Title: Neural Net Safety Monitor Design  
Paper Number - AIAA-2007-2812

Abstract

The National Aeronautics and Space Administration (NASA) at the Dryden Flight Research Center (DFRC) has been conducting flight-test research using an F-15 aircraft (figure 1). This aircraft has been specially modified to interface a neural net (NN) controller as part of a single-string Airborne Research Test System (ARTS) computer with the existing quad-redundant flight control system (FCC) shown in figure 2. The NN commands are passed to FCC channels 2 and 4 and are cross channel data linked (CCDL) to the other computers as shown. Numerous types of fault-detection monitors exist in the FCC when the NN mode is engaged; these monitors would cause an automatic disengagement of the NN in the event of a triggering fault. Unfortunately, these monitors still may not prevent a possible NN hard-over command from coming through to the control laws. Therefore, an additional and unique safety monitor was designed for a single-string source that allows authority at maximum actuator rates but protects the pilot and structural loads against excessive g-limits in the case of a NN hard-over command input. This additional monitor resides in the FCCs and is executed before the control laws are computed.

This presentation describes a “floating limiter” (FL) concept¹ that was developed and successfully test-flown for this program (figure 3). The FL computes the rate of change of the NN commands that are input to the FCC from the ARTS. A window is created with upper and lower boundaries, which is constantly “floating” and trying to stay centered as the NN command rates are changing. The limiter works by only allowing the window to move at a much slower rate than those of the NN commands. Anywhere within the window, however, full rates are allowed. If a rate persists in one direction, it will eventually “hit” the boundary and be rate-limited to the floating limiter rate. When this happens, a persistent counter begins and after a limit is reached, a NN disengage command is generated. The tunable metrics for the FL are (1) window size, (2) drift rate, and (3) persistence counter. Ultimate range limits are also included in case the NN command should drift slowly to a limit value that would cause the FL to be defeated.

The FL has proven to work as intended. Both high-g transients and excessive structural loads are controlled with NN hard-over commands. This presentation discusses the FL design features and presents test cases. Simulation runs are included to illustrate the dramatic improvement made to the control of NN hard-over effects. A mission control room display from a flight playback is presented to illustrate the neural net fault display representation. The FL is very adaptable to various requirements and is independent of flight condition. It should be considered as a cost-effective safety monitor to control single-string inputs in general.


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Figure 1 – F15 Intelligent Flight Control System Test Bed Aircraft
Figure 2 – Neural Net Controller Architecture with Flight Control Computers

Figure 3 – Floating Limiter Features
Neural Net Safety Monitor Design

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NASA DFRC
Overview

• Requirements
• Neural net interfaces
• Design approach
• Review of existing safety monitors
• New safety monitor developed
• Testing
• A surprise
• Flight data display playback
• Summary
Requirements

• Interface neural net controller with F15 enhanced control laws for flight test experiment
  – Flight conditions: 0.75M/20Kft, and 0.90M/25Kft
  – Maximum transients: + 2g vertical, + 0.5g lateral
  – Maneuvers: Straight & level, 3g wind-up-turn (WUT), simulated stabilator/canard failures, loads maneuvers; all maneuvers include pitch/roll/yaw (pqr) doublets

• Ground Rules/Constraints
  – Protect from exceeding any aircraft structural load limits
  – Avoid departure from controlled flight
  – Neural net commands shall support full control surface authority at maximum actuator rates
  – Minimize nuisance disengagements
Design Approach

- Specific Aircraft faults which occur while in neural net mode will cause a downmode to conventional mode with a 1 sec fader

- Safety monitors are executed in SCE3 at 80hz
- Disengagement triggers are instrumented and latched for analysis
- All validation testing is done using hardware in the loop closed loop simulation
Overview of Existing Safety Monitors

• Flight Computer Faults
  – Single failure of any dual channel signal
  – Dual failure of any quad channel signal
  – FC Configuration fault (Config fail)
  – Channel fail
  – BLIN (Bit Level Inspect) code
  – PAL (Pick-a-Limit) Violation
## FC PAL limits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Envelope #1</th>
<th></th>
<th>Envelope #2</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Lower Limit</td>
<td>Upper Limit</td>
<td>Lower Limit</td>
<td>Upper Limit</td>
</tr>
<tr>
<td>Angle of Attack</td>
<td>-4.0 deg</td>
<td>12.0 deg</td>
<td>-4.0 deg</td>
<td>12.0 deg</td>
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<tr>
<td>Sideslip Angle</td>
<td>-5.0 deg</td>
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<td>-5.0 deg</td>
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<tr>
<td>Pitch Angle</td>
<td>-180 deg</td>
<td>180 deg</td>
<td>-180 deg</td>
<td>180 deg</td>
</tr>
<tr>
<td>Bank Angle</td>
<td>-90 deg</td>
<td>90 deg</td>
<td>-180 deg</td>
<td>180 deg</td>
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<tr>
<td>Pitch Rate</td>
<td>-45 deg/sec</td>
<td>45 deg/sec</td>
<td>-60 deg/sec</td>
<td>60 deg/sec</td>
</tr>
<tr>
<td>Roll Rate</td>
<td>-75 deg/sec</td>
<td>75 deg/sec</td>
<td>-300 deg/sec</td>
<td>300 deg/sec</td>
</tr>
<tr>
<td>Yaw Rate</td>
<td>-15 deg/sec</td>
<td>15 deg/sec</td>
<td>-60 deg/sec</td>
<td>60 deg/sec</td>
</tr>
<tr>
<td>Normal Acceleration</td>
<td>0.0 g</td>
<td>3.0 g</td>
<td>-1.0 g</td>
<td>6.0 g</td>
</tr>
<tr>
<td>Lateral Acceleration</td>
<td>-0.5 g</td>
<td>0.5 g</td>
<td>-1.0 g</td>
<td>1.0 g</td>
</tr>
<tr>
<td>Mach</td>
<td>0.55</td>
<td>0.95</td>
<td>0.55</td>
<td>0.95</td>
</tr>
<tr>
<td>Qbar</td>
<td>253 psf</td>
<td>733 psf</td>
<td>253 psf</td>
<td>733 psf</td>
</tr>
<tr>
<td>Altitude</td>
<td>15000 ft</td>
<td>35000 ft</td>
<td>15000 ft</td>
<td>35000 ft</td>
</tr>
<tr>
<td>Pitch Stick</td>
<td>-3.1 in</td>
<td>5.46 in</td>
<td>-3.1 in</td>
<td>5.46 in</td>
</tr>
<tr>
<td>Roll Stick</td>
<td>-4.0 in</td>
<td>4.0 in</td>
<td>-4.0 in</td>
<td>4.0 in</td>
</tr>
<tr>
<td>Yaw Pedal</td>
<td>-3.25 in</td>
<td>3.25 in</td>
<td>-3.25 in</td>
<td>3.25 in</td>
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<tr>
<td>Throttle (PLA)</td>
<td>16.5 deg</td>
<td>130 deg</td>
<td>16.5 deg</td>
<td>130 deg</td>
</tr>
</tbody>
</table>
FC Configuration Faults

1. Lt Throttle Within PAL Limits
2. Rt Throttle Within PAL Limits
3. Flaps in Correct PAL Mode
4. Landing Gear in Correct PAL Mode
5. Throttle Switch in Correct PAL Mode
6. Spin Switch in Correct PAL Mode
7. Weight-On-Wheels in Correct PAL Mode
8. Qbar Limit Exceeded
9. Aircraft Not At Trim (pitch/bank monitor)
ARTS II Fault Monitors

• Built in Test Failures
  – failure detected through Periodic Bit (PBIT)
  – failure detected through Power Up Bit (PUBIT)
• Multibit ECC (error code correction) Memory Errors (ARTS-II will log the event and transition to FAILED)
• 1553 Communications Failure
  – 1553 Wrap Word Failure
• ARTS Neural Net (Sigma Pi) Failures
  – failure to initialize data recording
  – failure to register experiment with Executive
  – failure to receive data from SBC 1 (VXMP failure)
  – failure to send data to SBC 1 (VXMP failure)
ARTS II Fault Monitors
(Continued)

• Executive Failures:
  – failure to detect correct checksum
  – failure to receive data from Sigma Pi on SBC 2 (VXMP failure)
  – failure to send data to SBC 2 (VXMP failure)
  – The system monitor (SYSMON) task detects a problem with any other task such as failure to initialize or abnormal termination
  – SBC board boot failure

• Analog Failures:
  – analog card fails to load driver
  – analog card fails to calibrate

• Any disk I/O errors
Added strain gages to aircraft for loads measurements
• Converted existing loads model from FORTRAN to ADA, but memory size too large and execution time too long to fit in 80hz frame cycle in SCE3
• Existing loads model was not validated
• No confidence that existing fault monitors would prevent a Neural Net hardover from exceeding aircraft G and structural load limits
• Conclusion was a new safety monitor was needed
  – A Floating Limiter Design was developed
Floating Limiter Design

- Apply floating limiter windows for the sigma pi (neural net) commands (P,Q,R)
- Maximum rate of change is allowed within the window
- Limit the rate of change while on the floating limiter boundary
- Allow full authority up to the range limiter
- Provide flags to sigma pi to stop learning
NN Floating Limiter

Upper range limit (down mode)

Max persistence ctr, downmode

Rate limit drift, start persistence counter

Floating limiter

Sigma pi cmd (pqr)

Window size

Lower range limit (down mode)

Tunable metrics
Window delta
Drift rate
Persistence limiter
Range limits

Black – sigma pi cmd
Green – floating limiter boundary
Orange – limited command (fl_drift_flag)
Red – down mode condition (fl_dmode_flag)
Floating Limiter Metrics

- Small window size
- Large window size
- Persistence limits decreasing
- Faster to disengage
- Slower to disengage

- Fast drift rate
- Slow drift rate
Floating Limiter Regions

Initial; no fail
Transition
Final; after fail

Slow drift
Moderate drift
Fast drift
Simulation Testing

• Flight conditions (2 design points)
  – .75M/20Kft
  – .90M/25Kft (worst case)

• Maneuvers
  – Straight & level with pqr doublets
  – 3g WUT with pqr doublets
  – Simulated failures
    • Straight & level with pqr doublets
    • 3g WUT with pqr doublets
  – Loads maneuvers
Bank angle captures (60 deg)

P doublets
Q doublets
R doubles
Stab fails; 0 from trim
Stab fails; +2 from trim
Stab fails; -2 from trim
Stab fails; +4 from trim
Stab fails; -4 from trim
Stab fails; +4 from trim with p doublet
Stab fails; +4 from trim with q doublet
Stab fails; +4 from trim with r doublet
Sigma Pi hardover from trim; +p no fail
Sigma Pi hardover from trim; -p no fail
Sigma Pi hardover from trim; +q no fail
Sigma Pi hardover from trim; -q no fail
Sigma Pi hardover from trim; +r no fail
Sigma Pi hardover from trim; -r no fail
Sigma Pi hardover from trim; +p, 4 deg fail
Sigma Pi hardover from trim; -p, 4 deg fail
Sigma Pi hardover from trim; +q, 4 deg fail
Sigma Pi hardover from trim; -q, 4 deg fail
Sigma Pi hardover from trim; +r, 4 deg fail
Sigma Pi hardover from trim; -r, 4 deg fail
Sigma Pi hardover from 3g WUT; +p, 4 deg fail
Sigma Pi hardover from 3g WUT; -p, 4 deg fail
Sigma Pi hardover from 3g WUT; +q, 4 deg fail
Sigma Pi hardover from 3g WUT; -q, 4 deg fail
Sigma Pi hardover from 3g WUT; +r, 4 deg fail
Sigma Pi hardover from 3g WUT; -r, 4 deg fail
Roll doublet in 3g WUT
Pitch doublet in 3g WUT
Yaw doublet in 3g WUT
Within floating limiter: no rate limiting

Sigma Pi cmd, dps²

FL boundary

Sigma pi cmd

FL boundary

Time, sec
Outside floating limiter: Minor Rate Limiting

Red indicates rate limit

Sigma Pi cmd, dps²

Time, sec

FL boundary
Sigma pi cmd
FL boundary
Outside floating limiter: Moderate Rate Limiting

Red indicates rate limit
## Floating Limiter Constants

### Rt Stab Failure from Trim

<table>
<thead>
<tr>
<th>fl_drift_table_conf_file</th>
<th>P axis</th>
<th>Q axis</th>
<th>R axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 deg, dps³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transition</td>
<td>150</td>
<td>50</td>
<td>0.03</td>
</tr>
<tr>
<td>Final</td>
<td>500</td>
<td>90</td>
<td>0.01</td>
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<tr>
<td>+2 deg, dps³</td>
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<td></td>
<td></td>
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<tr>
<td>Transition</td>
<td>230</td>
<td>60</td>
<td>0.03</td>
</tr>
<tr>
<td>Final</td>
<td>700</td>
<td>60</td>
<td>0.02</td>
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<tr>
<td>+4 deg, dps³</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Transition</td>
<td>430</td>
<td>60</td>
<td>0.03</td>
</tr>
<tr>
<td>Final</td>
<td>850</td>
<td>60</td>
<td>0.02</td>
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<tr>
<td>-2 deg, dps³</td>
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<tr>
<td>Transition</td>
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<tr>
<td>Final</td>
<td>525</td>
<td>60</td>
<td>0.09</td>
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<tr>
<td>-4 deg, dps³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transition</td>
<td>430</td>
<td>60</td>
<td>0.03</td>
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<tr>
<td>Final</td>
<td>550</td>
<td>60</td>
<td>0.09</td>
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</table>

### Canard AOA fails

<table>
<thead>
<tr>
<th>P axis</th>
<th>Q axis</th>
<th>R axis</th>
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</thead>
<tbody>
<tr>
<td>Set 1; dps³</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Set 2; dps³</td>
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<tr>
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<tr>
<td>Final</td>
<td>100</td>
<td>20</td>
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</table>

### Metrics

<table>
<thead>
<tr>
<th>Initial drift, dps³</th>
<th>1.0</th>
<th>1.0</th>
<th>0.01</th>
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</thead>
<tbody>
<tr>
<td>Delta, dps²</td>
<td>200</td>
<td>52</td>
<td>0.10</td>
</tr>
<tr>
<td>Range limit, dps²</td>
<td>1000</td>
<td>500</td>
<td>0.10</td>
</tr>
<tr>
<td>Persistence time, sec</td>
<td>0.75</td>
<td>1.25</td>
<td>0.75</td>
</tr>
<tr>
<td>Transition time, sec</td>
<td>3</td>
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</table>
## Floating Limiter Outputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Bus</th>
<th>RT</th>
<th>SA</th>
<th>W</th>
<th>Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>fl_dmode_flag (0), p</td>
<td>fl_plim_flag(0) or fl_hrange_flag(0)</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>2</td>
<td>25</td>
<td>00</td>
</tr>
<tr>
<td>fl_dmode_flag (1), q</td>
<td>fl_plim_flag(1) or fl_hrange_flag(1)</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>2</td>
<td>25</td>
<td>01</td>
</tr>
<tr>
<td>fl_dmode_flag (2), r</td>
<td>fl_plim_flag(2) or fl_hrange_flag(2)</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>2</td>
<td>25</td>
<td>02</td>
</tr>
<tr>
<td>fl_drift_flag (0), p</td>
<td>NN cmd (p) is limited</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>2</td>
<td>25</td>
<td>03</td>
</tr>
<tr>
<td>fl_drift_flag (1), q</td>
<td>NN cmd (q) is limited</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>2</td>
<td>25</td>
<td>04</td>
</tr>
<tr>
<td>fl_drift_flag (2), r</td>
<td>NN cmd (r) is limited</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>2</td>
<td>25</td>
<td>05</td>
</tr>
<tr>
<td>fl_plim_flag (0) p</td>
<td>persistence ctr (p) is max – downmode</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>fl_plim_flag (1) q</td>
<td>persistence ctr (q) is max – downmode</td>
<td>bit</td>
<td>FC</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>11</td>
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<tr>
<td>fl_plim_flag (2) r</td>
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<td>bit</td>
<td>FC</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>12</td>
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<tr>
<td>fl_hrange_flag (0), p</td>
<td>NN cmd (p) is at hard range limit - downmode</td>
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<td>FC</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>13</td>
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<tr>
<td>fl_hrange_flag (1), q</td>
<td>NN cmd (q) is at hard range limit - downmode</td>
<td>bit</td>
<td>FC</td>
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<td>3</td>
<td>2</td>
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<td>bit</td>
<td>FC</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>
Sigma Pi Pitch Hardover

Sigma Pi pitch command hardover from trimmed flight

- Nz PAL limit hit
- Enhanced disengagement
- Floating limiter
- Drift boundary hit
- Enhanced disengagement
Sigma Pi Roll Hardover

Sigma Pi roll command hardover from trimmed flight

Floating limiter
Drift boundary hit
Enhanced disengagement

No enhanced disengagement (entire run)
Sigma Pi Roll Hardover: no floating limiter
Sigma Pi Roll Hardover:
with floating limiter
Sigma Pi Yaw Hardover

Sigma Pi yaw command hardover from trimmed flight

- Ny PAL limit hit, Enhanced disengagement
- Floating limiter, Drift boundary hit
- Enhanced disengagement

Time, sec

Lateral Acc, g

File=cde5.dat; Signal Suffix=nom; Date=[none]
File=cde6.dat; Signal Suffix=sm; Date=[none]
Sigma Pi Pitch Hardover
4 deg stab fail

Sigma Pi pitch command hardover from trimmed flight after 4deg stab fail
9/25K

4 deg stab fail
Floating limiter disengage
-1 Nz PAL limit
Enhanced disengage
Sigma Pi hardover (1000 dpss)
Sigma Pi Roll Hardover
4 deg stab fail

Sigma Pi roll command hardover from trimmed flight after 4 deg stab fail

Lateral Acc, g

Normal Acc, g

Angle of Attack, deg

Floating limiters signals

Sigma Pi hardover (1500 dps)

Time, sec

4 deg stab fail

Floating limiter disengage

Enhanced disengagement

4 AOA PAL limit

File=cdc10.dat; Signal Suffix=.nosm; Date=[none]
File=cdc9.dat; Signal Suffix=.sm; Date=[none]
Sigma Pi Yaw Hardover

4 deg stab fail

Sigma Pi Yaw command hardover from trimmed flight after 4deg stab fail

Ny PAL limit hit, Enhanced disengagement

Floating limiter Disengage Persistence time out
Sigma Pi - moderate doublets
floating limiter flags

Moderate Sigma Pi doublets after 4deg stab fail
.9/25K

File=fl_fail.dat; Signal Suffix=[none]; Date=[none]
Surprise
An Unexpected Test Anomaly

• Discrepancy excerpt:

“During dry runs of the supplemental HILS tests on ifcs_051g to simulate ARTSII failure modes, a four channel left stabilator shutdown was experienced as a result of dropping the ARTS_OK_to_Couple Flag in channel 2 with Neural Nets Enabled, and a simulated Stab failure. The test scenario was duplicated five times, one case all four channels of the left stabilator turned off. In all other cases, either just ch 1 and 2 or just ch3 and 4 stabilator failed (2 channel vs four channel fail). The test was run at M.75 @20K with PAL=8 and DAG=21 (4 deg left stab bias).”

BLIN code F143 = left stabilator current disconnect
An Unexpected Test Anomaly

• **Analysis**
  An FCC fault in channel 2 was created which resulted in that channel initiating the downmode logic from neural net to the conventional control laws. This downmode logic did not occur during the same minor frames in the FCC, resulting in different commands to the 4 channel actuator electronics. Consequently, a force fight was created which triggered the stab current monitor.

• **Corrective Action**
  Add downmode information to the FCC cross channel data link so that all the FCC channels transition in the same frame thereby eliminating the force fight condition
Mission Control Data Display
- from flight playback

• IADS display playback showing floating limiter from the neural net pitch command being set
• 3g WUT maneuver with 2 deg left stab lock fail set
• Neural net engaged
Floating Limiter Summary

- Meets disengage transients criteria for NN hardover (accelerations and loads)
  - Worst case 4 deg stab failure
  - Worst case canard failure
  - Worst case flight condition
  - Aggressive maneuvering flight
- Piloted simulation shows disengagements are acceptable, also validated from flight test
- No nuisance disengagements
- Concept may be applied to any single string controller, not only neural net commands