JOURNAL OF AIRCRAFT
Vol. 43, No. 4, July–August 2006

Prognostics and Health Management as Design Variable in Air-Vehicle Conceptual Design

David S. Bodden,* Wes Hadden,† Bill E. Grube,‡ and N. Scott Clements§
Lockheed Martin Aeronautics Company, Ft. Worth, Texas 76108

Flight critical systems in air vehicles achieve required reliability through different redundancy design techniques including physical system redundancy. Prognostics and health management technology provides the opportunity to eliminate some of the physical redundancy (and associated weight) through implementation of accurate remaining useful life algorithms. Consideration of this subsystem design approach up front during the conceptual design process rather than downstream during the detailed design phase of the air vehicle system can produce a more optimal air-vehicle configuration with regard to reliability and weight. Results are presented for an unmanned air-vehicle design optimization, which included remaining useful life algorithm confidence, control surface actuator redundancy, and control surface configuration as optimization variables. Optimization constraints included landing dispersion, mission reliability, and mission availability. Reductions in air-vehicle weight were achieved with reasonable algorithm confidence requirements.

I. Introduction

PROGNOSTICS and health management (PHM) related technologies have been viewed as a significant technology exploitation area in the past decade. The increasing number of papers cataloged in the Inst. of Electrical and Electronics Engineers Aerospace Conference and other conferences are a validation of this growing interest. One facet of the current generation of PHM technologies is condition-based maintenance, where estimation of remaining useful life (RUL) provides the potential to eliminate time change interval (TCI)-based maintenance concepts, resulting in reduced life-cycle cost (LCC) for systems, subsystems, and components.

The implementation of RUL estimation algorithms is one of the enabling technologies in highly integrated logistics concepts such as the autonomic logistics system currently in development for the Joint Strike Fighter (JSF) program.[1–3] The autonomic logistics concept is envisioned to be an automatic, seamless set of processes that will minimize the logistics footprint and cost while maintaining high mission reliability. As illustrated in Fig. 1, the JSF system employs a suite of both onboard and off-board RUL algorithms to provide prognostic and diagnostic capabilities for the air-vehicle systems, allowing reconfiguration and optimization of the air-vehicle configuration during a mission. The simultaneous, wireless, or ground-based transmission of the system health information to the autonomic logistics system enables implementation of a "just-in-time" approach to the parts supply chain.

The JSF air vehicle is unique in that it is being designed from program go-ahead with the incorporation of PHM technology. However, the technology is not being implemented as a safety critical application and, consequently, has not influenced the levels of physical system redundancy needed to meet reliability requirements for systems such as the flight control system. These systems were designed to meet various reliability requirements through the conventional approaches of highly reliable components and varying levels of physical system redundancy.

Received 5 May 2005; revision received 29 June 2005; accepted for publication 29 June 2005.

*Technical Fellow, Flight Control/Vehicle Management Systems, 1 Lockheed Boulevard; david.s.bodden@lmco.com.

†Senior Staff Systems Engineer, 1 Lockheed Boulevard; wes.hadden@lmco.com.

‡Systems Engineer, 1 Lockheed Boulevard; bill.e.grube@lmco.com.

§Systems Engineer, 1 Lockheed Boulevard; scott.clements@lmco.com.

Because an accurate RUL algorithm indirectly enhances system reliability, a natural question arises as to whether or not you could directly take credit for increased component and subsystem reliability resulting from condition based maintenance concepts. And if so, could you eliminate physical system redundancy? For air vehicles, this would be quite a carrot because of weight savings.

The focus of this paper is on what the authors will refer to as second-generation PHM technology insertion. Second generation refers to the implementation and dependency of PHM technology in safety critical applications. Consider the following two tenets.

A. Tenet 1

Accurate formulation and reliable implementation of remaining useful life algorithms result in a reliability of one for a particular component, subsystem, or system.

Well, not really, but it sounds good on paper. If one can always predict the remaining useful life of a component with an accurate time-to-failure window that exceeds the maximum mission length, then the component would never fail in flight, and physical system redundancy would not be required. However, as pointed out in Ref. 4, determination of remaining useful life is a probabilistic event, and one cannot know exactly when a component will fail because the factors responsible for failure generally have unknown future values. However, a statistical bound to a certain confidence level can be placed on a remaining useful life prediction based on previously experienced failures in a manner similar to that used to predict a mean time between failure (MTBF) for a piece of hardware. Consequently, in a system analysis the effects of RUL prediction confidence or effectiveness and the subsequent impact of the RUL algorithm on system reliability, could be evaluated.

B. Tenet 2

Optimization of the air-vehicle configuration for reliability facilitates an optimal system/subsystem design for reliability.

Basically, what is being claimed here is that to achieve an optimal air-vehicle design (optimal with regard to weight for example) the reliability requirements should be considered during the conceptual design process. For example, consider the two air-vehicle configurations illustrated in Fig. 2. Which of the two configurations would be the optimal configuration with regard to weight and mission reliability? with regard to weight and life-cycle cost? What is the optimal number of control surfaces and physical actuator redundancy?

In this paper, we begin an examination of these two tenets with regard to air-vehicle conceptual design optimization. Specifically, we wish to optimize the number of control surfaces, levels of physical actuator redundancy, and RUL algorithm confidence levels in

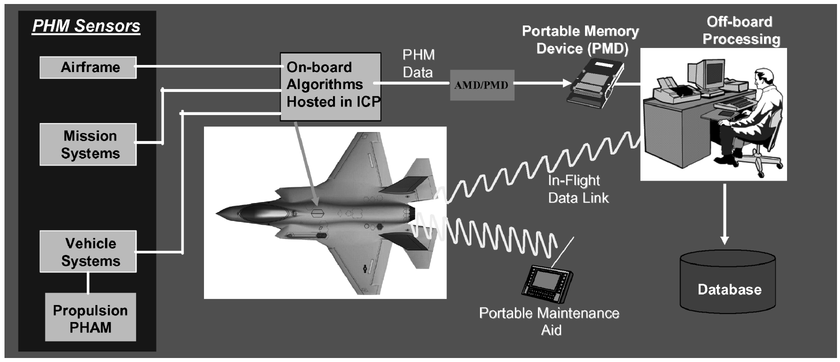

Fig. 1 PHM integration in Joint Strike Fighter vehicle systems.

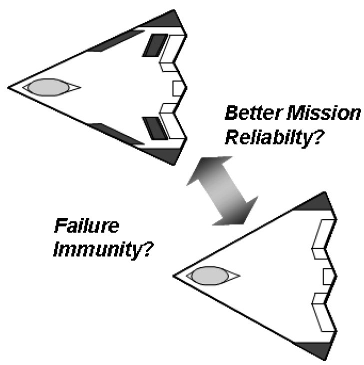

Fig. 2 Notional UAV conceptual design.

order to meet specified reliability constraints while minimizing the vehicle weight and life cycle cost. Optimization constraints and requirements are identified, and an optimization process and methodology with PHM as a design variable are developed and evaluated. Note that the term PHM as used in this paper refers to incorporation of RUL algorithms.

II. Air-Vehicle Conceptual Design Process

The typical conceptual design process is illustrated in Fig. 3. A reference design mission along with numerous performance criteria such as time to accelerate, turn rate, etc. provides the design constraints. A reference-vehicle configuration is drawn up, and a reference technology set is selected to provide the appropriate level of technology insertion. The air-vehicle design is then optimized to meet the mission and performance constraints. Optimization usually involves adjusting design parameters such as wing sweep, wing area, engine cycle, etc. This first optimization pass is obviously performance based.

The next step of the process is to perform cost/benefit or optimization studies with regard to achieving physical reality with the air-vehicle design. Typical parameters include subsystem design, avionics, propulsion, structural design, etc. It is at this point in the conceptual design that it is feasible to evaluate optimizing the air-vehicle design for reliability with PHM technology as a design variable.

A. Air-Vehicle Study Configuration

In selecting an air-vehicle conceptual design for this research, an unmanned-air-vehicle (UAV) design was targeted because of the historic high loss rates for UAVs,[5] along with the increasing focus in the military for unmanned air-vehicle platforms. Consequently, a UAV conceptual design provided the near-term opportunity for the most impact of this methodology. The selected configuration was the sea-based endurance (SBE) conceptual design developed by Lockheed Martin Aeronautics Company using internal independent research and development funding. The SBE was developed as a follow-on to the multirole endurance conceptual design, which resulted from a contracted research and development program with NAVAIR.[6] The SBE design is illustrated in Fig. 4.

Key features that led to the selection of the SBE design included:

1) A six-degrees-of-freedom simulation had been developed along with a flight control system and autopilot. This was necessary for evaluating the consequences of failure for critical failure modes.

2) The flight control actuators incorporated in the design were electrohydrostatic actuators (EHA), similar to those used on the JSF Aircraft. Reliability data for the actuators along with modeling data would be readily available.

3) The SBE is designed to land and take off from naval carriers. The carrier landing task would provide quantifiable performance metrics with regard to assessing the consequence of failures.

To conduct the optimization problem outlined in Sec. I, additional control surfaces were added to the baseline configuration as an optimization option. Preliminary stability and control analysis indicated that splitting each of the flaperons and rudders into two segments each would provide the optimization space of interest. The SBE with "split" control surfaces is illustrated in Fig. 5.

B. Electrohydrostatic Actuators

Electrohydrostatic actuators are self-contained actuation systems that consist of a mechanical component designated as the EHA and an electrical component designated as the electronic unit (EU). The EHA incorporates an integral electric-motor-driven hydraulic pump powering a linear hydraulic ram. The EHA comes in two variations: a simplex version and a dual redundant version. The EU contains both the power drive electronics (PDE) and the control electronics (CE). The EU similarly comes in both simplex and dual variants. The simplex version contains one CE and one PDE, whereas the dual version contains two CEs and two PDEs. A schematic of both versions is shown in Fig. 6.

III. Reliability Requirements

To provide the reliability constraints on the optimization problem, reliability metrics that exposed critical failure probabilities and could be modeled at the conceptual design level were sought. It was desired that the requirements set the rate of critical failures to both a design controllable and verifiable measure of performance, while also providing acceptable levels of aircraft availability. Finally, the requirements should provide for achieving air-vehicle loss rates consistent with manned fighter aircraft.

A. Failure Immunity

Failure immunity identifies the consequences of failure of a failure mode or a combination of failure modes. Failure immunity is different from a classical mission reliability or failure coverage requirement in that probabilities are not "rolled up" or aggregated at the top level to determine the total probability. There is no need to sum the probabilities of a variety of functions to produce a total probability of loss of function for failure immunity. Only the probability of each individual cut set that is sufficient to cause loss of function is analyzed. A cut set is a component fault or group of component faults that logically combine to form a single functional

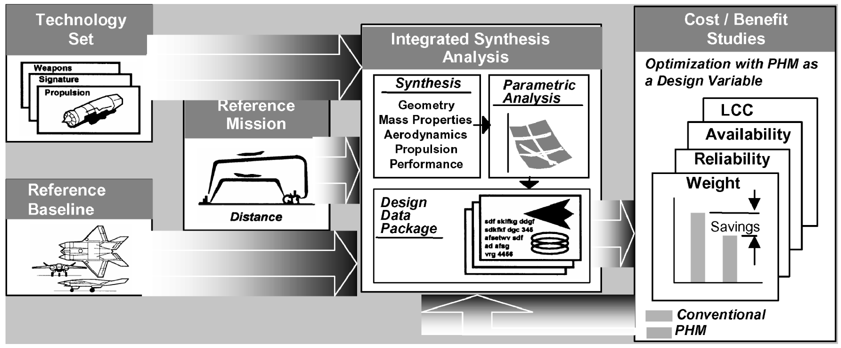

Fig. 3 Air-vehicle conceptual design process.

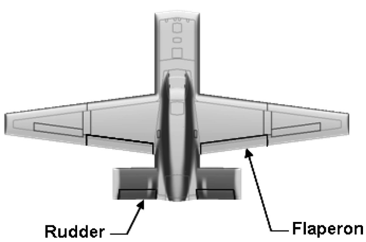

Fig. 4 SBE aircraft utilizes rudders and flaperons for control.

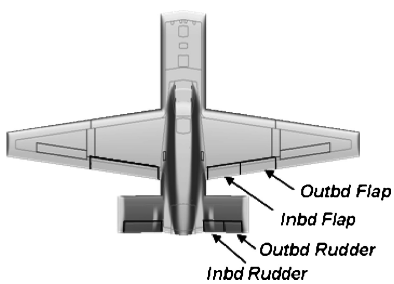

Fig. 5 SBE UAV with split flaperons and rudders.

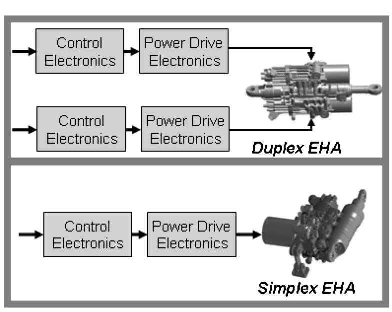

Fig. 6 Electrohydrostatic actuator variants.

fault. The FI requirements used in this study were consistent with manned-vehicle requirements:

1) The air vehicle shall maintain flying qualities sufficient to operate after any single failure that has a probability of occurrence greater than 1×10^{-7} per flight hour.

2) The air vehicle shall maintain flying qualities sufficient to return to its point of origin after any single failure or combination of failures that has a probability of occurrence greater than 1×10^{-7} per flight hour.

The failure immunity requirements indicate that an assessment must be performed to evaluate the consequences of any single failure or multiple failures that do not meet the probability of occurrence criteria. The SBE aircraft is designed to operate off of an aircraft carrier and conduct a long-range reconnaissance mission with a maximum duration of 13.5 h. It is not designed as a combat air-vehicle. Consequently, the critical task with failures is to be able to land on the carrier.

In landing on the carrier, the desired touchdown point is midway between the number two and three wires. Considering that the wires are 40 ft apart and that it is assumed that there are only three wires, the tolerable longitudinal landing dispersion at touchdown is −60 ft (aft) and +20 ft (forward). Laterally from the centerline, +10 ft is considered desirable dispersion tolerance.

B. Mission Reliability

A mission-reliability requirement provides a statistical assessment of the overall fleet loss rate. Unlike the approach in the failure immunity analysis where the failure rate that causes critical failures is applied as a time-independent event, mission reliability factors in the length of the mission with the failure rate that causes a critical failure.

$$\mathrm{PLOA} = 1 - e^{-\lambda t}$$

where PLOA is the probability of loss of aircraft, λ the critical failure rate of the item, and t the length of the mission in flight hours. Note that in the context of this paper, PLOA and mission reliability can be considered as the same.

In setting a requirement for mission reliability consistent with manned vehicles, the approach outlined in Ref. 5 was first considered. In this reference, the argument is made that based on historical data an unmanned air-vehicle loss rate of 2.3×10^{-5} per flight hour allocation to the flight control system would provide a PLOA consistent with manned air-vehicles. Transforming this PLOA on the basis of 10,000 missions with a mission length of 13.5 hours, the requirement would be 3.1 losses per 10,000 missions. Considering an allocation of this loss rate caused by the actuators of 14%, the requirement was set at 0.43 losses per 10,000 missions.

Historical fighter data at Lockheed Martin based on conventional integrated servoactuators indicated that an allocation to the flight control actuation would be closer to 0.13 losses per 10,000 missions. Consequently we chose to utilize these two values as an upper and lower bound in the optimization studies.

C. Mission Availability

An availability requirement reflects the percent of time a product would be available for use and provides a means to trade the time between failures and the time to repair in order to achieve the highest mission performance. Inherent availability A_i is the design controllable availability and excludes induced failures, suspected failures, preventive maintenance downtime, supply delays, and administrative delays. It is defined as

$$A_i = \frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}}$$

where MTBF is the mean time between failure and MTTR the mean time to repair. The availability requirement for the actuation system was set equal to the performance of the actuation systems of manned fighters, which is approximately 99%.

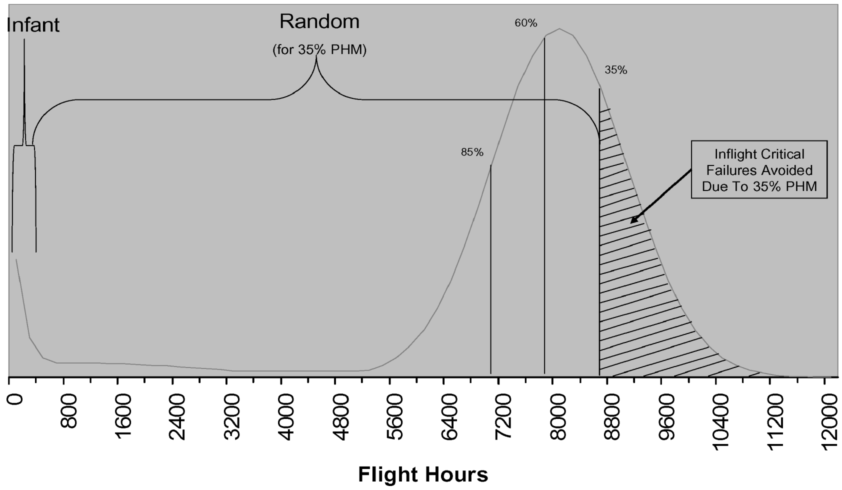

Fig. 7 PHM effectiveness definition.

IV. Modeling

PHM was modeled in the study as a percent effectiveness (e.g., 85, 60, or 35%) to correctly detect and announce the onset of the loss of a critical function at least one mission length in advance of the failure actually occurring. Figure 7 provides a notional view of a probability density function (PDF) for the infant, random, and wear-out failures. Infant mortality was assumed to be removed by the supplier/overhaul facility through an effective screening process. The remaining areas were modeled one of two ways. The first area addresses those failures that cannot be prognosticated at least one mission length before they occur. This area has the appearance of a random failure and is modeled as such. The second area is where prognostics can detect and report the failure before the mission starts. For example, the 35% line, on the curve at about 8600 hours, is the point on the PDF where 35% percent of the critical failures can be detected and reported at least one mission length in advance.

Time-change-interval (TCI) modeling was also performed to assess the impact on PLOA. This was estimated by analyzing the supplier's FMECA and removing those failure rates that could be expected to be mitigated through a depot overhaul. Also considered in the TCI analysis was supplier replacement of fluids and seals whenever an EHA is returned to the depot. The analysis resulted in an estimate that 63% of failures and wear modes could be corrected at a TCI of 2000 flight hours.

A. Failure Immunity

The probabilities associated with a failure condition were determined from the supplier's FMECA and reliability/maintainability prediction reports. This analysis identified single faults or combinations of faults that would cause components and systems to fail, depriving the vehicle of control functions needed for meeting landing dispersion requirements. Single or multiple failures that did not meet the failure immunity probability of occurrence requirements were then analyzed with regards to landing dispersion requirements. The process is illustrated in Fig. 8.

To assess the consequences of failures with regard to meeting the landing dispersion criteria, batch simulations were run with both single and multiple failures for various combinations of split and nonsplit control surfaces that allowed the landing dispersion to be modeled for any failure combination: 1) no failures; 2) left rudder; 3) left flap; 4) inboard flap; 5) outboard flap; 6) inboard rudder; 7) outboard rudder; 8) left rudder, second failure; 9) left flap, second failure; 10) left flap and right rudder; 11) inboard rudder and inboard flap; 12) inboard rudder and outboard flap; 13) outboard rudder and inboard flap; 14) outboard rudder and outboard flap; 15) left inboard rudder and left outboard rudder; 16) left inboard flap and left outboard flap; and 17) right inboard rudder and left flap. The

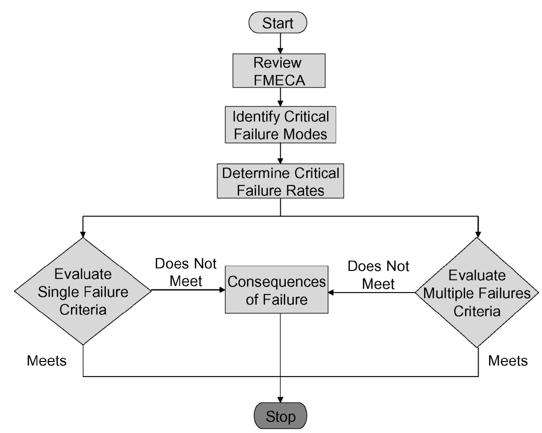

Fig. 8 Failure immunity analysis process.

simulations were conducted for both glide slope and lateral offsets and in worst-case winds and gusts.

In general, the SBE aircraft could meet the dispersion criteria for single or multiple failures except for a rudder failure or dual flap failure. For configurations where the rudder was split into two segments, only same-side dual rudder failures resulted in an inability to meet the landing dispersion criteria. The primary reason for the air-vehicle tolerance to failure was the control system design. Lockheed Martin has developed a decentralized, hierarchical control system architecture and design synthesis approach that utilizes a control allocation scheme[7,8] to continuously optimize available control power to meet mission requirements. When a control surface failure is detected, the remaining control surfaces are continuously "reconfigured" to optimize allocation of available control power as required in each controlled axis.

B. Mission Reliability

The mission reliability model calculates PLOA using a series-parallel mission success diagram as illustrated in Fig. 9. The results from the landing dispersion analysis for the SBE showed mission success required three subsystems to function: 1) either flap system, left or right; 2) the left rudder subsystem; and 3) the right rudder subsystem. RELEX RBD, a commercial mission reliability software tool, was used to create the mission success block diagram representation and to calculate the PLOA. Within RELEX, EHAs and EUs were modeled as components with varying levels of PHM, and these elements were combined in logical ways to represent the configuration under study. The EHA was modeled with and without a TCI.

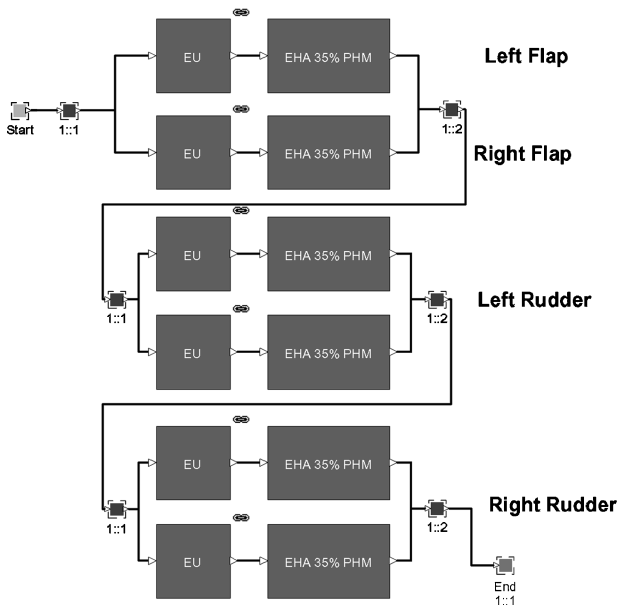

Fig. 9 Typical RELEX mission success model.

C. Mission Availability

Mission availability was calculated for each option by obtaining the values of MTBF and MTTR from the reliability and logistic predictions and using the equation for A_i identified in Sec. III.

D. Life-Cycle Cost

The following equation identifies the factors used in modeling the life-cycle cost for each of the air-vehicle configuration options.

$$\begin{aligned}\text{SupportCost}\\ &= (\text{OnAircraftMMH/FH})(\text{TotalFleetFlightHrs})(\text{LaborRate})\\ &+ (\text{OffAircraftMMH/FH})(\text{TotalFleetFlightHrs})(\text{LaborRate})\\ &+ (\text{ItemWeight})(\text{Shipping\&PackagingRate})(\text{RemovalRate})\\ &+ (\text{AverageSparePartCost})(\text{SparePartRate})\\ &+ (\text{UnitCost})(\text{CondemnRate})\\ &+ (\text{UnitCost})(\text{LRCSparesRequired})\end{aligned}$$

Customer library data for level-of-repair analyses were used as the basis for labor rates and packaging and shipping rates. The MMH/FH predictions generated in the logistic predictions were used to determine the amount of support that the different options would require.

For configuration options with PHM, the advantages of being able to schedule/prepare maintenance for impending failures were factored into the analysis. The following equation was used to estimate the costs associated with maintaining each of the air-vehicle configuration options and to take advantage of advance warning of failures through RUL predictions.

$$\begin{aligned}\text{SupportCost}\\ &= (\text{OnAircraftMMH/FH})(\text{PHMFactor})(\text{TotalFleetFlightHrs})\\ &\times (\text{LaborRate})\\ &+ (\text{OffAircraftMMH/FH})(\text{TotalFleetFlightHrs})(\text{LaborRate})\\ &+ (\text{ItemWeight})(\text{Shipping\&PackagingRate})(\text{RemovalRate})\\ &+ (\text{AverageSparePartCost})(\text{SparePartRate})\\ &+ (\text{UnitCost})(\text{CondemnRate})\\ &+ (\text{UnitCost})(\text{LRCSparesRequired})(\text{PHMFactor})\end{aligned}$$

The on-aircraft maintenance times were adjusted to remove delay times and other inefficiencies because PHM should allow the maintainer to schedule approaching maintenance activities to achieve the greatest efficiency of resources. Similarly, it was assumed that PHM will afford the logistic chain the ability to reduce the safety level spare LRC quantities caused by the advanced warning of spare needs. Note that the direct LCC associated with the development and maintenance of the RUL algorithms was not modeled because of the current lack of data. It was assumed in the optimization studies that lower values of RUL algorithm effectiveness would result in lower overall LCC.

E. Weight

Weight was modeled as increments to the baseline configuration weight where the baseline consisted of the airframe as illustrated in Fig. 4 with duplex actuators on each control surface. Weight increments were calculated to model the effects of varying the level of actuator redundancy on each control surface and to model the effects of splitting the control surfaces. The latter included modeling the effects of changing the substructure to compensate for the new load paths.

V. Optimization

The optimization problem is stated as follows: Optimize the air-vehicle configuration to minimize the weight and life-cycle cost subject to the following constraints:

1) Landing dispersion for longitudinal is $-60 < x < 20$ and for lateral is $-10 < y < 10$.

2) Mission reliability PLOA ≤ 0.43 or ≤ 0.13.

3) Mission inherent availability $A_i \geq 0.99$.

The optimization space is summarized here:

For the airframe configuration,

$j = 1$: Baseline
$j = 2$: Split flaps
$j = 3$: Split rudders
$j = 4$: Split flaps and rudders

For the actuator configuration,

$k = 1$: Simplex
$k = 2$: Duplex
$k = 3$: Simplex flap and duplex rudder
$k = 4$: Simplex with duplex electronics

For the PHM configuration,

$m = 1$: No PHM
$m = 2$: 85% PHM effectiveness
$m = 3$: 60% PHM effectiveness
$m = 4$: 35% PHM effectiveness
$m = 5$: No PHM with TCI (2000 hrs)

The design parameters j, k, and m represent the combinations of airframe design and PHM effectiveness that were modeled with regard to weight, life-cycle cost, mission reliability, and mission availability. For each combination of parameters, the consequences of failures in terms of landing dispersion were also modeled for the worst-case failure mode of those identified earlier. As discussed in Sec. IV, this was generally limited to single failures of the rudder. Multiple failures were not a factor in the optimization because the failure immunity analysis identified the probability of occurrence to be less than the requirement of 1×10^{-7}.

The design parameter m, which corresponds to the level of PHM effectiveness, was modeled two ways: 1) applied to the EHA only and 2) applied to both the EHA and EU. Even though the maturity of PHM for mechanical systems is significantly greater than electronic systems, modeling of the effects of electronics PHM provided the opportunity to assess if there were any significant impacts.

In performing the optimization, typical gradient search algorithms would have required relatively smooth continuous data in order to calculate the required gradients. Because the models developed for this problem did not conform to this constraint, a genetic-algorithm optimization routine was implemented.

A genetic algorithm (GA) uses the ideas of biological reproduction and survival of the fittest to direct the optimization search.[9] To set up the genetic optimization, a configuration (or point in the search space) is first described as a chromosome or set of genes. Each gene corresponds to a particular trait of the configuration. For this optimization the genes correspond to the control surface configuration, actuator type, and PHM effectiveness, as illustrated in Fig. 10.

The results of the optimization are summarized in Table 1. Cases 1–4 in Table 1 provide the optimal design results for no PHM, no

Table 1 Optimization results

Case	Mission reliability constraint (Failures/10,000 missions)		PHM effectiveness required, %	Δ Weight, lbs[a]	Δ LCC, \$ M[a]	Optimal configuration		
	0.13	0.43				j	k	m
1) No PHM[b]	X	——	——	−45	−11.7	3	4	1
2) No PHM–TCI[b]	X	——	——	−45	21.6	3	4	5
3) EHA PHM[b]	X	——	35	−45	−11.8	3	4	4
4) EHA/EU PHM	X	——	60	−101	−35.7	1	3	3
5) No PHM[b]	——	X	——	−45	−11.7	3	4	1
6) No PHM–TCI	——	X	——	−101	−14.6	1	3	5
7) EHA PHM	——	X	35	−101	−33.1	1	3	4
8) EHA/EU PHM	——	X	35	−101	−32.7	1	3	4

[a]As compared to the baseline configuration (no split control surfaces, duplex actuators). [b]Could not meet the mission availability criteria for these cases.

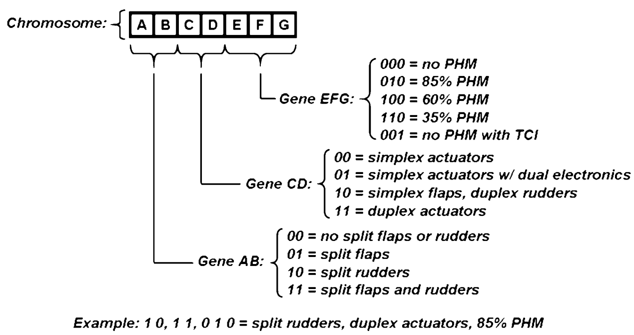

Fig. 10 Chromosome definition for GA optimization.

PHM with TCI, EHA PHM, and EHA with EU PHM with the mission reliability constraint set at the more stringent bound of 0.13 failures per 10,000 missions. For cases 1–3, the optimal design would be split rudders with simplex actuators and duplex electronics and no PHM. This result can be attributed to two factors. First, the stringent mission reliability constraint drives the optimization into a higher physical redundancy threshold that could not be offset by the impact of PHM. Second, in examining the FMECA for the EHA, only about 18% of the failure modes are considered critical. Consequently, PHM is not providing significant benefit with regard to critical failure modes.

Case 3 with 35% PHM effectiveness showed a slight improvement over case 1 with regard to LCC as a result of assumptions in the LCC modeling that PHM would result in fewer spare requirements and reduced maintenance time. However, as identified in Sec. IV, LCC contributions associated with development and maintenance of the PHM capability were not modeled, which would most likely eliminate this benefit. None of these solutions met the mission availability constraint of 99% but were very close, around 98.8%.

Providing PHM for the EU and EHA (case 4) resulted in a significantly improved conceptual design from both a weight and life-cycle cost standpoint. This can be attributed to the EU percentage of critical failure modes being around 45%. PHM for the EU is consequently much more effective from a mission reliability standpoint. An interesting point associated with this solution is that the optimal solution is the baseline configuration with simplex flap actuators instead of duplex. If this configuration design were for a manned air-vehicle, it would most likely be considered unacceptable because it does not provide fail-op/fail-safe capability for the rudder, even though the statistical requirements were met. If a fail-op/fail-safe constraint were a requirement, it would be incorporated in the landing dispersion modeling, and this configuration would not have met the requirements.

Cases 5–8 are a reoptimization with the mission reliability constraint set at the upper bound of 0.43. The best solution of these four optimizations is case 7, which is the same configuration as case 4 except that EU PHM is not required because of the less stringent mission reliability requirement.

The incorporation of a scheduled time change interval provided a viable configuration design solution for both mission reliability constraints. However, as expected, the life-cycle cost associated with this solution tended to make it infeasible, especially for the more stringent mission reliability constrain, which drove the physical redundancy required upwards resulting in a higher parts count and associated increase in LCC caused by TCI.

VI. Conclusions

The implementation of PHM as a design variable was demonstrated to impact the conceptual design with regard to weight, life cycle, mission availability, and mission reliability. The optimal design solution and level of PHM effectiveness required were sensitive to the constraint on mission reliability and, to a much lesser extent, on mission availability. Overall, the implementation of PHM did not have the impact that was anticipated prior to the start of the study. This can be contributed to the high inherent reliability of the EHAs. The EHA MTBFs utilized in the modeling were based on manned fighter applications and associated high reliability. Including EHA reliability as an optimization parameter would seem to be a logical next step. It is expected that PHM would have a significantly higher impact on the conceptual design if lower reliability actuators were incorporated.

To improve and expand this optimization methodology, the life-cycle costs associated with PHM need to be modeled and implemented. Of course, this would be a significant challenge because of the lack of data and field experience. To utilize PHM in a safety critical application as presented in this paper would most likely have a significantly greater impact on LCC as compared to current applications of PHM.

References

[1]Henley, S., Currer, R., Scheuren, B., Hess, A., and Goodman, G., "Autonomic Logistics—The Support Concept for the 21st Century," *Proceedings of the IEEE Aerospace Conference*, Nov. 2000.

[2]Smith, G., Schroeder, J., Navarro, S., and Haldeman, D., "Development of a Prognostics & Health Management Capability for the Joint Strike Fighter," *Proceedings of the Autotest Conference*, 1997.

[3]Ferrell, B., "Air Vehicle Prognostics and Health Management," *Proceedings of the IEEE Aerospace Conference*, Nov. 2000.

[4]Engel, J., Gilmartin, B., Bongort, K., and Hess, A., "Prognostics, The Real Issues Involved with Predicting Life Remaining," *Proceedings of the IEEE Aerospace Conference*, Nov. 2000.

[5]Clough, B., "Autonomous UAV Control System Safety—What Should it Be, How Do We Reach It, and What Should We Call It?," *Proceedings of the IEEE National Aerospace and Electronics Conference*, 2000.

[6]Wadley, J., Tallant, G., and Ruszkowski, R., "Adaptive Flight Control of a Carrier Based Unmanned Air Vehicle," AIAA Paper 2003-5596, Aug. 2003.

[7]Virnig, J., and Bodden, D., "Multi-Variable Control Allocation and Control Law Conditioning When Control Effectors Limit," AIAA Paper 94-3631, Aug. 1994.

[8]Bordignon, K., and Bessolo, J., "Control Allocation for the X-35B," AIAA Paper 2002-6020, Nov. 2002.

[9]Back, T., Hammel, U., and Schwefel, H.-P., "Evolutionary Computation: Comments on the History and Current State," *IEEE Transactions on Evolutionary Computation*, Vol. 1, No. 1, April 1997, pp. 3–17.