Reliability Based Design Recommendations for an Electromechanical Actuator Test Stand

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ABSTRACT

The quality and robustness of data sets of faulted electromechanical actuators (EMAs) are necessary to strengthen aircraft prognostic data analysis of such systems. Primary flight surface control actuators are of particular interest because the lack of known failure data erodes the confidence of the component and subsequently sub-system health predictions. To aid in this research, an EMA test stand has been designed and built to help in predicting the life and wear characteristics of faulted actuators with respect to their nominal counterparts. Faults are injected into the actuator during in-flight experiments while actuator parameters are recorded and then post-processed on the ground. This paper provides an assessment of the availability and reliability of the current EMA test stand design. Using the performance history of similar components in the field, this paper specifically demonstrates design aspects of the test stand that affect test system design and fault data quality. The study has been conducted to validate the test stand design, as well as offer design recommendations to increase test stand availability and ability to supply quality and robust fault to failure data sets. *

1 INTRODUCTION

Electromechanical actuators (EMAs) have been sought recently as the future of primary flight control surface actuation. Centralized hydraulic and electrohydraulic actuators are the current state of the art and although their installations are well understood, they are inefficient, require massive amounts of maintenance, and are susceptible to single point-failures (NTSB, 1989, NTSB, 2000). Commercial airlines have used centralized hydraulics for over 30 years while the military has installed the electrohydrostatic actuators (EHA) onboard the most recent flagship aircraft – the F-35 joint strike fighter. EMAs provide an alternative to accomplish the same task while at the same time being operable in space, passively cooled, lighter, more maintainable, and easier to integrate both mechanically and electrically into the aircraft (Dodsbir, 2009). Therefore, they are of particular interest over a wide range of applications from ships (Jenney, 2005, Tesar and Krishnamoorthy, 2008) to aircraft (Fuerst, et al., 2008, Janker, et al., 2008, Schwabacher, et al., 2002). However, their benefits come with a price: the inherent failure modes within the EMA require an advanced prognostics and health management (PHM) system and/or condition-based maintenance (CBM) system to be installed, guaranteeing the actuation system is as reliable and robust as its predecessors. The task of the PHM/CBM system is to detect and isolate incipient and abrupt failure modes as well as predict their effect on primary actuator control performance (Hvass and Tesar, 2004). As embedded diagnostic and prognostic technology matures, these systems can be implemented to complete life and mission critical tasks (Schwabacher, 2005, Schwabacher and Goebel, 2007). The science of prognostics is often a convoluted and difficult to apply to a complex system (Engel, *et al.*, 2000, Hess, *et al.*, 2005, Hess, *et al.*, 2006, Saxena, *et al.*, 2008). Yet, predicting faults in components whose environment is often highly stochastic can be made easier by employing knowledge bases of seeded failure data sets (Berenji and Wang, 2006, Byington, *et al.*, 2004, Uckun, *et al.*, 2008, Vachtsevanos and Wang, 1999). Specifically, building test stands to inject known faults into components, running experiments in an environment similar to their operating conditions,

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recording component parameters (motor current, temperature, position and velocity error rates, vibrations), and identifying fault signatures in the actual operating environments become very critical. This is due to the fact that prognostics cannot rely on mathematical models and real time data alone, because most diagnostic techniques assume the fault or failure is either physically and mathematically derivable, insensitive to extraneous variables, and uncorrelated with other features. In reality, one or more or these assumptions are not true (Vachtsevanos, *et al*., 2006). The true fault signature is most often buried deep within the raw data and that very real fact is all the more reason to invest in the collection and study of quality failure data sets.

Very little failure data is publically available to the field of prognostics that is not from a laboratory setting or completely artificial (Ma, 2007). To address this problem for EMAs in particular, a body of research has emerged to not only seed failures in EMAs (Balaban, et al., 2009, Balaban, 2009, Bodden, et al., 2007, Jensen, et al., 2000), but also to diagnose, predict, and control them when a failure does occur (Brown, et al., 2009, Orchard and Vachtsevanos, 2009). A current EMA test stand is currently going through flight experiments at NASA Ames Research Center. To complement the design for fault seed experiments, a reliability and risk study must be completed, assessing the test stand's effectiveness at providing a platform for those experiments (Mahadevan and Smith, 2003). Methods and techniques will be taken from a mature field of research exists that focuses on ascertaining system reliability (Billinton and Allan, 1992, Dodson and Nolan, 2002, Kapur and Lamberson, 1977, O'connor, *et al*., 2002).

To address this need, this paper presents an availability and reliability study conducted on the original operational flyable EMA test stand design (Balaban, 2009, Koopmans, et al., 2009, Koopmans and Tumer, 2010) using three traditional fault and reliability analysis techniques, that is, FMECA, fault tree analysis and reliability block diagrams. The purpose of the test stand is to provide a platform for running seeded fault experiments onboard aircraft. This paper will help establish FLEA availability, as well as component and system reliability characteristics of these actuators during operation and testing. The comparison of results from the different tools will help qualify the test procedures and the test stand itself for airworthiness and for verifying that the data obtained can be applied to actuator health predictions. The following sections present related background for the study, how the software tools calculate the desired metrics, uncertainties within the component models, followed by results, discussion, and design recommendations.

2 RELATED WORK

One of the goals of prognostics is to supply information about component and system health in a timely manner to interested parties, including pilots (in case of flight-critical failures), maintenance crews (asset management), field captains (mission-critical failures), or even the aircraft itself (automatic reconfigurable control strategies). Having direct access to this information will improve air safety, cost of ownership, and time for repairs. The military has published handbooks NPRD-95 and MIL-HDBK-217F that contain high level component replacement information, but nothing regarding types of failures, fault signatures, or actuator class (Denson, *et al*., 1994, DOD, 1991). The authors, in collaboration with NASA Ames, are beginning to build the knowledge base for EMA failures by means of an EMA test stand designed and built on behalf of NASA Ames Research Center (Koopmans, et al., 2009). Having run flight test aboard a C-17 and scheduled for the UH-60 platform, the test stand has demonstrated it is operable in flight. At this stage, improvements on the design are sought, and can be made regarding the assumptions behind the fault injections, test procedures, and system operation; basically a study to decide the validity of inferences drawn from the data sets (Koopmans and Tumer, 2010).

2.1 The EMA Test Stand

The EMA test stand, hereby referred to as FLEA (short for FLyable Electromechanical Actuator) is a proof of concept platform built in 2009 to record data of faulted EMAs passively operating onboard aircraft (Koopmans, *et al*., 2009). Installed as cargo, it contains three EMAs – one load and two test actuators coupled with electric magnets (*Figure 1*), a computer and data acquisition system, several sensors, and an external shell filling an 18" x 18" x 18" volume. Adaptors for user/flight engineering interfaces are located on the outside of the shell. FLEA communicates with the flight data computer via serial or Ethernet ports and obtains dynamic pressure, attack & incident angles, and other parameters to calculate an input load for the respective actuator. Each test actuator follows a flight profile in terms of position and velocity while a switch arbitrarily determines if the nominal or faulted actuator is in service. Each test actuator contains a sensor suite recording the same parameters: housing and ball nut vibration, motor and ball nut temperature, motor current, voltage, position, and velocity. These measurements are then recorded and available for download and post-processing once the flight has ended.

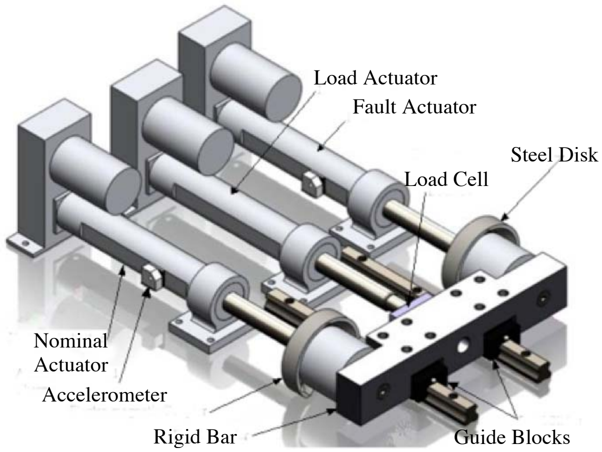

Figure 1: The actuator assembly. Only one test actuator is connected to the coupling at a time.

2.2 The Need for Availability

In the models used for this paper, the concept of availability is used and is hence defined briefly here. FLEA is unique in that it is not always operating, it undergoes preparations in the lab before each experiment onboard the aircraft. Therefore, any problem found during experiments can be addressed before the next one. Yet, during experiments, FLEA must operate as designed because if a failure was to occur, a great deal of time and money is wasted. A low probability of unavailability during any given flight time is desired.

2.3 The Need for Reliability

In addition, the concept of reliability is used in the models that describe FLEA usage. For FLEA to be considered reliable, it will have to operate successfully for the duration of each flight, supplying quality data, without an unexpected or unscripted error. Since the period of time required to obtain the test results (beginning from fault inception to declared failure) is unknown, FLEA must be able to operate for an indefinitely long period of time; or in other words, have a high probability of reliability. FLEA is designed to operate in an aircraft environment with the assumption that no failures will occur in the testing apparatus that are not intentional. In a real world application, EMAs have proven to be unreliable with respect to their ball nut assemblies. Part of the purpose of this study is to determine what the useful life expectancies of FLEA components are as they were designed. A reliable test stand will operate free of unintended errors until the conclusion of the experiments. Risks associated with lowering this probability include failure to provide usable data, generating misleading data, or the life of the load actuator (or even the actuator that is presumed nominal) being shorter than expected.

3 ANALYSIS TOOL CHARACTERISTICS

Assessing system reliability can provide critical insights and information to the designer, including relative component contributions on a system level. By ensuring that each possible failure mode of each component is examined for its effect on the performance and reliability of the overall design, these methodologies greatly reduce omission errors and increase system functionality. The analysis of FLEA will be performed using ITEM Toolkit's modules for fault tree analysis (FTA), and reliability block diagrams (RBD) (Itemsoftware, 2007). A separate FMECA will also be presented highlighting mechanical components custom built for the fault injection experiments.

3.1 FMECA

Failure Mode, Effects and Criticality Analysis (FMECA) is a widely used information tool in engineering (DOD, 1984, AIAG, 2008). This reliability study will complete a brief FMECA of parts of the system not already covered in related work (Balaban, *et al*., 2009). Expert knowledge will be the basis for the initial guesses of severity, detectability, and occurrence. These three parameters will be multiplied together to form the Risk Priority Number (RPN). By focusing design efforts on components with the largest RPNs while cross checking with the reliability model predictions, a more reliable FLEA may be designed. While FMECA is good at identifying initiating faults, and determining their local effects, it is not good at examining multiple failures or their effects at a system level. The following tools allow for system inference of failure propagation.

3.2 Fault Tree Analysis

Fault Tree Analysis (FTA) is a top down approach to failure analysis (Vesely, *et al*., 1981). The analysis begins with an undesirable top state and attempts to determine all of the component failures or combinations of failures that could contribute to that undesirable top state. As with FMECA, the data for this analysis relies on expert knowledge to correctly identify all of the contributing failures and the logical connections between them in addition to populating the model with reliability parameters.

Fault Tree Analysis (FTA) is built with failure events coupled with logic gates to show the contributions of each component on system reliability. FTA can indicate how well a system can withstand single or multiple initiating faults and how those faults interact. For this study, each failure event is focused on mechanical failures with two reliability parameters – failure rate and repair rate.

3.3 Reliability Block Diagram

A Reliability Block Diagram (RBD) is a graphical method for determining how component reliability contributes to the reliability of its overall system (Modarres, *et al.*, 1999). An RBD is a series of blocks representing system components that are connected in series or parallel depending on whether or not the system is operable given the failure. The system is available if and only if a linear unbroken path is possible from start to finish. For this study, each component is given a failure and repair rate, assuming that after each failure the system is unavailable for the duration of the failed components repair rate. Both FTA and RBD return the same probabilities: system unavailability and reliability, along with percent of component contributions to system reliability.

3.4 Component representation

The homogeneous Poisson process is an appropriate preliminary model to employ for representing component failure rates in reliability block diagrams and fault tree analyses (Kiureghian, *et al.*, 2005). Consider a component with attributes λ_i and μ_i denoting mean failure rate relative to the total time (including repair durations) and mean component repair rate for each failure, respectively. The value λ_i can be calculated by dividing the number of component failures over a period of time by the period length (include repair times). The value μ_i can be calculated by dividing the number of component failures by the sum of repair times over a period of time. For example, if a component took 48 hours to repair once, its repair rate value would be 0.0208. Hence, the component model describes the random failures and repairs of the component in rate per unit time, is completely described by the two parameters λ_i and μ_i, and consequently holds the following assumptions:

1. Component failure rates do not change with time;
2. Components experience random failures in time, independently of each other, and each failure entails a random duration of repair before the component is put back into service;
3. Failed component repair duration is independent of the states of other components;
4. The component faults within the system are ergodic, that is, the model employs a statistical concept stating that inferences are possible about a system over a short period of time that hold regardless of how long it has been in operation.

The reliability models will use the following equations to calculate both component and system probabilities and percentages. The following equation determines the probability that a component (*i = 1*) is unavailable for operation at any given time *t* (Equation 1), known as component unavailability (Itemsoftware, 2007).

$$Q(t) = \frac{\lambda}{\lambda + \mu}\left[1 - e^{-(\lambda+\mu)t}\right] \tag{1}$$

The probability that a component will fail per unit time *t*, given that it was working correctly at time zero, is denoted as the component failure frequency (Equation 2).

$$\omega(t) = \left(1 - Q(t)\right)\lambda \tag{2}$$

3.5 System Representation

Once each component is modeled using dedicated failure and repair rates in addition to equations 1 and 2, cut sets must be defined. A cut set is the minimum set of components whose joint failure results in system failure. The failure frequency of an individual cut set is shown in Equation 3:

$$\omega_{CutSet} = \sum_{j=1}^{n} \omega_j \prod_{\substack{i=1 \\ i \neq j}}^{n} Q_i \tag{3}$$

where *n* is the number of events within the cut set, ω_j is the failure frequency of the j^{th} event in the cut set, and Q_i is the unavailability of the i^{th} event in the cut set. The failure frequency of the system is shown in Equation 4:

$$\omega_{System} = \sum_{i=1}^{n} \omega_{CutSet_i} \prod_{\substack{j=1 \\ j \neq i}}^{n} \left(1 - Q_{CutSet_j}\right) \tag{4}$$

where *n* is the number of cut sets within the system, ω_{CutSet} is the failure frequency of the i^{th} cut set, and Q_{CutSet} is the unavailability of the j^{th} cut set. Next, the overall system reliability is calculated using the system unavailability, given by Equation 5:

$$R(t) = e^{-(1-Q(t))} \tag{5}$$

Reliability is defined here as the probability the system is operating from time zero to time *t*, given the system was repaired to an operational state at time zero. Another parameter of interest is the conditional failure intensity (CFI) seen in Equation 6, which represents the probability the system will fail, given it was working as designed at time 0.

$$\lambda(t) = \frac{\omega_{System}(t)}{1 - Q(t)} \tag{6}$$

Finally, to determine a specific events contribution to the system unavailability, the Fussell-Vesely importance measure is used, shown in Equation 7.

$$IMP_{FV} = \frac{\sum Q_{CSwithBlock|Event}}{\sum Q_{CStotal}} \qquad (7)$$

Here, the metric sums the cut set unavailability given a specific failure with respect to total cut set unavailability. A change in the unavailability of a high importance valued event will have a significant effect on system unavailability.

To summarize, component unavailability and failure frequency will be computed for the system calculations, failure frequency is the probability of a failure within time *t*, independent of whether a failure has occurred before time *t*. The reliability and the conditional failure intensity metrics give pure values for the probability of a working system and no failures occurring during operational time. Keeping all this in mind, we can proceed with the mathematical modeling framework. However, several uncertainties must be considered regarding component integration and design before failure and repair rates are populated, discussed next.

4 COMPONENT RELIABILITY MODELS

The following discussion is intended to analyze potential sources of model uncertainty and the effects on the components failure and repair rates.

4.1 Reliability Data Sources

In order for the analysis tools to be used, each component must be linked with a failure rate (usually in failures per 10^6 hours) and repair rate (number of repairs per duration of repair). NPRD-95 and MIL-HDBK-217F reliability data is derived from maintenance records collected from 1970 to 1994 and statistically analyzed to a standard measured in failures per million cycles; they will be the primary source of failure information for this study. The fact that this information was collected from actual field data increases the confidence of the model results. While the failure data is not specific to any particular part or manufacturer, it is a good indication of what can be expected from any given class of part. Neither handbook contains repair rates, therefore, they will be estimated for all components based on expert knowledge of FLEA during building and testing (Koopmans, *et al*., 2009). Also, to complete the models, failure rates of components not contained within the handbooks were estimated by the authors.

For this study, it is assumed that the airborne rotary wing (ARW) or helicopter environment can be used to adjust published reliability data numbers. Failure rates under this designation generally have higher failure rates than those installed on ground units or other airborne platforms. *Table 1* shows critical FLEA component failure parameters.

Table 1: Components failure rates found within NPRD-95 and corresponding environmental factors within MIL-HDBK-217F.

Component	**Environment**	**Failures / 10^6 hrs**	**Factor**
Linear EMA	ARW	1108	16
Linear EMA	GB	78	1
Accelerometer	AI	603	6
Thermocouple	ARW	63	16
Optical Encoder	GM	206	7
Load Cell	GF	22	2

In this table, GB indicates a ground laboratory assignment, AI indicates general airborne inhabited areas without environmental extremes, GM indicates equipment installed on wheeled or tracked vehicles, and GF indicates ground fixed position. The purpose of Table 1 is to show the relative failure values of similar components assumed to be designed and installed properly. For this reason, if the data found for FLEA components was not directly taken from the ARW environment, the actual failure rates were multiplied by the appropriate factor. However, the two components taken directly from ARW have been multiplied by an additional factor based on built in design modifications for measuring ball nut vibrations. Furthermore, knowing FLEA was constructed as a prototype, it is safe to assume that the component failure and repair rates will be much larger.

Repair rates will be estimated in terms of business days for completion including time for: removal, shipping, custom machining, installation, calibration, and testing. For example, the linear guide assembly repair rate is 0.0416 or one repair per 24 business hours.

4.2 Base Plate

The foundation of the test stand is the base plate – it constrains all actuator and linear rail degrees of freedom. Vertical displacement and two rotational degrees of freedom are constrained with the top face of the plate while the remaining two displacements and one rotational degree of freedom are constrained by the hole patterns. FLEA reliability is affected through misalignment of the actuator and linear guide assemblies and indirectly from the strength of aluminum threads within the base plate. Errors in the hole patterns for the actuator mounts and linear rails as seen in *Figure 2* easily propagate to interacting components and the fault data produced. Steel fasteners gall aluminum threads quickly as the linear rails have been seen shifting during lab experiments and considering the high vibration environment of a helicopter, the threads become a much more significant design challenge.

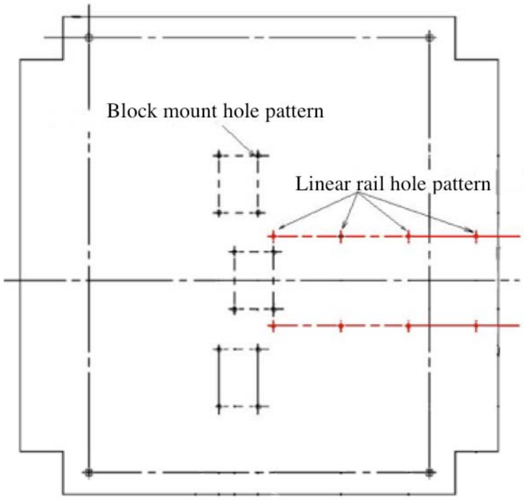

Figure 2: Hole patterns on the base plate.

As for assigning a failure rate, the rate due to fully reversed shear loading has been calculated as negligible, but thread failure rate due to fastener insertion and removal has been estimated as 2.5e-4 per thread: assuming the thread strips after 100 secure cycles and an average of 1 secure cycle per 40 hours. Furthermore, base plate repair rate has been estimated at 0.0125.

4.3 Actuators

Three variables negatively affect the reliability of the three actuators installed, including their alignment relative to each other and to the linear guide assembly, coupling to the guide assembly, and fault modifications. Throughout the design process it was assumed that the actuators would travel parallel to each other and the linear rails. Misalignment however, has proven to be a very real problem in both actuator performance and data collection. During misalignment, the motor will draw additional current to overcome the additional resistance required to travel the same distance – shortening useful actuator life and masking the true motor current signal with a false one. Next, space constraints required tabs to be welded under the gearbox casing for added support and attachment to the base plate (*Figure 3*). These actions are not manufacturer approved and introduce misalignment issues. Next, the test actuators couple to the rigid bar via electric magnets and steel disks threaded over the actuator stud. These disks (seen on the right of *Figure 4*) have unthreaded themselves during testing, ultimately resulting in zero actuator coupling. Assuming the actuator stud threads are rolled steel and experience 100 lb_f of fully reversed tensile loading, fatigue analysis estimates 7.45 x 10^9 cycles until thread failure. Of course the threads do not undergo pure tensile loading due to alignment issues, but for testing purposes thread failure is negligible. But, the loosening of the steel disk is not, while it may shear threads if aggravated. Also, several modifications to the actuator housing were completed so that sensors could monitor important measurements, particularly aspects of the ball nut (*Figure 4*).

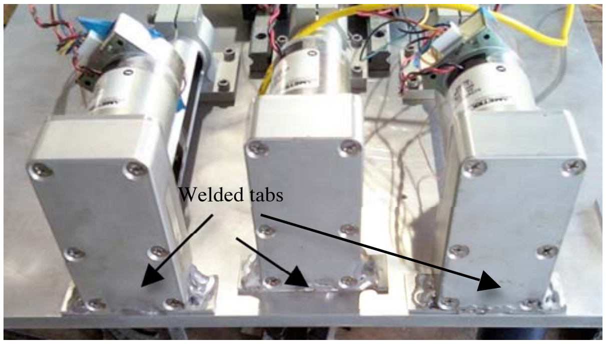

Figure 3: Tabs on the bottom of the actuator housing provide additional support and rigidity.

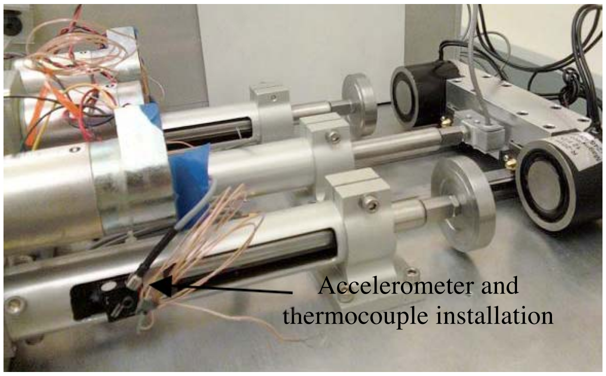

Figure 4: The thermocouple and accelerometer shown measure bearing raceway temperature and ball nut vibrations respectfully.

Here, the seals have been bypassed and the lead screw is completely exposed to the environment, exacerbating bearing and ball nut debris problems. In general, flight certified actuators contain a thrust bearing for alleviating radial loads on the ball bearings, but one does not exist for the actuators FLEA is testing. Nevertheless, each actuator is assigned a different failure and repair rate as seen in *Table 2*.

Table 2: Actuator failure and repair rates.

Component	Failure Rate	Repair Rate
Load Actuator	2.86e3	1.38e-2
Nominal Test Actuator	3.32e-3	1.04e-2
Faulted Test Actuator	5.52e-3	0.83e-2

The logic behind the failure rates is based first off the original 1108 value in *Table 1*, factors for the quality of the actuator, fault modifications, alignment (tolerance stack up from base, actuator block mounts, rigid bar, and linear rails contribute to a vertical misalignment of ±0.005”), couplings, and the load actuator for operating twice as long as either test actuator. For estimation purposes, these values are reasonable for a prototype test platform.

4.4 Linear Rails and Guide Blocks

The linear rail and guide block assembly is the foundation of the coupling, leading the actuators along a linear path and supporting the electric magnet. Positioning the rails relative to the actuators is a significant step for assuring quality FLEA operation. The linear rail manufacturer publishes formulas that will help predict the life span of their slides based on an applied radial load P, as shown in Equation 7:

$$50\left(\frac{C}{P}\right)^3 = Life(km) \tag{7}$$

where C is the basic dynamic loading for the model of slide (8.33 kN). Misalignment causes the applied load and although this load is difficult to calculate, the manufacturer publishes empirical data linking vertical and horizontal displacement with a rolling resistance (Thk, 2010) as well. Vertical misalignment is not an issue with the linear rail life estimate as the guide block is able to absorb a vertical displacement between the two rails up to 0.01” and the current tolerance is below that value. Horizontal misalignment however is a significant issue as base plate machining may easily produce tolerance errors where upon a displacement of 0.004” imposes almost 6 extra lb_f of rolling resistance. *Figure 5* is used to infer the linear guide assembly failure rate. The applied load P is derived by straining the rigid bar for a displacement value, while the 4” travel along the rail is completed an average of once per ten seconds. Since the experimental failure rates for the linear guide assembly were determined based on data from slide performance in a laboratory setting, the actual failure rate was multiplied by a factor of ten to approximate a helicopter environment. Therefore, assuming a 0.003” horizontal misalignment, the failure and repair rate for the linear rail and guide block assembly were set at 2e-30 and 4.16e-2 respectively.

4.5 Sensor Features

Equally as important as the components they are attached to, the sensors must operate and record data reliably. Their installations are of particular importance because of the prototype nature of FLEA.

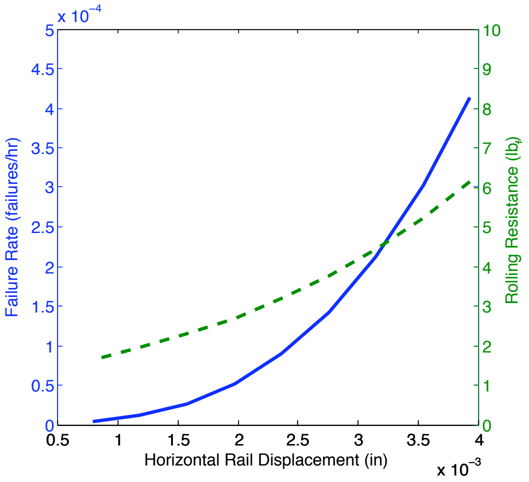

Figure 5: A graph depicting linear guide assembly failure rate (solid line) and rolling resistance, relative to a horizontal displacement taken from (Thk, 2010).

Four accelerometers, four thermocouples, and one load cell are the most critical sensors because they measure essential parameters for the fault data sets, are exposed to the environment, and require wires plus signal conditioning. The ball nut sensor installations require machining of the actuator housing for access and careful attachment and routing of accelerometer and thermocouple wires. The thermocouple is located along the bearing raceway inside the ball screw assembly, while the wiring to the signal conditioning board is delicate. The accelerometer mounts to a metal block glued to the ball nut while a few 4-40 threads secure the sensor in place. The load cell is rigidly connected to the load actuator and rigid bar using two threaded bolts. *Table 3* shows the suggested failure and repair rates within the models.

Originally taken from *Table 1*, the sensors were multiplied by the environmental factor and corresponding design uncertainties and divided by 10^6 to arrive at their current value. The accelerometer bolt has loosened during testing and come in contact with the actuator housing, rendering the experiment useless and along with the load cell, is subject to high transient vibrations during testing and experiments. The failure rates reflect the designers concern about flight environment effect on critical sensors.

Table 3: Sensor failure and repair rates.

Component	Failure Rate	Repair Rate
Accelerometer	7.6e-3	4.16e-2
Thermocouple	1.26e-3	2.5e-2
Load Cell	6.16e-4	4.16e-2

4.6 Others

Components not included in the handbooks, too abstract to calculate, or not considered critical to FLEA reliability are given an average failure rate of 2e-4 and 1.25e-2 repair rate. These components are either over-designed, electronic, or software related.

4.7 Summary

This section has presented critical FLEA components and their integration issues with the rest of the system and how they affect overall reliability. The following models will indicate the component contribution to system reliability, opening the design for needed changes.

5 SYSTEM RELIABILITY MODEL DEVELOPMENT

With the necessary components thoroughly analyzed with respect to their reliable generation of quality data sets, ITEM Toolkit can be used next to calculate the system parameters of interest: unavailability, reliability, failure frequency, and individual component contributions to system availability. A FMECA is presented along with fault tree and reliability block diagrams developed using ITEM's modules.

5.1 FLEA FMECA

The FMECA presented in *Table 4* is the standard benchmark for critical component identification. Completed from the original FLEA designer and tester's point of view, it encompasses custom FLEA components and actuator modifications not covered in previous detailed FMECAs (Balaban, *et al*., 2009). The table focuses on FLEA installation and operation. An interesting note is to see how the risk priority numbers and Fussell-Vesely values correlate.

5.2 FLEA Fault Tree Model

The FLEA fault tree model is shown in *Figure 6*. The fault tree has a top state of bad/no data, meaning the analysis focused on finding origins of the measurement and recording (or lack thereof) of non-quality data; non-quality data being an unreliable source in actuator health predictions. The model begins with identifying the last place the data resides before download after flight experiments – on the computer hard disk. From there the model propagates through the electrical components followed by the mechanical components, stopping at the FLEA structure. Most of the electrical and computing entities of FLEA were not populated with failure or repair rates because they were considered insignificant relative to their mechanical counterparts and little justifiable reliability information is available.

Each of the initiating events (round symbols) represents a component of the test stand that may introduce or cause misleading data. Primary focus is on the bottom two levels of the tree; here the sensors, couplings, and actuators reside inside the actuator assemblies.

5.3 FLEA Reliability Block Diagram Model

The FLEA reliability block diagram is shown in *Figure 7*. Starting with the load actuator, mechanical energy is imposed on the actuator assembly for the duration of the flight experiment. A linear force is transferred to the coupling while an equal and opposite force is transferred to the actuator mount. The nominal and faulted test actuators distribute energy to their respective sensors, followed by the securing components to the base plate. For availability verification, a node exists after each parallel group of components that requires all paths flowing into it, be available for successful system operation.

Table 4: A FMECA of the FLEA system, containing only custom components.

System	Component	Fault	Failure	Detectability	Occurrence	Severity	RPN
Actuators	Load Actuator	extended duty cycle	no force control	3	6	8	144
		misalignment	bad data	6	5	3	90
	Nominal Actuator	misalignment	bad data	6	5	3	90
	Faulted Actuator	fault injection mod	no data	5	5	8	200
Coupling	linear rail	misalignment	overloading / bad data	4	8	5	160
		manufacture error	bad data	5	3	5	75
	guide block	misalignment	bad data	4	8	5	160
		overloading	flaking / bad data	6	4	3	72
	load cell	overloading	no force control	5	5	9	225
		short circuit	no force control	5	1	8	40
		open circuit	no force control	5	1	8	40
	rigid bar	misalignment	bad data	3	4	5	60
	electric magnet	open circuit	no couple/no data	7	1	8	56
		short circuit	no couple/no data	7	2	8	112
	steel disk	loose thread	liberation	6	7	9	378
	fasteners	strip thread	bad data	3	6	8	144
Structures	Base plate	Thread strip	bad data	8	7	8	448
		Hole accuracy	bad data	3	4	4	48
	Tslot	loose fastener	increased vibrations	8	2	4	64
Data Acquisition	Ball nut mount	casing contact	no vibration data	4	3	9	108
	accelerometer	high vibration	no vibration data	3	3	7	63
		coupling to board	no vibration data	7	4	7	196
	thermocouple	ground	no temperature data	3	4	7	84
		wire sever	no temperature data	7	3	7	147
	signal processing	open circuit	no data	3	2	5	30
		short circuit	no data	3	3	6	54

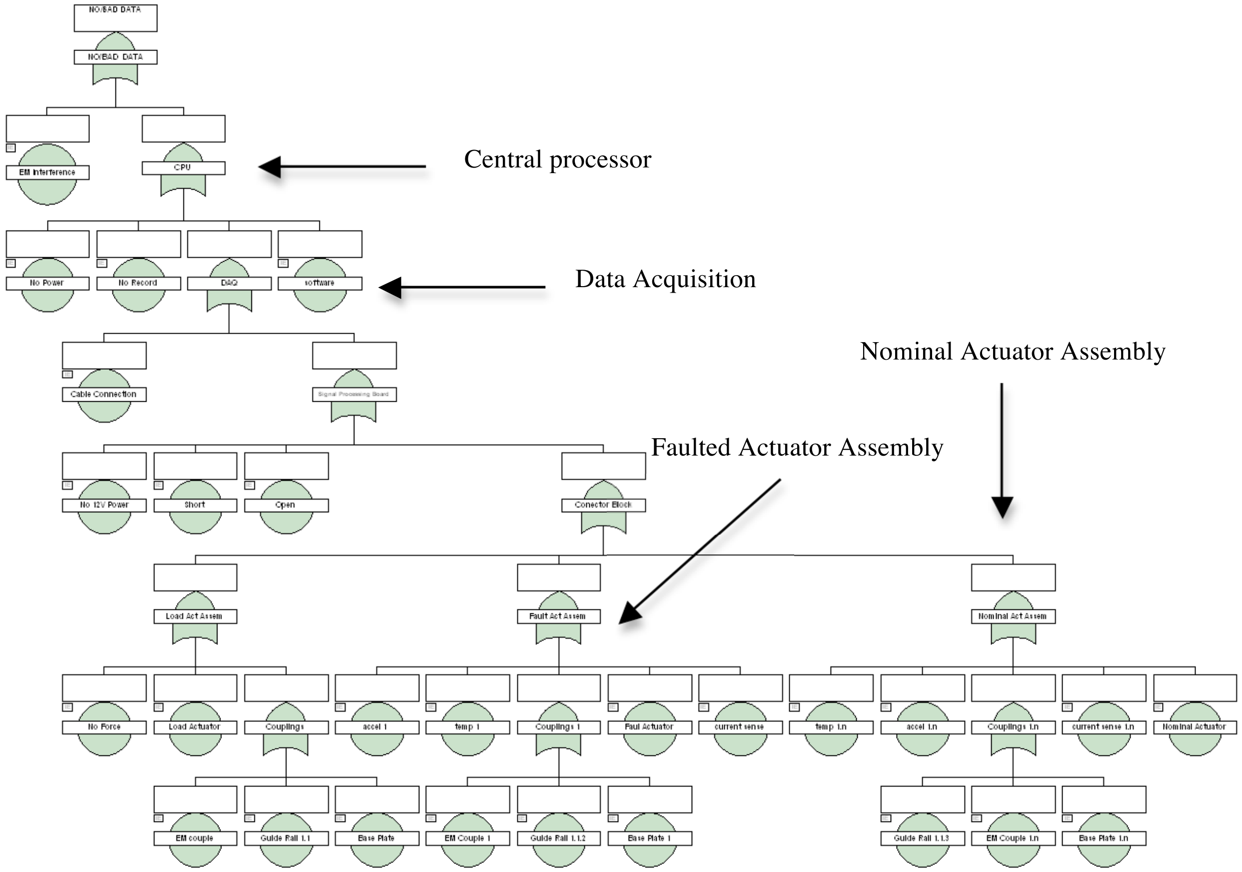

Figure 6: System fault tree model. Top state is no/bad fault data, dropping into the central processor, data acquisition, sensors, actuators, and support hardware.

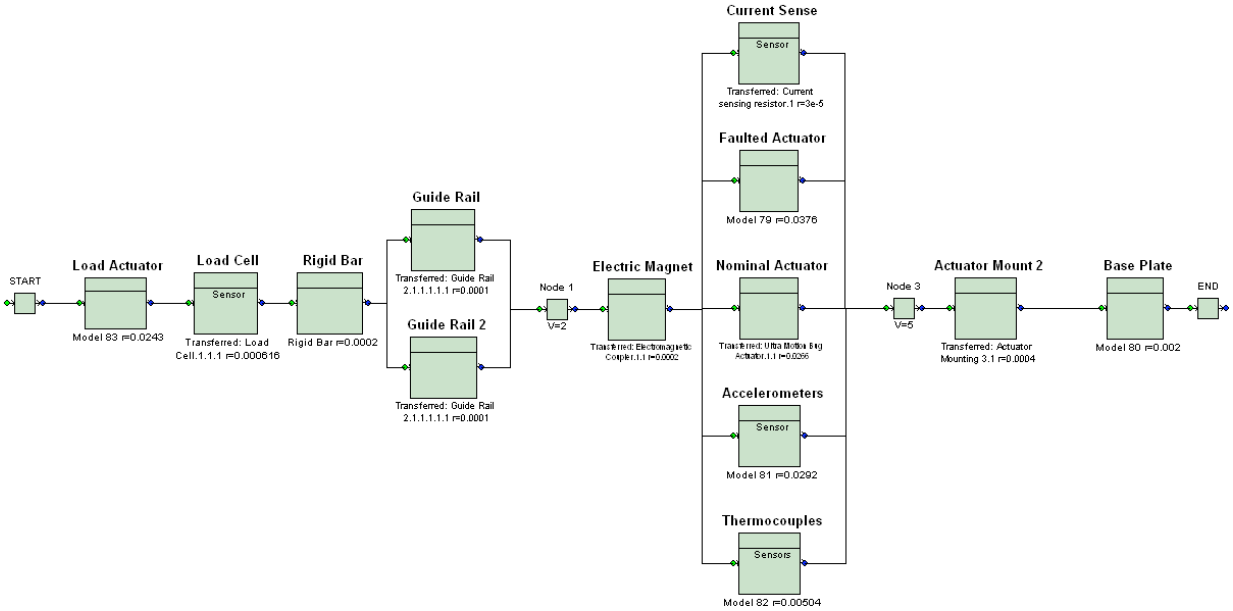

Figure 7: System reliability block diagram. START node on left initiates path from flight computer, into the system, ending with the base plate and other supporting structures.

6 ANALYSIS RESULTS

Running the models and calculating reliability values per the equations defined in Section 3, ITEM toolkit generates tabulated results detailed in the following sections. A time of operation was defined as two hours, or the average flight test duration for EMA fault injection experiments.

6.1 Fault Tree Analysis

The model suggests a high probability of reliable FLEA operation during a flight experiment. The analysis results from ITEM, shown in *Table 5*, indicate that FLEA has over a 96 percent chance of operating as designed during the two-hour test.

Table 5: ITEM toolkit fault tree analysis results.

Unavailability (Q)	0.094
Failure Frequency (ω_{system})	0.046
CFI (λ)	0.051
Reliability	0.963
Fussell-Vesely contributor	Accelerometers, 0.58
	Fault Actuator, 0.11
	Thermocouples, 0.10
	Nominal Actuator, 0.06
	Load Actuator, 0.05

However, there is a 5 percent chance FLEA experiences some sort of failure during the two-hour window. It appears from the ranking of components via the Fussell-Vesely calculation that the components most likely to cause problems are the accelerometers, responsible for over half of the system unavailability. Comparing the percent contributions relative to the FMECA, the components do not necessarily match up with the highest risk numbers. This may be due to the bias within the FMECA and lack of failure data regarding the custom components.

6.2 Reliability Block Diagram Analysis

The second reliability model also suggests a high probability of experiment completion, as the analysis results indicate a 98 percent change of reliable operation. *Table 6* presents the output from ITEM; FLEA appears to be a more reliable system according to this particular analysis. Furthermore, there is less than a 5 percent chance FLEA experiences a failure during testing. The Fussell-Vesely calculations also indicate the accelerometers contribute the most to system unavailability as a result of the long repair time and multiple installations. Checking with the FMECA, the one accelerometer does not have the highest risk, however when multiple are added together, then the FMECA begins to agree with the fault tree analysis. The high risk associated with the base plate and steel disk are not reflected with the analysis.

Table 6: ITEM toolkit reliability block diagram results.

Unavailability (Q)	0.085
Failure Frequency (ω_{system})	0.042
CFI (λ)	0.046
Reliability	0.912
Fussell-Vesely contributor	Accelerometers, 0.62
	Fault Actuator, 0.12
	Thermocouple, 0.11
	Nominal Actuator, 0.07
	Base Plate, 0.04

7 DESIGN RECOMMENDATIONS

The results presented here address critical component design and reliability analysis, and provide a dearth of design recommendations for building the next generation test stand that can more reliably generate quality actuator fault data sets and hence enable better actuator health monitoring. First, we acknowledge the fact that there is only one FLEA available for analysis, and that obtaining accurate component failure and repair rates is difficult; nevertheless, we believe that the reliability information was obtained from a legitimate source and used valid assumptions. Second, the standard FMECA was completed by the original FLEA designer and builder, which might introduce some bias; however, we believe that the designer was most intimately involved with the test stand, and hence is a reliable source for this information. And finally, the study was taken a step further by including fault tree and reliability block diagrams, albeit requiring stringent model assumptions; they produced meaningful results, at least from a mechanical point of view. Nevertheless, the validity of the model assumptions must be taken into consideration. The output is not coupled with a confidence level because the sample size is one, but that should not discredit the results. In fact, all of the assumptions expressed in section 3.4 do not hold over the life of FLEA; component failures do propagate through the system, failure rates do change over time, and as with any system with humans in the loop, ergodic trends will surface. But for a two-hour flight time, the assumptions hold true. Therefore, the following FLEA design recommendations are given:

- Require CNC machining for all alignment sensitive components
- Design for quick repair of high risk components
- Secure FLEA components
- Increase actuator assembly work envelope
- Avoid the use of steel screws in aluminum plates
- Ensure FLEA enclosure is free of debris
- Add service loops and stress relief to all wiring within the test stand

7.1 Ensure Alignment

Refering to *Table 5* and *Table 6*, in order to reduce the actuator unavailability contribution, actuator alignment is one design aspect that could be changed. Flight surface control actuators are usually installed as two-force members, allowing for additional degrees of freedom as the controlled flight surface directs the flight surface. As a result, their alignment is constrained to a single plane. It is difficult to replicate this setup in a test environment because the actuators are coupled and de-coupled from their load; so the actuators must be constrained in all six degrees of freedom and hence their fixed alignment is of paramount importance. CNC machining is advised for the hole patterns on the base plate and the rigid bar because the remaining actuator assembly parts are installed relative to their location. To replicate the actuator environment and measure similar loading effects, this recommendation is critical to the quality of FLEA's fault data sets.

7.2 Design for Quick Repair of Critical Components

Each repair rate holds the assumption that the component being repaired is not immediately available and must be ordered, machined, installed and calibrated like new. Having sensors and other high-risk electrical or mechanical components ready for installation is advised for quick turnaround. This practice would reduce the amount of accelerometer and thermocouple contribution to the system unavailability.

7.3 Secure FLEA components

The steel target disks should be secured with cotter pins or lock nuts and washers. Press fits or synthetic thread locks are also an option. The liberation of the steel disk within a high vibration environment is very likely, but nonetheless unacceptable. The actuators, sensors, linear rails, and the rigid bar should also be assembled with fasteners that contain lock nuts and/or lock washers to prevent them from coming loose during flight. It is worthy to note that increasing the flight time to four hours reduces system reliability to 85 percent. Knowing the models suggests that accelerometers contribute the majority of the reliability issues; design efforts should focus on more secure attachments, possible wireless applications, and good maintenance.

7.4 Increase Actuator Assembly Work Envelope

Introducing additional uncertainty in the vertical alignment of each actuator in the form of welded tabs is not advised; therefore increasing the size of the actuator assembly will remove the need for tabs in the first place. Doing so will promote accuracy in the installation and alignment of the actuators and increase the quality of the data sets. To further improve horizontal and vertical adjustment issues, a dedicated mounting bracket should be installed.

7.5 Avoid the Use of Steel Screws in Aluminum Plates

Screwing a steel fastener into an aluminum-threaded body will result in galling, regardless of the loading conditions. Stressing the fact that although, the base plate contributes a small amount to system unavailability during flight time, it should not be assumed that the threads are reliable. Steel fasteners should be used as through bolts with steel nuts and washers to secure the actuators and linear guide assembly. The FMECA risk priority number is the highest for the aluminum thread failure (448) and although the reliability models do not reflect this inference, a small design effort will eliminate this risk from affecting system reliability. Steel hardware will also allow for slotting of the aluminum plate and more adjustments available for alignment and installation of multiple actuators.

7.6 Ensure FLEA Enclosure is Free of Debris

Since the actuators casings have been opened to permit the installation of sensors. The seals that would ordinarily keep out debris have been rendered useless. To prevent actuator containments, the FLEA shell should keep out large particles. The addition of gasket material where the shell joins together will aid in the protection of the actuator lead screw assembly and prolong actuator availability.

7.7 Add Service Loops and Stress Relief to All Wiring

While it is not within the scope of this reliability study, it is worth noting that the wiring required to carry signals and power within FLEA needs to be considered airworthy and follow military specifications.

8 CONCLUSIONS

This paper has contributed to the development of quality EMA fault data through the analysis of critical component design and operation coupled with a reliability study of the FLEA itself over a two-hour flight experiment. This study presented various analysis tools to help infer FLEA availability and individual component contributions to system reliability and the guarantee of quality fault data sets. The analysis shows FLEA to have 0.91-0.96 probability of reliable performance during testing. The results for the two analysis types agree with each other, indicating that the system was modeled correctly.

Using the design recommendations will be an essential part of the next generation FLEA, giving the designer the confidence that their implementation will produce a more reliable EMA test stand, and generate quality and robust actuator fault data sets.

ACKNOWLEDGMENT

This research is supported in part by the Air Force Office of Scientific Research under Grant Number AFOSR FA9550-08-1-0158. Any opinions or findings of this work are the responsibility of the authors, and do not necessarily reflect the views of the sponsors or collaborators.

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