A PROGNOSTICS APPROACH FOR ELECTRONIC DAMAGE PROPAGATION AND ANALYSIS IN ELECTROMECHANICAL ACTUATOR SYSTEMS

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Abstract: As the aviation industry evolves toward next-generation fly-by-wire vehicles, hydraulic actuators are being replaced with their electro-mechanical actuator (EMA) counterparts. By eliminating fluid leakage problems while reducing weight and enhancing vehicle control, the feasibility of EMAs in avionic applications has been established. However, due to the inherent nature of electronic components and systems to degrade and eventually fail, improved diagnostic and prognostic methods are required to maintain the all-electric aircraft at safe levels. In this paper, an innovative approach to the emulation of avionic EMA operation is presented. A state-of-the-art testbed, which integrates a fault-enabled 12 VDC Switch Mode Power System (SMPS) with a fault-enabled servo drive H-bridge circuit, will be presented. Realistic load profiles can be applied to this scaled-down EMA testbed while executing the in-flight actuator motion commands in real-time. To examine and mitigate the effects, the EMA hybrid emulator is designed to support fault insertion of degraded electronic components, such as the power transistors of the motor drive, to analyze the servo loop response of an aged actuator system. The EMA motion trajectory, or position, data is acquired with various degradation levels of power electronics components in order to populate a fault-to-failure progression (FFP) database of actuator servo loop response signatures. Ultimately, the FFP signature database is leveraged to develop prognostic methods to assess the State of Health (SoH), estimate Remaining Useful Life (RUL), and support Condition-Based Maintenance (CBM) of avionic EMA systems.

Key words: **Diagnostics; prognostics; health management; condition-based maintenance; electromechanical actuator; actuator; IVHM**

Introduction: Fly-by-Wire Systems: Fly-by-wire systems have been noted as an important method of improving aircraft safety and reliability but have introduced different fault modes requiring mitigation [1]. Fly-by-wire aircraft use computerized Full Authority Digital Electronic Control (FADEC) systems to control engine fuel-flow rate, flight surface movements, and other activities. A computer can make hundreds of flight corrections and updates per second. In theory, this should lead to more economical, smoother, and safer air flight. Greater, more precise control has, in turn, made possible aircraft that are aerodynamically unstable. With the pilot removed from direct connection to the flight control surfaces in a fly-by-wire aircraft, knowledge of component failure modes has become critical in an industry already filled with maintenance issues and mission-critical equipment.[1], [2]

NASA's IVHM Project: The goal of NASA's Integrated Vehicle Health Management (IVHM) project is to improve the safety of both near-future and next-generation air transportation systems by reducing system and component failures as causal and contributing factors in aircraft accidents and incidents. The IVHM project should develop technologies to determine system/component degradation and damage early enough to prevent or gracefully recover from in-flight failures. These technologies will enable nearly continuous on-board situational awareness of the vehicle health state for use by the flight crew, ground crew, and maintenance depot. A main emphasis of the project is to develop automatic methods for detection, diagnosis, and prognosis of the vehicle at a system and subsystem level. This is accomplished through: analysis of electrical, thermodynamic, and mechanical failures; the analysis of the interaction of environmental hazards on vehicle systems and subsystems; and the study of damage and degradation mechanisms, to more accurately assess the vehicle's health state. [1]

Ridgetop Group's Role: Ridgetop's role in NASA's IVHM project was to develop of diagnostic and prognostic methodologies to assess the state of health (SoH) and estimate the remaining useful life (RUL) of the power electronics employed in a typical avionic EMA subsystem. Through quality collaboration with the NASA Ames Research Center (ARC), a model-based laboratory testbed was delivered to identify and characterize the fault-to-failure progression (FFP) signatures of dominant failure modes associated with the EMA servo drive and to analyze the propagation of damage through the drive. A high-fidelity computer model was developed and correlated with the laboratory testbed to enable further analysis of simulated motor drive faults and damage propagation. The Ridgetop testbed has been integrated into the ARC Advanced Diagnostics and Prognostics Testbed (ADAPT), shown in Figure 1. The ADAPT system will simulate in-situ EMA failure modes and allow logistics decisions. The testbed can also be adapted for in-flight emulation of real-time actuator control signals and load profiles. [1], [2]

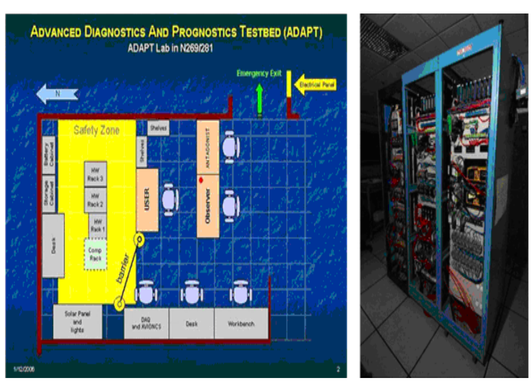

Figure 1: ADAPT Laboratory at NASA/Ames

The Ridgetop EMA Emulator: Based on the concept that damage or degradation of a servo loop is manifested in the characteristic Proportional Integral Differential (PID) control-loop response to a load change or disturbance stimulus, position control or regulation of a Brushless DC (BLDC) motor system was an ideal candidate for application of Ridgetop's patent-pending RingDown^{TM} technology. With this technique, the actuator health can be assessed by measuring the following error, or difference between the target position and actual position, associated with an EMA motion command. The compact suitcase testbed, shown in Figure 2, was constructed to test the hypothesis on a scaled-down model of an aircraft EMA system. This state-of-the-art testbed, which integrates a fault-enabled 12 VDC Switch Mode Power System (SMPS) with a fault-enabled servo drive H-bridge circuit, offers a powerful tool for conducting electronic component damage propagation analysis and prognostic algorithm development on a scaled-down, portable EMA model.

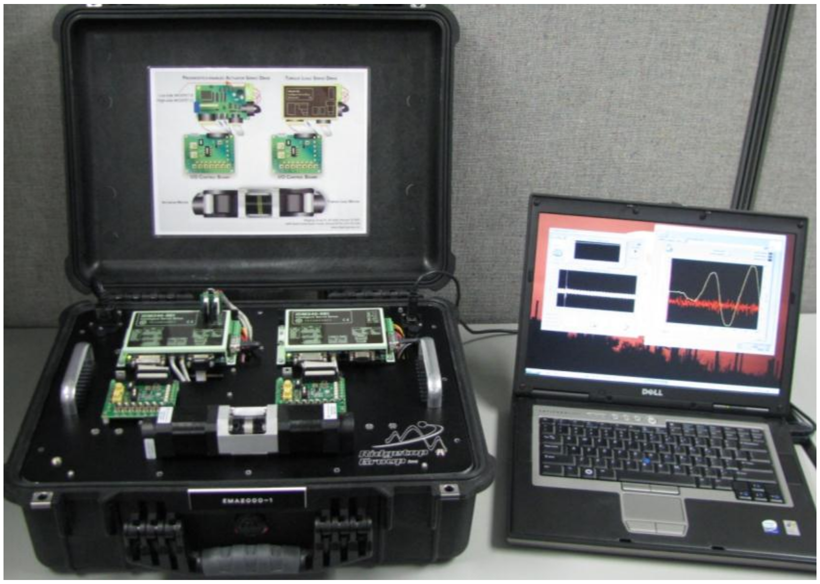

Figure 2: Ridgetop's EMA2000 power prognostics hybrid testbed

Using software, user-programmable motion trajectories and load profiles are applied to the testbed to investigate the servo drive response to various fault conditions. Properly interfaced to an avionic control system, the scaled-down testbed is capable of in-flight emulation of EMA operation under realistic load conditions and actuator damage profiles.

The fault-enabled 12 VDC logic supply has been packaged with the actuator servo drive and brushless DC (BLDC) motor in a single, portable suitcase enclosure to form a hybrid testbed capable of autonomous, as well as integrated, SMPS and EMA prognostic experimentation. Figure 3 is a block diagram of the EMA2000 hybrid testbed, highlighting potential fault injection points for critical EPS components. In this configuration, Ridgetop's RingDown technology is applied to both the voltage regulation servo loop of the logic SMPS and the position regulation servo loop of the actuator's BLDC motor.

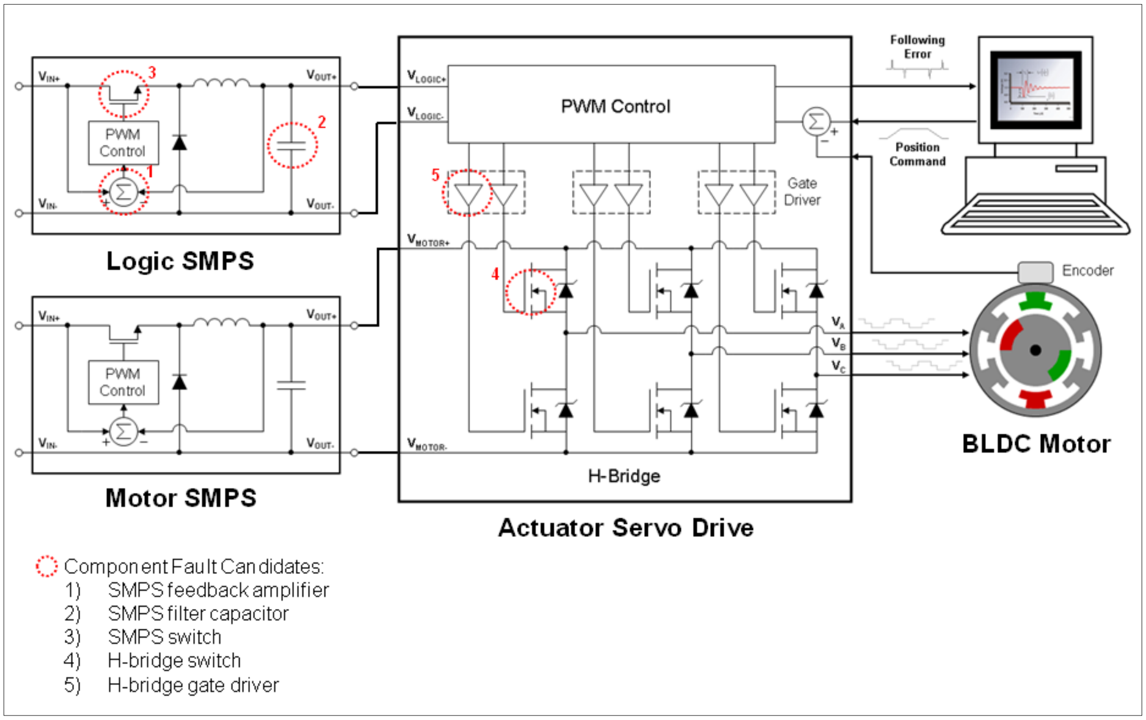

Figure 3: Block diagram of EMA2000 hybrid testbed architecture

The prognostics-enabled RD2010 Testbed utilizes a synchronous buck converter topology. The unit utilizes a 1 mega sample per second (MSPS) analog-to-digital converter (ADC) for acquiring the SMPS impulse response. In terms of characterizing the FFP signatures required for Ridgetop's RingDown analysis methodology, the data acquisition system offers excellent sampling resolution and fidelity.

A functional illustration of the EMA2000 testbed is provided in
Figure 4. In this arrangement, identical BLDC motors are coupled shaft-to-shaft to emulate actuator motion with programmable load behavior. The actuator motor, on the left side of the diagram, is configured in position mode, while the load motor, on the right side of the diagram, is configured in torque mode. Depending on the desired emulation mode, the torque load can be programmed to oppose or assist actuator motion. Sophisticated load profiles, including combinations of static, step, and impulse loads, can be created and synchronized with the motion trajectory to emulate actual avionic flight control scenarios.

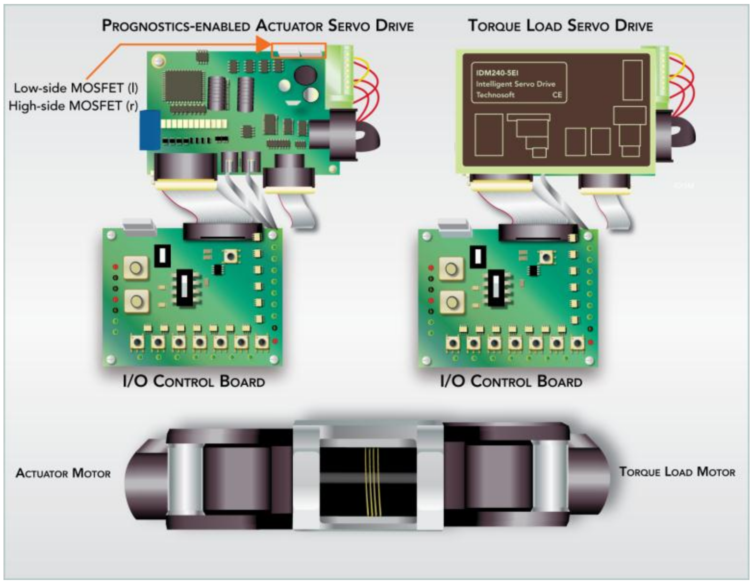

Figure 4: Functional illustration of Ridgetop's EMA2000 testbed

Emulator Hardware: In Figure 5, the close-up view of the EMA2000 top panel shows the configuration of hardware within the portable prognostics-enabled testbed. The position servo drive installed on the left side of the top panel has been retrofitted with sockets to enable insertion and removal of individual metal oxide semiconductor field-effect transistor (MOSFET) devices, or installation of a compact PCB to programmatically switch between healthy and degraded power transistors that comprise Phase A of the servo drive's H-bridge circuit.

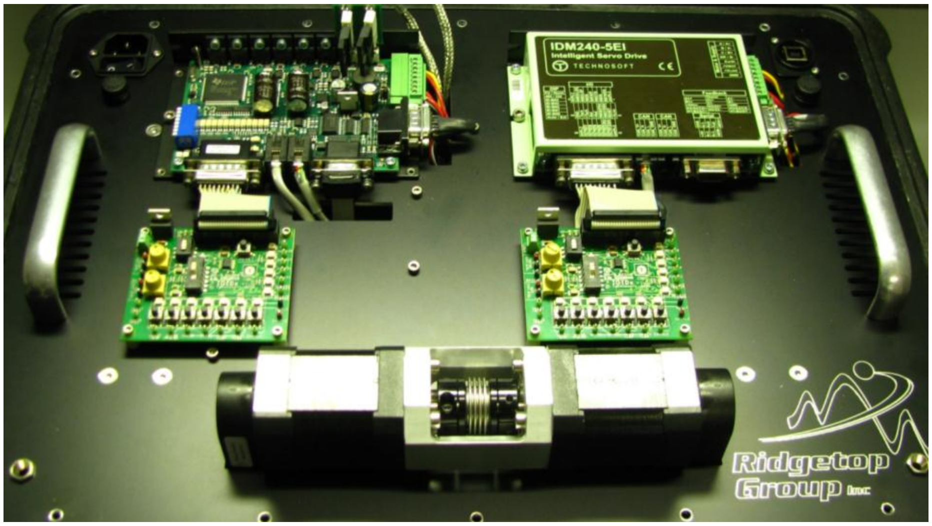

Figure 5: EMA2000 top panel

The position servo drive is equipped with a single-phase MOSFET switch board (SMSB), Figure 6. Note, however, that the SMSB can easily be scaled to accommodate programmatic switching of all three phases of the H-bridge. On previous research [3], aging was performed on multiple IRFZ44N MOSFET devices. The only result seen at the time was the destruction of a few devices, a threshold voltage (V_{T}) shift, and increasing R_{DS} On-Resistance. The desire was that a significant following error change would be measureable before a failure.

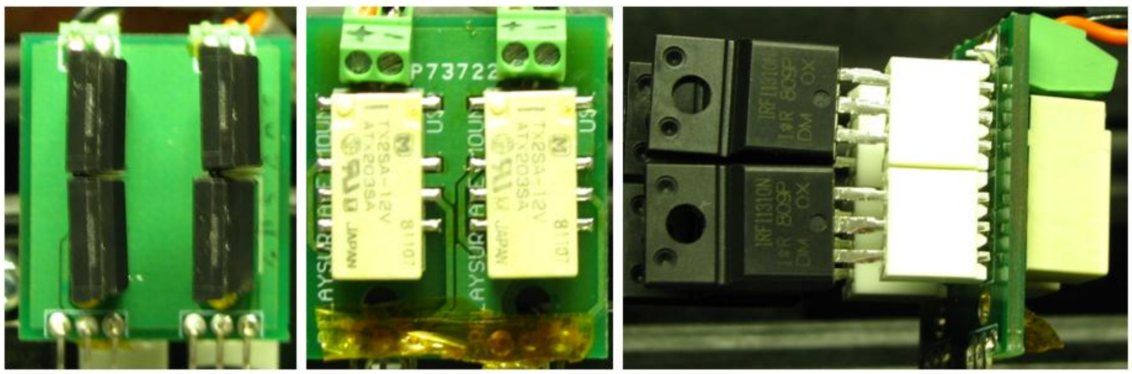

Figure 6: SMSB front, back, and side views showing MOSFETS, relays, and layout

The SMSB, which is essential to Ridgetop's programmatic fault injection capability, uses simple double-pole, double-throw relays to control which MOSFET from a pair is enabled in the H-bridge circuit while the other is effectively grounded. By facilitating programmatic replacement exchange of a healthy MOSFET with a degraded one, the SMSB allows the user to safely alter servo drive health without the risk of manual device handling. As a result, the dangers associated with electrostatic discharge (ESD) and transient current impulses are eliminated protecting expensive servo drives from severe damage. Furthermore, the SMSB supports programmatic control of the EMA2000 required for autonomous operation during flight testing.

Emulator Software: The EMA2000 hybrid prognostic testbed is currently supported by two separate software application programs: Ridgetop EMA2000 1.0.0 and Ridgetop RD2010 1.0.0. Each application provides an intuitive GUI to control the fault injection and data acquisition tasks of the associated testbed hardware.

A screen shot of the Ridgetop EMA2000 1.0.0 control panel is provided in Figure 7. Note that the custom motion sequence illustrated in the figure was extracted from actual F-18 control surface flight data provided by the ARC and translated for emulation on the EMA2000 testbed. The MOSFET Switch Control highlighted in the bottom right corner of the GUI enables programmatic fault injection into Phase A of the H-bridge. With two banks (upper and lower) of high- and low-side MOSFET devices installed in the SMSB, servo drive response can be characterized with multiple fault modes or degradation profiles during the experimental flight test.

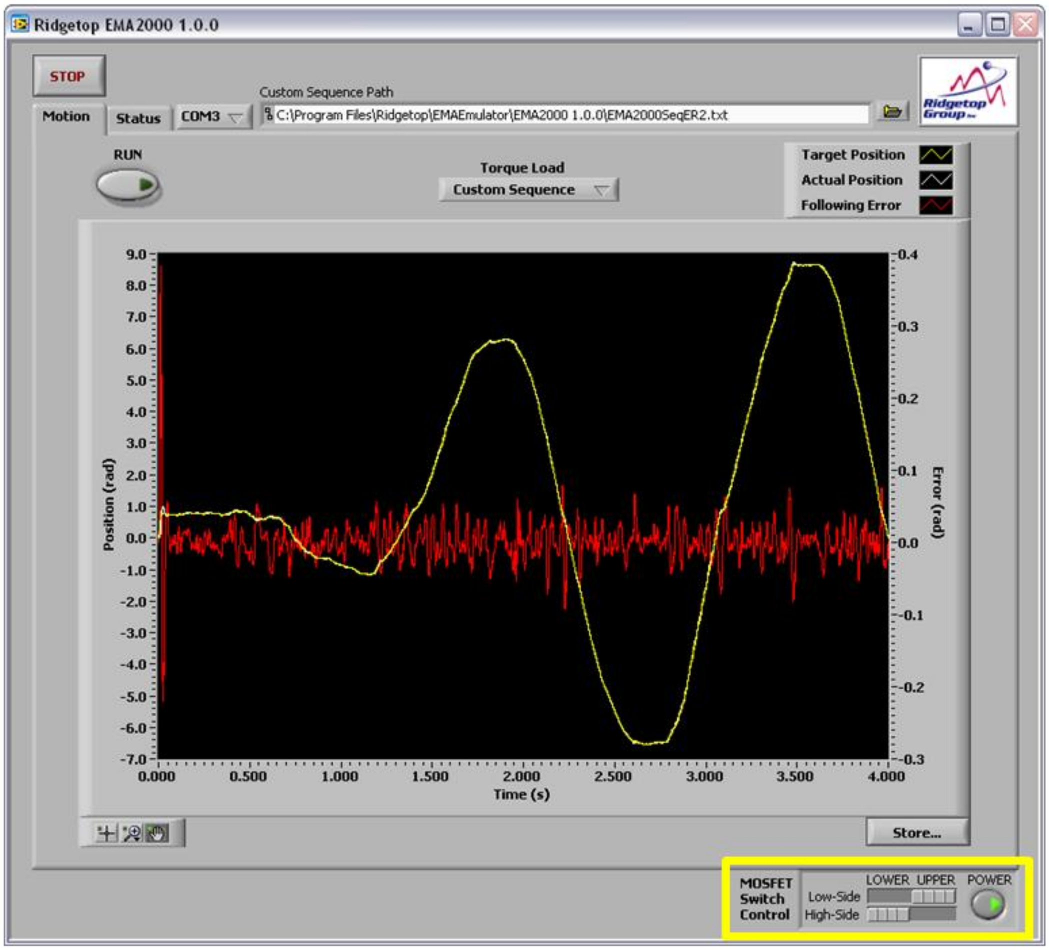

Figure 7: Ridgetop EMA2000 1.0.0 GUI with MOSFET switch controls

Along with adding enhanced MOSFET fault injection control to the EMA2000 software, introduction of the Ridgetop RD2010 1.0.0 control panel to support the fault-enabled 12 VDC logic supply integrated with the EMA2000 marks the first instantiation of Ridgetop's patent-pending Health Distance™ algorithm in a prognostics-enabled testbed application.

As shown in Figure 8, a historical presentation of the SMPS SoH is provided by the real-time chart highlighted at the top of the GUI, while an instantaneous SoH measurement is provided by the "fuel gauge" highlighted in the bottom right corner.

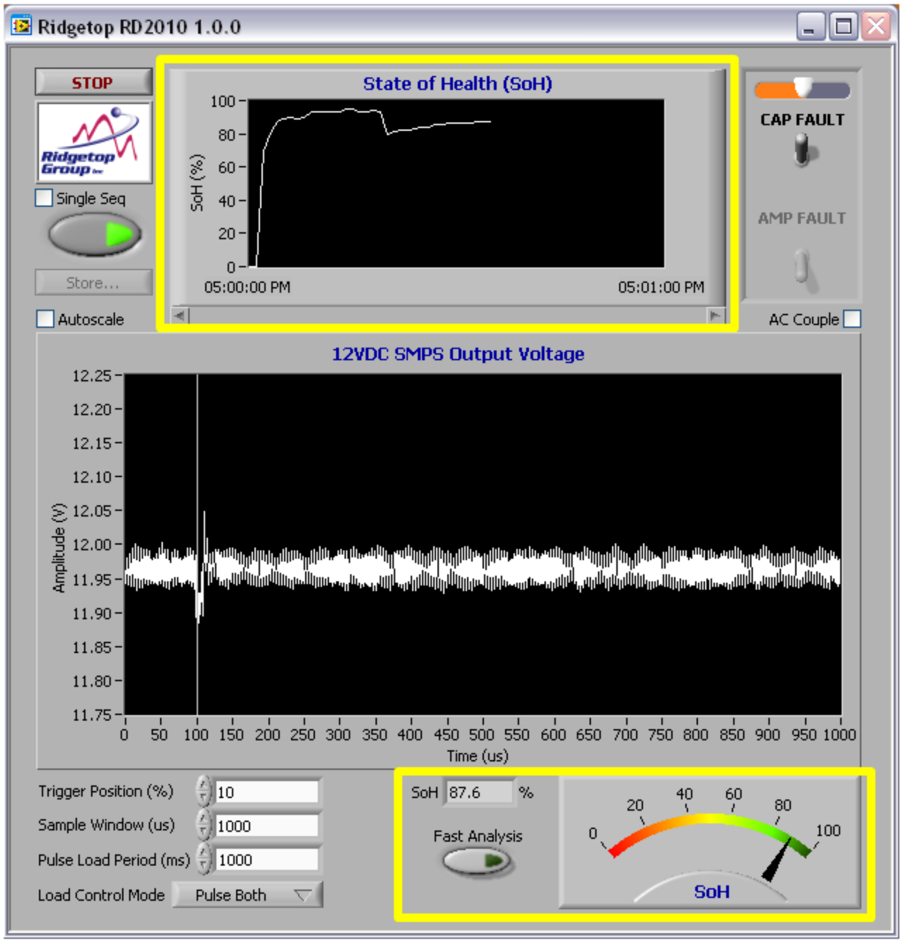

Figure 8: Ridgetop RD2010 1.0.0 GUI with state-of-health indicators

Data Analysis: The Health Distance algorithm has grown into a well-characterized EPS health management solution. When refining the algorithm, an unusually low output appeared when attached to the 12 V supply, and it was thought to be an algorithm programming error; however, the next day the switching controller stopped working. This unplanned event provided a useful confidence boost that this method is a valid solution for predicting the RUL from trending and pattern recognition in SoH.

Technical development has continued and the processing has benefited greatly from the new 1 MSPS sampling rate. The first step in the algorithms process is to calculate the Fourier transform shown in Figure 9. The resolution in the frequency domain is now extended up to 500 kHz without violating the Nyquist limit, although the data around 500 kHz appears negligible. This increased resolution has more than doubled the previous maximum frequency that could be observed. This update required an increase in the resolution of the algorithm computations. Previously, the data after the second step had been categorized into 30 different bins, but with the new approach this caused a gross over-approximation, so the bin count was increased to 50 (Figure 10).

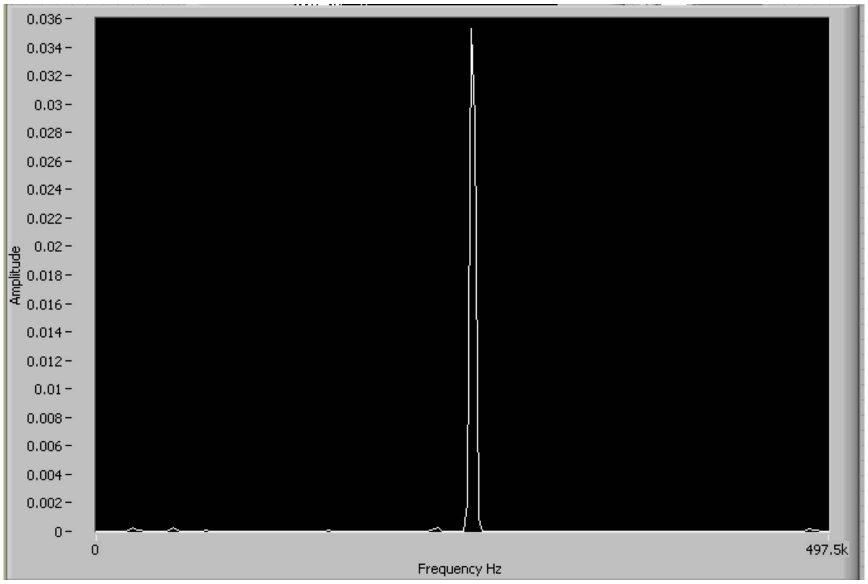

Figure 9: Frequency versus magnitude plot of healthy EPS to 500 kHz

The results of this development show how changes in the health are directly correlated to the level of damage in the system. This damage can manifest in many ways, and the biggest indicator is the ripple voltage amplitude. Other factors that do not have readily observable indicators include the switch controller logic degradation. That change can be seen in the frequency domain.

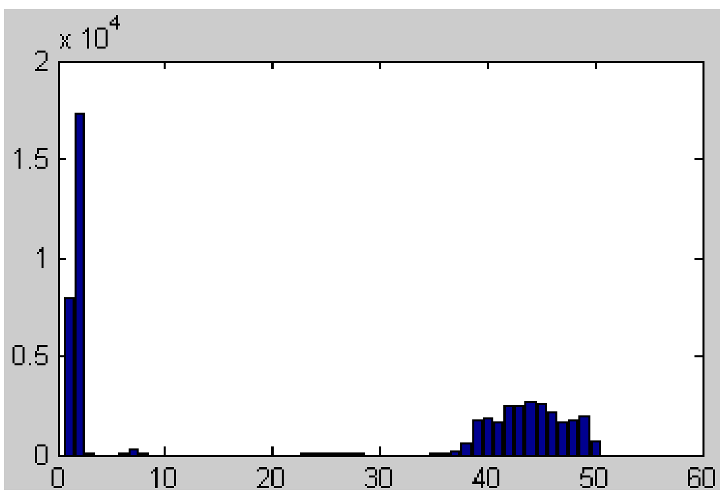

Figure 10: Training data with increased resolution

The simulated degradation has a very small impact on the power SoH computation due to the robust switch controller compensating for the degradation. But the SoH change does exist, as can be seen in the histogram in Figure 11. These data were collected with LabVIEW and imported to MATLAB, where the statistics toolbox developed the probability density functions shown.

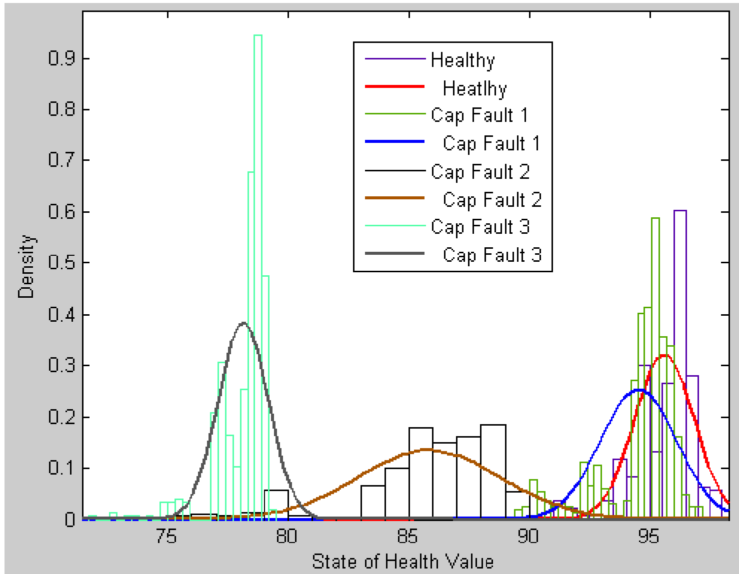

Figure 11: Distribution of calculated health for different levels of degradation

Since this application is designed to work in real time with the motor power systems, it must be trained with the load enabled to calculate an accurate SoH of the EPS when the motor is running. To complete this goal, the motor will be set to operate in a repetitious fashion with the power monitoring software being trained and running in parallel, as shown in Figure 12.

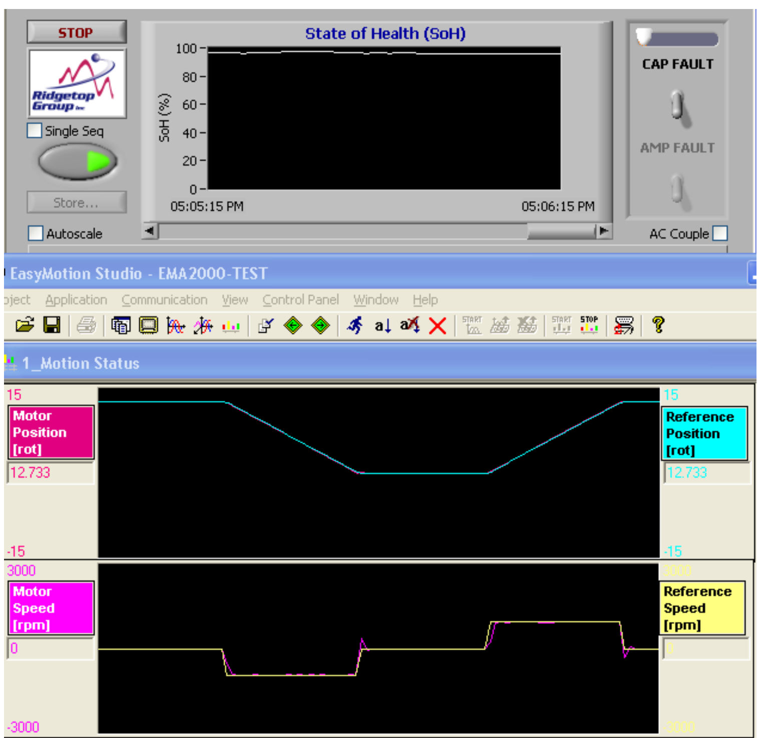

Figure 12: Computing SoH in real time with EMA load

The histogram in Figure 13 shows very little difference between the motor operating health of the EPS and no-load EPS health.

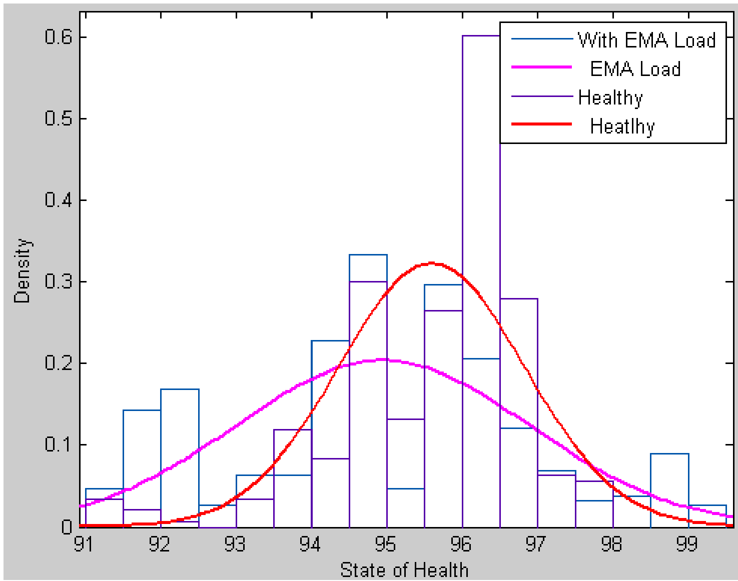

Figure 13: Algorithm performance with EPS driving EMA versus no-load healthy EPS

The results show a shift in the mean of about -0.5%, which is tolerable. To achieve the highest accuracy in the prediction, training data should be measured with load attached and activated.

Conclusion and future developments: Leveraging the component failure mode ranking of a representative 5 VDC SMPS, laboratory aging data, device physics-of-failure analysis, and simulation results, Ridgetop and its partners at the NASA ARC have witnessed the evolution of RingDown, from a collection of bread-boarded hardware sensors and bench-top instruments to a highly integrated and portable testbed. Culminating with application of a prognostics-enabled 12 VDC SMPS to Ridgetop's state-of-the-art EMA2000 hybrid testbed, a steady increase of our EPS prognostics Technology Readiness Level (TRL) has RingDown extremely well-positioned for successful introduction into commercial markets.

Ridgetop has demonstrated that a state-of-the-art testbed, which integrates a fault-enabled 12 VDC SMPS with a fault-enabled servo drive H-bridge circuit, offers a powerful tool for conducting electronic component damage propagation analysis and prognostic algorithm development on a scaled-down EMA model.

Ridgetop is currently working on the development of a top-level application for flight testing the EMA2000 aboard the Blackhawk EH-60 Helicopter. A screen capture of the application main GUI is provided in Figure 14. This top-level application will:

- capture targeted actuator flight control and load data in real time,
- transform flight data into position/load profiles understood by the EMA2000,

- emulate the motion sequences with various MOSFET degradation modes, and
- log the EMA2000 application state and results of each emulation mode.

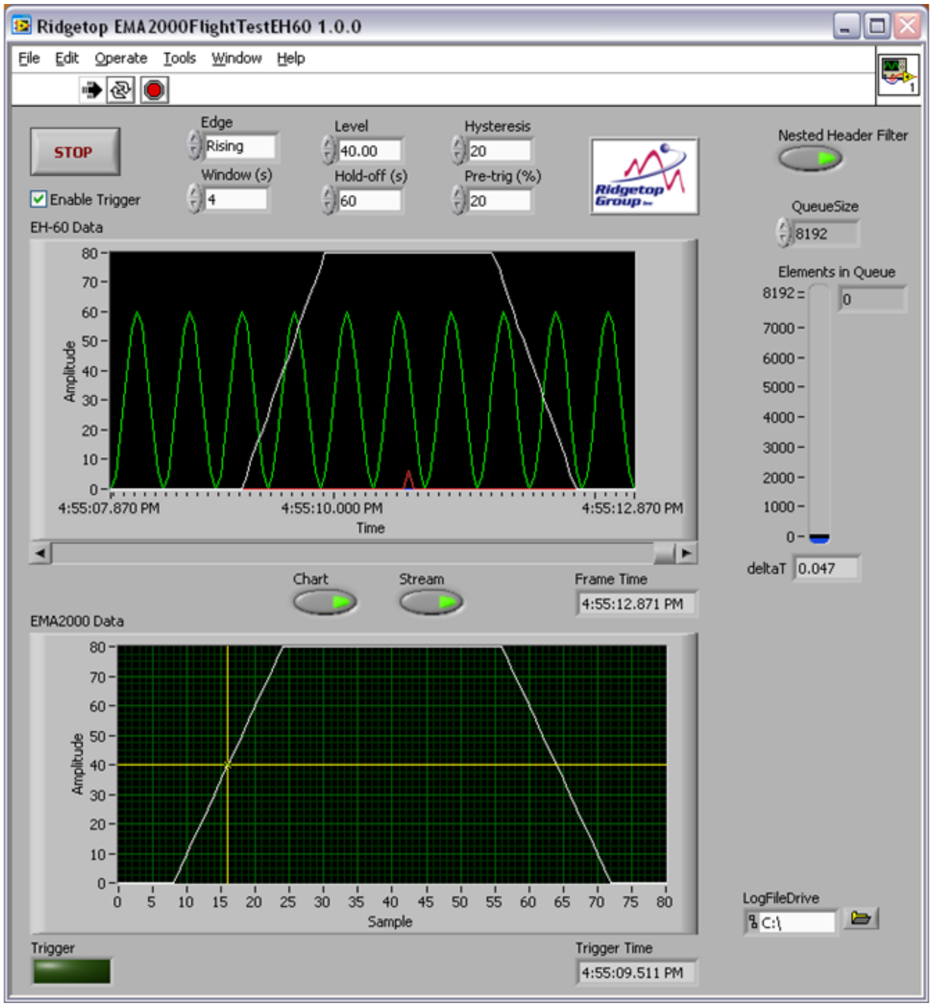

Figure 14: Main GUI for Ridgetop EMA2000 flight test application

The Graphical User Interface (GUI) provides real-time display and file storage of eight user-selectable channels of the raw RS-232 data stream transmitted by the on-board EH-60 flight control/data acquisition system. To test the Ridgetop EMA2000 flight test application, a simple modification was made to the EH-60 LabVIEW Emulator program provided by the ARC to replace two channels of this real-time data stream with position and load data suitable for our EMA Emulator.

As shown in the screen capture, the familiar trapezoidal motion profile (white) and impulse load (red) were successfully embedded in the data stream and used to trigger the emulation of a custom motion sequence on the EMA2000. As the real-time EH-60 Data is received and fed into the upper chart display, it is analyzed for the user-specified trigger condition. The trigger parameters, including rising or falling edge, trigger level and hysteresis (in radians), circular buffer size and hold-off (in seconds), and the percentage of pre-trigger data to include in the emulation are provided on the top of the GUI. Together, the hysteresis and hold-off parameters are intended to help guard against erratic and inadvertent triggering of the EMA2000 testbed. Upon detection of a valid trigger, the captured motion trajectory is transformed, along with the dynamic load condition simultaneously experienced by the associated flight control surface, into a suitable scale for real-time emulation on the EMA2000.

As previously shown in the block diagram of Figure 3, the EMA2000 was designed to enable the insertion of degraded electronic components, such as the power transistors of the servo drive, to analyze the servo loop response of an aged actuator system. Using a controlled process, such as that provided by the ARC's Accelerated Aging and Characterization System, MOSFET devices can be aged and inserted into the servo drive test sockets to acquire FFP signatures of the actuator Following Error, from no degradation to total device failure. The acquired data is recorded in a PHM database and used to develop prognostic methods, or analysis algorithms, to assess the SoH and estimate the RUL of the actuator power stage.

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Biography:

[1] **Neil Kunst** is an Engineering Project Manager at Ridgetop Group, Inc. He earned his BSEE from the University of Arizona, where he was a member of the Tau Beta Pi National Honor Society. Mr. Kunst received the Silver Bowl award and awards for outstanding achievement in Physics. He previously worked for Hamilton Test Systems, Intelligent Instrumentation, Inc., Mosaic Design Labs, Inc., Environmental Systems Products, Inc., Dataforth Corp., and SMSC. He also owned and operated his own firm, Palmtree Software, before joining Ridgetop. Mr. Kunst has more than 20 years of experience in product engineering, systems engineering, test engineering, logic design, software development, project management, and consulting.

[2] **Sonia Vohnout** earned her MS in Systems Engineering from the University of Arizona in Tucson. With a diverse background and experience, Sonia is well-suited to manage Ridgetop's commercialization efforts from its many government-funded projects. Sonia joined Ridgetop after successfully building an electronic subassembly business in Mexico, working as a Systems Engineer at IBM and handling overseas installations of

software with Modular Mining Systems (now part of Komatsu). During her career, she has held executive management and senior technical positions. In addition, Sonia has co-founded several companies. Sonia is a board member of the Society for Machinery Failure Prevention Technology (MFPT) (www.mfpt.org), an interdisciplinary technical organization strongly oriented toward practical applications. Sonia recently founded the Prognostic and Health Management (PHM) Professionals LinkedIn Group (www.linkedin.com), a fast growing group whose objectives are to: Discuss PHM related topics, network with others in the PHM community, and increase awareness of PHM.

[3] **Chris Lynn** is an Electrical Engineer at Ridgetop Group, Inc. His expertise is in computer modeling, determining the reliability of critical systems and predicting their failures. Chris graduated from the University of Arizona where he studied device physics and computer modeling of systems. Mr. Lynn graduated from the University of Arizona, Tucson, with a BSEE, and is pursuing his MSEE.

[4] **Dr. Byoung Uk Kim** is a senior R&D engineer at Ridgetop Group Inc., where he has contributed to ground-breaking technological improvements in self-healing system, electronic prognostics and reasoning algorithms. His current research involves integrating Ridgetop's sensor array technology with reasoning engines and developing incorporated self-healing algorithms, data analysis and data fusion in high performance computing environments. Interesting areas are high performance computing and security and trust computing. He is the co-organizer of workshop on Autonomic and High Performance Computing (AHPC 2010).