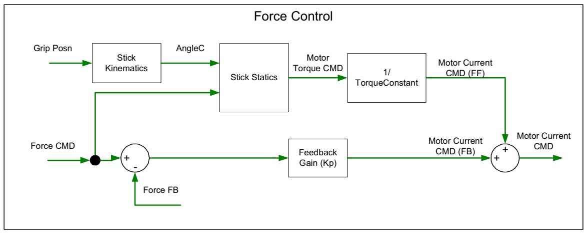

Figure 10: Block diagram of the Active Sidesticks force control system.

In order to provide a smooth feel it was necessary to use force feedback. The grip force sensed by a load cell is compared with the commanded force generated by the impedance model. This error is used by a feedback component to generate a current command proportional to the error. The commanded force is used by a feedforward term to generate the second component of the current command. The feedforward term uses an inverse model of the actuator and drive electronics. These two components are summed and presented to the current control loop as the commanded current.

4.1.4 Motor commutation

We use a motor commutation scheme based on the "sine drive". That is, the rotor position measurement is used to generate current commands such that the stator mmf and the rotor mmf are orthogonal. However, the servo amplifiers still regulate current whose frequency is proportional to the speed of the rotor. Since the nominal motor (electrical) speed is around 2000 rpm (34 Hz), and the bandwidth of the current regulator is about 800 Hz, we do not expect any significant attenuation of the current.

4.2 Dual stick operation

In dual stick operation, a pilot's sidestick and a co-pilot's sidestick will operate simultaneously. There are two modes of operation: Independent mode, and Cross-coupled mode. In Independent mode each stick moves independently of the other and the force feedback experienced by each operator is governed purely by that sidestick's impedance model. In cross-coupled mode, the force control loop in each sidestick uses force feedback from itself as well as the other sidestick. The result is that each sidestick operator now feels the algebraic sum of the forces generated by the two operators. The operator generating the higher force wins and the two sticks move in a coordinated fashion.

4.2.1 Independent mode

The controller topology for dual-stick operation in independent mode is simply two single-stick controllers acting independently on respective sticks. This is the default mode of dual-stick operation

4.2.2 Cross-coupled mode

In the Cross-coupled mode the real-time executable adjusts the current command to each stick by monitoring the difference in the position feedback between the two sticks. In effect this "couples" the two sticks by adding a stiffness term that is a function of the difference between the positions of the two sticks.

V. SUMMARY

Using a rapid control prototyping environment and many COTS components we were able to obtain some promising results. Single stick operation successfully implemented spring return, breakout forces and soft-stops. Cross-coupled stick operation implemented force-fighting in addition to all the features of single-stick operation. Our conclusion is that with some proper packaging of the laboratory test stand it can be made portable and demonstrated to potential customers.

VI. ACKNOWLEDGEMENTS

The authors thank Mr. Darryl Stachniak for his support and suggestions during the conceptual design of the Active Sidesticks. The help from Thomas Rusak in the design and integration phase is also gratefully acknowledged.

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